Simultaneous extensional exhumation across the Alboran Basin: Implications for the causes of late orogenic extension

J.P. Platt  Research School of Earth Sciences at University College London—Birkbeck, Gower Street, London WC1E 6BT, UK
M.J. Whitehouse Laboratory for Isotope Geology, Swedish Museum of Natural History, Box 50007, SE-104 05 Stockholm, Sweden
S.P. Kelley Department of Earth Sciences, Open University, Walton Hall, Milton Keynes MK7 6AA, UK
A. Carter Research School of Earth Sciences at University College London—Birkbeck, Gower Street, London WC1E 6BT, UK
L. Hollick Research School of Earth Sciences at University College London—Birkbeck, Gower Street, London WC1E 6BT, UK

ABSTRACT

Large-scale crustal thinning of the Alpine orogen in the westernmost Mediterranean (Alboran Sea and surrounding regions) was rapid, simultaneous over an area of 60,000 km², and took place ~25 m.y. after the main crustal thickening event. Crustal thinning, which locally exposed subcontinental mantle, was accompanied by high-grade metamorphism and partial melting. Both U-Pb dating of zircon and thermal modeling of cooling histories indicate that the thermal peak was reached between 23 and 21 Ma over the entire region. Final exhumation and cooling followed immediately. Possible explanations for this dramatic late orogenic extension include subduction rollback, slab detachment, lithospheric delamination, and convective removal of subcontinental lithosphere. Of these processes, only convective removal of subcontinental lithosphere predicts a significant time lapse between crustal thickening and the onset of extension, the simultaneity of extension over the whole region, and heating of rock during rapid exhumation to produce the high-grade metamorphic event.

Keywords: metamorphism, geochronology, zircon, Alboran Sea, Betic Cordillera.

INTRODUCTION

The Alboran domain is a type example of late orogenic extension: a contractional orogen, formed in early Tertiary time, underwent rapid crustal thinning in the middle Tertiary, resulting in the subsidence of much of the region below sea level (Platt and Vissers, 1989). Thinning occurred during continuing convergence between Africa and Iberia and was accommodated by crustal thickening in a peripheral thrust belt that defines the external Betic-Rif arc. This phenomenon is arguably an extreme example of processes that are active today in regions such as the Aegean and, on a larger scale, in extending collisional plateaus such as Tibet. The ultimate fate of such collapsing orogens may be the formation of new ocean basins, as has started to happen in the Tertiary age for this event is suggested by a Sm-Nd age of 21.5 m.y. on garnet and clinopyroxene (Zindler et al., 1983), a U-Pb age of 1.7 Ma on zircon (Sa Ânchez-Rodriguez and Gebauer, 2000), and a mean Lu-Hf age of 255 m.y. at ODP Site 976 in the Alboran Sea, and two regions of high-grade metamorphic rocks in the central and eastern Betic Cordillera. Data from each location are summarized in Figure 2, and the geologic relationships are described briefly in the rest of this section. The full radiometric data are given in the supplementary tables (Tables DR1–DR4).

Orogenic Peridotites and Their Crustal Envelopes

The Ronda and Beni Bousera massifs are sheet-like bodies of mantle peridotite as thick as several kilometers interlayered within high-grade metamorphic rocks of crustal origin (Torné et al., 1992). Graphite pseudomorphs after diamond indicate that the peridotites have at some stage been at depths >150 km (Davies et al., 1993; Pearson et al., 1989). Part of their exhumation history may have taken place in the early Mesozoic during separation of Eurasia from Gondwana, but they were brought from ~70 km depth to mid-crustal levels during the later stages of Alpine orogeny, accompanied by heating and melt percolation (Van der Wal and Vissers, 1993; Lenoir et al., 2001). A middle Tertiary age for this event is suggested by a Sm-Nd age of 21.5 ± 1.8 Ma on garnet and clinoxyroxene (Zindler et al., 1983), a U-Pb age of 19.9 ± 1.7 Ma on zircon (Sánchez-Rodríguez and Gebauer, 2000), and a mean Lu-Hf age of 25 ± 1 Ma on garnet (Blichert-Toft et al., 1999), all from garnet pyroxenite layers in the peridotites.

