The thermal history of the lower crust recorded by zircon growth and recrystallization: an ion microprobe (SHRIMP) study from the Ivrea zone (Southern Alps)

G. Vavra
D. Gebauer
R. Schmid

Department of Earth Sciences, ETH-Zentrum, CH-8092 Zürich, Switzerland

Introduction

The thermal history of granulite facies terrains, especially in its prograde part, is poorly dated by most mineral-based isotopic decay systems, because they become closed only after cooling from the thermal peak. The U/Pb system in non-metamict zircon makes the only known exception. Due to the extremely low diffusivity of chemical components within such zircons, internal zoning patterns resulting from overgrowth and recrystallization are preserved even at the highest temperatures attained in the earth's crust. They are revealed by cathodoluminescence imaging of zircon grains and are U/Pb-dated by the ion microprobe. The attribution of the various domains in zircon crystals to metamorphic and anatectic processes in the host rocks is the crucial point for resolving the thermal history of the granulites.

Methods

Different categories of crystal domains (overgrowth, recrystallization) were distinguished by SEM-based cathodoluminescence imaging. Crystal domains were analyzed for U/Pb ratio and concentrations of U and Th, using the sensitive high resolution ion microprobe (SHRIMP I) at ANU in Canberra. The expected analytical errors (1σ) for individial analyses are between $\pm$ 5 and $\pm$ 10 Ma for the ratio $^{206}Pb/^{238}U$ and between $\pm$ 8 and $\pm$ 21 Ma for the ratio $207Pb/^{235}U$. Since our zircon ages are confined to the interval between 350 and 225 Ma, where the concordia approaches a straight line, all U/Pb data plot, within analytical error limits, at or very near the concordia curve. Some categories of crystal domains define clusters of $^{206}Pb/^{238}U$ ages. The dispersion of ages within one of the clusters is considerably larger than for other clusters. Since this difference is not due to different counting statistics, the relatively large dispersion may partly result from a true range of measured ages. Therefore, the means of clusters are considered as average ages and the standard deviation (1σ) is quoted to compare the different dispersion of clusters.

Petrography and geological context of the granulite samples

A metasedimentary and a metaigneous (tonalitic) granulite were sampled in the Ivrea Zone. The metasediment is layered and zircons were separately obtained from two adjacent layers, a metapelite (Gt + Sil + Ksp) and a quartzite (Qtz + Gt $\pm$ Ksp) layer. Since this sample is a boulder, its location relative to intruded mafic magmas is not exactly known. The metatonalite (Plag + Qtz + Gt + Opx), on the other hand, occurs as a deformed septum within the basal part of the mafic body in Val Sesia.

Zircon evolution in the metasediment

Both layers of the metasediment (pelitic and quartzitic) contain detrital-shaped zircons as cores within an isometric overgrowth. In the metapelitic layer, the overgrowth started by numerous and frequently unstable crystal faces. In part of the crystals, the overgrowth tended towards less numerous and more stable faces, and this is generally followed by a small amount of crystal resorption. In the quartzitic layer, on the other hand, large and stable crystal faces are present from the outset and almost every crystal became resorbed after the overgrowth stopped. In the metapelitic layer, the individual $^{206}Pb/^{238}U$ data of the overgrowth are broadly dispersed between 294 and 258 Ma (mean 278 $\pm$ 10 Ma). However, in the quartzitic layer, the data are confined to a much narrower and younger interval between 265 and 257 (mean 262 $\pm$ 3 Ma). The relatively large dispersion of ages from the metapelitic layer is probably due to a true range of overgrowth ages. This gets additional support from the fact that, where 2 analyses were obtained from the same grain, the outer zone of overgrowth is younger than the internal one. Furtheron, the presence of morphologically distinguishable overgrowth stages points to more than one growth episode. A second cycle of overgrowth with an average age of 225 $\pm$ 4 Ma is present only in the metapelitic layer and, here, only in zircon crystals which have not been affected by previous resorption.

