13. FISSION TRACK ANALYSIS OF DETRITAL APATITES FROM SITES 859, 860, AND 862, CHILE TRIPLE JUNCTION¹

Annette D. George² and Kerry A. Hegarty³

ABSTRACT

Fission track analysis of detrital apatite grains recovered from sediment samples of upper Pliocene to Quaternary age from the Chile Triple Junction (Sites 859, 860, and 862), shows that the apparent ages of individual grains are older than the stratigraphic ages. The apatite fission track data indicate that there has been no significant postdepositional heating (i.e., maximum paleotemperatures have never exceeded ~60°C). The apatite grains, therefore, derive their fission track characteristics from the source area. The mineral assemblages are similar in all samples and indicate that this source area was dominated by crystalline basement and a volcanic terrain. The track-length distributions characterized by relatively long means (13–14 μm) are a significant feature of the fission track data, given that the apatite grains were eroded from mixed sources of a known broad age range. These data record moderately rapid cooling through ~110°C, which we attribute to moderately rapid uplift and erosion of the source area, followed by transportation and deposition of the sediment.

Two distinct age populations are recognized in the combined samples from each of the three sites. The younger population is represented by a fission track age of $\sim 7 \pm 2$ Ma, whereas the older population gives an age of $\sim 25 \pm 5$ Ma. The younger age group is interpreted as revealing the time of moderately rapid cooling, produced by uplift and erosion of the source area. Recognition of this late Miocene (~7 Ma) event in the fission track data coincides with several major processes, including magmatism and tectonism, which have been documented already in the area. Erosion of the source (arc-forearc) region at this time is most likely a direct result of tectonic uplift caused by collision and subduction of one or two segments of the Chile Ridge. The older age (~25 Ma) identified in the fission track data records a discrete cooling event which we interpret as denudation and/or deformation of the forearc-arc region as a consequence of oblique convergence at the Chile margin.

INTRODUCTION

Collision of the Chile Ridge spreading center and the Chile Trench provided the thematic focus for Leg 141 of the Ocean Drilling Program. The Chile Triple Junction is presently located at 45°40'S–47°S off the coast of southern Chile (Fig. 1), and previous marine geophysical studies indicate that the triple junction has migrated northward from the site of initial collision at approximately 15 Ma (Herron et al., 1981; Cande et al., 1987).

Various tectonic and geological processes have been inferred in the forearc and arc region as a direct consequence of ridge subduction, including rapid vertical movements, elevated geothermal gradients and anomalous near-trench magmatism (DeLong and Fox, 1977; DeLong et al., 1979; Marshak and Karig, 1977; Forsythe et al., 1986). Recognition of these effects in the stratigraphic record was one of the primary objectives of Leg 141. Fission track analysis is an appropriate technique to investigate these effects because it utilizes the sensitivity of fission tracks in uranium-bearing minerals at low temperatures to determine the timing of cooling (e.g., uplift and erosion) events. A fission track study was undertaken using detrital apatites from sediment samples from three of the five drill sites: 859 and 860 in the collision zone, and site 862 approximately 25 km south on the Taitao Ridge (Fig. 1). Fission track ages and track-length distributions from these samples are interpreted with respect to the tectonic evolution of the forearc region and the postdepositional thermal history of the sediments.

APATITE FISSION TRACK ANALYSIS

Background

Apatite fission track analysis (AFTA) of detrital grains in sediments and sedimentary rocks is a powerful method for interpreting and modeling the thermal histories of sedimentary basin-fills. The observation that fission tracks in apatite anneal at temperatures below ~110°C over geological time makes them particularly useful in petroleum exploration and basin modeling (e.g., Naeser, 1981; Gleadow et al., 1983; Gleadow et al., 1986). In sediments that lack a significant postdepositional overprint (sediments that have not been heated significantly since deposition, i.e., less than ~60°C), fission track analysis may be used to establish source terrain cooling histories. The fission track age provides constraints on the time elapsed since the source rocks cooled through about 110°C, and the track-length distributions can be used to determine the thermal history which can be used to study the history of uplift and erosion (e.g., Agar et al., 1989; Kamp et al., 1989; Corrigan and Crowley, 1990; Arne, 1992). Furthermore, fission track ages may help define the source terrain(s) from which the sediments were eroded (e.g., Gleadow et al., 1983; Duddy et al., 1984; Hurford and Carter, 1991).

Estimates of maximum paleotemperature and time of maximum temperature are derived from AFTA data using well-established modeling techniques. The basis of the AFTA technique, principles of interpretation, and the kinetics of the annealing model describing fission track behavior used in this study have been described in a series of papers (Gleadow et al., 1983; Green et al., 1986; Laslett et al., 1982; Laslett et al., 1987; Duddy et al., 1988; Green et al., 1989).

Sample Preparation and Analytical Procedures

Samples of 10 to 40 cm³ were taken from sandy intervals of turbidites in cores from Sites 859, 860, and 862 (Table 1). Unconsolidated core samples were disaggregated by stirring in 0.1% Calgon solution in an ultrasonic tank, then wet sieved through a 63- μm mesh to recover the sand fractions. The two cemented samples were crushed to sand

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² School of Earth Sciences, The University of Melbourne, Parkville, Victoria 3052, Australia. (Present address: Department of Geology, The University of Western Australia, Nedlands, W.A. 6009, Australia.)

³ Geotrack International, P.O. Box 4120, Melbourne University, Victoria 3052, Australia.

Table 1. Core samples from Leg 141 sites used in fission track analysis.