1GSA Data Repository item 2003024, Tables DR1–DR4, U-Th-Pb, Ar-Ar, and fission-track data on zircons and on apatites, is available from Documents Secretary, GSA, PO. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

© 2003 Geological Society of America. For permission to copy, contact Copyright Permissions, GSA, or editing@geosociety.org. Geology; March 2003; v. 31; no. 3; p. 251–254; 4 figures; Data Repository item 2003024.
The crustal rocks overlying the peridotites commonly show an apparently coherent metamorphic zonation from high-pressure granulite facies rocks at the contact to low-grade or unmetamorphosed rocks 5 km higher in the structural sequence (Argles et al., 1999; Bouybaouène et al., 1998), indicating that exhumation of the peridotite massifs was primarily a consequence of extreme crustal thinning. Pressure-temperature paths from the crustal envelope indicate decompression at increasing temperature to shallow depths (Argles et al., 1999). U-Th-Pb ion-microprobe analyses of zircons from the granulites give high-precision ages in the range 22.7 ± 21.3 Ma (Figs. 2 and 3). The dated zircons are equant, with a structureless gray appearance under cathodoluminescence (Fig. 4), and some have relict cores that give a wide range of older ages, suggesting a detrital origin (Table DR1; see footnote 1). The early Miocene ages likely correspond to the peak temperature of metamorphism (~800 °C). The Ar-Ar and fission-track ages show that cooling was extremely rapid and was completed in ~1 m.y. (Fig. 2).

**ODP Site 976**

High-grade pelitic schist and migmatitic gneiss drilled at ODP Site 976 in the Alboran Sea show decompression from 1050 MPa (40 km depth) to 350 MPa (13 km depth) accompanied by an increase in temperature from 550 ± 50 °C to 675 ± 25 °C (Soto and Platt, 1999). This event was followed by exhumation to the surface and rapid cooling. The core did not yield metamorphic zircon, but Ar/Ar dating on micas and apatite fission-track analyses indicate that cooling from 420 °C during the final stage of exhumation occurred very rapidly in the interval 20.5–18 Ma (Fig. 2), which coincides with the start of sedimentation in the Alboran Sea basin (Platt et al., 1998). Thermal modeling suggests that cooling from peak temperature started at 22–21 Ma.

Platt et al. (1998) suggested that the thermal evolution required the complete removal of lithospheric mantle from beneath the region; they referred to this process as delamination, but noted that convective removal of lithosphere could produce the same effect, given the likely temperature at the Moho and a wet peridotite rheology (Houseman and Molnar, 1997).

**Central and Eastern Betics**

Radiometric ages from high-grade pelitic schist and anatectic granite in two other locations in the Betic Cordillera confirm and extend these data. In the Almuñécar region (Fig. 1), a zoned metamorphic sequence increases in grade from chloritoid zone downsection to sillimanite gneiss. From the garnet zone up in grade, all rocks show evidence for decompression from relatively high pressure assemblages including kyanite and rutile in pelitic rocks to low-pressure assemblages containing either andalusite or sillimanite followed by andalusite. The present-day metamorphic sequence is strongly condensed, and decompression was accompanied by intense ductile deformation. The U-Pb zircon age (19.3 ± 0.3 Ma), Ar-Ar ages on micas, and fission-track data on apatite all indicate very rapid cooling from peak temperature in ~1 m.y. (Fig. 2). Sillimanite gneiss and anatectic granite from the Sierra Cabrera yielded zircons that were either relict or undatable owing to excessive U contents and high common Pb, but one grain yielded a maximum age of 19.8 Ma. This age is supported by a Rb-Sr isochron age from the granite of ca. 20 Ma (Zeck et al., 1989). The Ar-Ar ages on micas are in the range 19–18 Ma, and rapid exhumation is confirmed by an Ar-Ar age of 18.3 ± 1.0 Ma on volcanic
Figure 3. Inverse concordia diagrams for time interval ca. 26±18 Ma, showing U-Th-Pb zircon analyses by secondary-ion mass spectrometry (ion microprobe) from samples in this study. Data are uncorrected for common Pb, and ages are obtained by regressing data through common-Pb composition corresponding to present-day average terrestrial Pb (Stacey and Kramers, 1975: \( ^{207}\text{Pb}/^{206}\text{Pb} = 0.83 \pm 0.1 \)). Outlier analyses represented by open symbols are omitted from regressions. For PB383, squares and circles represent zircons separated from bulk rock and garnet concentrate, respectively. MSWD—mean square of weighted deviates; n—number of samples. For tables of data, see footnote 1 in text.

Figure 4. Cathodoluminescence images of selected zircon grains from samples PB69 and PB182. These are similar to grains from PB383 (Platt and Whitehouse, 1999). Note relict (probably detrital) cores in some grains and structureless character of early Miocene metamorphic rims and new grains.

detritus in overlying sedimentary rocks of early Miocene age (Scotney et al., 2000).