Zircon evolution in the metatonalite

Five $^{206}Pb/^{238}U$ data from protolithic crystal domains displaying a perfectly preserved magmatic growth banding define a cluster at the upper limit of all data. The clustering of the analyses points to a closed U/Pb system and the mean (345 $\pm$ 4 Ma) is attributed to the age of the magmatic crystallization of the rock. Similar to the metasedimentary zircons, the protolithic zircons of the metatonalite were first overgrown and later became resorbed. However, the proportions of overgrowth and resorption are different. For most crystals in the metatonalite, the resorbed volume exceeded the amount of earlier overgrowth, and only in rare crystals small remnants of the early overgrowth exist. The $^{206}Pb/^{238}U$ ages of 3 such remnants range from 297 to 281 Ma, which is comparable to the earliest overgrowth in the pelitic layer of the metasediment. Approximately 5% of the zircon crystals in the metatonalite have a clearly different evolution as the remainder, in that the volume of overgrowth by far exceeded the volume of subsequent resorption. Two analyses of this overgrowth yielded $^{206}Pb/^{238}U$ ages at 271 Ma. The analysis of a thin seam of recrystallization immediately below the resorbed surface yielded almost the same age (272 Ma). If the 3 ages are considered together, it appears that both, growth and corrosion, occurred at 271.5 $\pm$ 3 Ma (95% c.l. for the standard error of the mean). In addition to overgrowth and resorption, the protolithic parts of crystals became partly recrystallized. 4 analyses from domains which are most recrystallized, according to internal zoning pattern and low U content, yield a cluster of $^{206}Pb/^{238}U$ ages at 275 $\pm$ 3 Ma.

Implications for the thermal and petrogenetic history of the granulites

It is a common characteristic of zircons from all investigated granulite samples that overgrowth on protolithic zircons occurred first and that resorption, if it occurred, followed the overgrowth. The resorption can be safely attributed to the formation of anatectic melt which caused the well known restitic composition of the granulites. The source for the pre-resorption overgrowth must have been Zr-carrying rock-forming minerals which decomposed during increasing temperatures and released their Zr into the metamorphic fluid or anatectic melt. Therefore, the oldest ages of overgrowths (294 Ma in the metapelite, 265 Ma in the quartzite, 297 Ma in the metatonalite) are maximum ages for the formation of anatectic melt. Any earlier formation of anatectic melt, for example at Caledonian or Early Hercynian times, can be excluded. It is suggested that, in the metapelite, the earliest overgrowth (294 Ma) dates the start of the reaction $Bi + Qtz + Sil \rightarrow Gt + Ksp + H_2O$, which initiated anatectic melting at the transition from the amphibolite to the granulite facies. The Zr for zircon overgrowth was probably provided by the decomposing Bi. From previous baro-thermometry work this reaction initiated at approximately 700°C. This reaction did not occur in the adjacent quartzitic layer due to lacking sillimanite. Here Bi decomposed and anatectic melt formed not earlier than 265 Ma. This reaction required either a sufficient increase in temperature far beyond 700°C or an isothermal decompression. In the metatonalite, the major pulse of overgrowth occurred at 271.5 $\pm$ 3 Ma. It is suggested that this dates the breakdown of Zr-carrying amphibole and minor biotite by dehydration melting. Most probably, this event is related to the intrusion of the mafic body, which encloses the tonalitic septum. The recrystallization of protolithic domains within the tonalitic zircons provides independent evidence that the temperature maximum occurred after 275 $\pm$ 3 Ma.

In the quartzitic metasediment and in the metatonalite, the supply of Zr from decomposing minerals became exhausted at some stage, when anatectic melt continued to form. This caused the transition from overgrowth to resorption of zircon. In the metapelite, in which biotite is still preserved, the Zr-supply from decomposing Bi became never completely exhausted and most zircon crystals continued to grow during the entire interval of anatectic melting. The youngest age of overgrowth during the late-Variscan granulite facies is 258 Ma. Thereafter, the anatexis must have stopped. Since Bi was not completely decomposed, anatectic melt could form again in the metapelite during a high-temperature or decompression event at 225 $\pm$ 4 Ma, causing the second cycle of zircon overgrowth.