DISCUSSION AND CONCLUSIONS

Peak temperatures of metamorphism (in the range 650–800 °C) appear to have been reached between 23 and 19 Ma across the entire Alboran domain. The maximum significant difference between the U-Pb zircon ages in different locations is <3 m.y., and no clear pattern is apparent in the distribution of ages (Fig. 1). Peak temperature was immediately followed by rapid cooling to near-surface temperatures by ca. 18 Ma. The data strongly suggest that the thermotectonic event that caused the high-temperature metamorphism and associated rapid extensional exhumation occurred nearly simultaneously over the entire region, now 300 x 200 km in extent. Note that the widespread evidence for heating during decompression (Soto and Platt, 1999; Argles et al., 1999) suggests that peak temperature does not correspond to the start of extension, which is estimated on the basis of thermal modeling to have begun several million years earlier (Platt et al., 1998; Platt and Whitehouse, 1999).

The timing and near-simultaneity of the exhumation event across the Alboran domain have two important implications. First, there is a significant time gap between the main phase of crustal thickening and the onset of crustal thinning. The timing of the thickening event is not well determined, but available radiometric and stratigraphic data suggest a late Eocene age (Vissers et al., 1995). This interpretation is supported by the presence of metamorphic detritus in Oligocene sedimentary rocks surrounding the Alboran domain (Lonergan and Mange-Rajetsky, 1994) and by apatite with fission-track ages in the range 44–28 Ma (Lonergan and Johnson, 1998). More recent arguments that Miocene U-Pb ages on zircon relate to subduction events (Sánchez-Rodríguez and Gebauer, 2000; Sánchez-Vizcaíno et al., 2001) are difficult to sustain: the geologic evidence clearly indicates that they relate to stages in the exhumation history of the Alboran domain. Zircon growth was likely to have been a result of partial melting or of decompression reactions during exhumation. The evidence therefore suggests a delay of ~25 m.y. between the crustal-thickening event and the onset of crustal thinning. This delay is a characteristic and predicted feature of the process of convective removal of thickened lithospheric roots beneath collisional orogens (Houseman and Molnar, 1997) and is not predicted by any other mechanism for postorogenic extension.

The second implication of the data is that there was no diachronity in the pattern of extension within the Alboran domain. Extension driven by delamination or rollback of subducting lithosphere should migrate as the locus of sinking lithosphere migrates. The main thrust front between the Alboran domain and the external Betic-Rif arc migrated westward ~250 km over a 10 m.y. period in the Miocene, and both mass-balance considerations and seismological evidence (Seber et al., 1996; Calvert et al., 2000) suggest sinking of lithospheric mantle during this process, but there is no evidence for a corresponding migration of the locus of extension within the Alboran domain. Rather, it appears that a rapid and profound exhumation event occurred across the Alboran domain in earliest Miocene time, followed by slower and widely distributed extension during the middle and late Miocene (Comas et al., 1999). This evidence is most consistent with the rapid removal of lithospheric mantle under the entire Alboran region in a short time period, rather than an asymmetric and continuous process such as delamination or subduction rollback.

The causes of extension at a late stage in the orogenic cycle continue to be vigorously debated. England and Houseman (1989) ad-
vanced an elegant and powerful hypothesis that explained the present-day thinning of the Tibetan Plateau in terms of the buoyancy forces resulting from the surface elevation created by thick crust and convective removal of lithospheric mantle beneath Tibet. The delayed onset of convective removal, predicted by numerical models of the behavior of a conductive thermal boundary layer developed in a fluid with nonlinear viscous behavior, can explain the relatively abrupt transition to crustal thinning ~40 m.y. after the onset of crustal thickening in this system. The presence of active subduction zones adjacent to some of the late orogenic extensional basins in the Mediterranean region suggests that loads exerted by the subducting slab may also contribute to backarc extension, but it is noteworthy that the Aegean, Pannonian, Tyrrhenian, and Alboran Basins were all initiated on sites of previous crustal thickening and, in each case, extension started several tens of millions of years after the thickening event. Our observations on the delayed onset of extension and the lack of diachronocity to the extensional event in the Alboran region, and the heating of rock during rapid exhumation, suggest that convective removal of mantle beneath collisional orogens may be a common factor in initiating late orogenic extension in regions as diverse as Tibet and the Neogene Mediterranean basins.

ACKNOWLEDGMENTS
Supported by grants 533/10828 from the Natural Environmental Research Council of Great Britain (to Platt), The Nordic geological ion-microprobe facility (NordSIM) is jointly funded by Denmark, Norway, and Finland; Whitehouse acknowledges the support of a senior research fellowship from Vetenskapsrådet, Sweden.

REFERENCES CITED


Sánchez-Rodríguez, L., and Gebauer, D., 2000, Mesozoic formation of pyroxenites and gabbros in the Ronda area (southern Spain), followed by early Miocene subduction metamorphism and emplacement into the middle crust: U-Pb sensitive high-resolution ion microprobe dating of zircon: Tectonophysics, v. 316, p. 19–44.


Manuscript received 26 June 2002
Revised manuscript received 24 October 2002
Manuscript accepted 25 October 2002
Printed in USA