Sample number ^a	Hole	Core, section, interval (cm)	Depth (mbsf)	Depositional age ^h	Sediment/rock type
RD30-6	859B	17R-1, 27-29	264.57	late Pliocene	Carbonate-cemented muddy sandstone
RD30-5	859B	17R-4, 67-69	269.47	late Pliocene	Carbonate-cemented muddy sandstone
RD30-1	860B	5H-7, 60-66	39.50	late Pliocene	Silty sand
RD30-2	860B	6H-6, 57-59	47.47	late Pliocene	Fine-medium sand
RD30-3	862A	1H-2, 42-45	1.92	Neogene (2 m.y.) ^c	Silty fine sand
RD30-4 ^d	862A	1H-3, 13-14	3.13	Neogene (2 m.y.)	Silty fine sand
		1H-3, 125-127	4.25	Neogene (2 m.y.)	Silty fine sand
		2H-3, 94-97	9.34	Neogene (2 m.y.)	Muddy fine-medium sand
		2H-5, 69-72	12.09	Neogene (2 m.y.)	Muddy fine-medium sand
		2H-7, 52-55	14.92	Neogene (2 m.y.)	Muddy fine-medium sand

^a Sample numbers assigned by Geotrack International.^b Biostratigraphic assignment.^c Deeper parts of hole (not sampled here) are possibly late Pliocene.^d RD30-4 is a composite of the sand fractions from the five core samples listed; each had low individual sand components.

Figure 1. Location of the Leg 141 sites at the southern Chile margin (shaded) in the vicinity of the triple junction defined by collision of the Chile Ridge spreading center and associated transforms with the Chile Trench (heavy line with teeth on upper plate). TP = Taitao Peninsula; GDP = Golfo de Penas Basin; LOF = Liquine-Ofqui fault zone. The dashed line is the 200 m bathymetric contour.

size prior to washing. The apatite grains were separated from the coarse fractions by conventional heavy liquid and magnetic separation techniques, with all six samples providing excellent apatite yields.

The apatite separates were prepared for fission track analysis using the external detector method (Gleadow, 1981; Green, 1986) which enables apparent ages to be calculated on individual grains. Apatite grains were mounted in epoxy resin on glass slides and etched for 20 seconds in 5N HNO₃ at 20°C to reveal the fossil tracks. Neutron irradiations were undertaken in the X-7 facility of the Australian Nuclear Science and Technology Organization's HIFAR reactor at Lucas Heights. Tracks in 20 grains per sample were counted, and ages calculated using the standard fission track age equation (Hurford and Green, 1982). Full analytical data for each sample are given in the Appendix, and a summary of results is presented in Table 2. Horizontal confined fission track lengths were measured in each sample and mean lengths are given in Table 2. All errors are given as $\pm 1\sigma$ in the tables.

PROVENANCE

The sand fractions of each sample were examined in thin section to establish the nature of the source terrains. All samples are composed predominantly of quartz, with subordinate feldspar, brown volcanic glass, basic-intermediate volcanic lithic fragments, green amphibole, and plutonic-metamorphic lithic fragments. Biotite, epidote, zircon, and opaque oxides are common accessory minerals. The mineral assemblage indicates derivation from at least two sources, crystalline basement and a volcanic terrain. These sources are consistent with the known onshore geology in southern Chile which is dominated by the Late Jurassic to early Miocene Patagonian batholith, with Miocene volcanic centers and Quaternary calc-alkaline volcanoes (Forsythe and Nelson, 1985; Cande and Leslie, 1986). A pre-Late Jurassic metamorphic terrain is also exposed onshore in this area, and although no grains could be unequivocally assigned to this source, the possibility exists that it provided some of the sediment to the sample sites. Thus, the source area is the arc-forearc region, including both the continental basement and superimposed magmatic arc rocks.

RESULTS AND INTERPRETATIONS

The AFTA data generated for this study are of very high quality because of the excellent apatite yields, generally moderate to high uranium contents, and low present-day sample temperatures. Two AFTA samples from each of the three sites provided six samples which were initially processed independently.

AFTA parameters (single-grain ages and confined track-length measurements) were determined for each of the six samples (Figs. 2 and 3; Table 2). Calculated fission track ages for each sample are quoted for comparison in Table 2, but are not used in the interpretation of thermal history, as the single grain ages in all but one sample (RD30-6) do not represent a single population of ages, and the spread of single grain ages must be considered.

Postdepositional Thermal History

At an error of $\pm 2\sigma$, none of the fission track ages of individual apatite grains is significantly younger than the corresponding stratigraphic age of any of the samples (Appendix; Table 2). These age data, together with track-length modeling, show that maximum postdepositional paleotemperatures could not have exceeded $\sim 60^\circ\text{C}$, and provide clear evidence that there has been little to no postdepositional heating.

Evidence for Predepositional Heating/Cooling

One of the most striking features of the data is the relatively long mean length characterizing the distribution of horizontal confined

Figure 2. Histograms of single grain fission track ages for samples from Leg 141 holes.

track measurements in each sample (in the range 13.3 to 14.2 μm , Table 2). The long mean lengths suggest that most of the tracks have experienced only a small degree of annealing since track formation, and together with the age data, provide further support for little postdepositional heating of the sediment. We interpret the track-length data to indicate that most of the fission tracks formed after moderately rapid cooling (i.e., $>20^\circ\text{C}/\text{Ma}$) of the source rocks from paleotemperatures of $\sim 110^\circ\text{C}$ or more. Had the source cooled slowly, (i.e., $<10^\circ\text{C}/\text{Ma}$), the length distribution would contain a shorter component of tracks, in the range 7–12 μm (e.g., Gleadow et al., 1986), which represent those tracks that were partially annealed during the slow cooling event.

It is clear from petrographic work, coupled with the known on-shore geology, that the sediments (including the apatite grains) were derived from more than one source. The source rocks are dominantly plutonic and volcanic types, and vary in age from Late Jurassic to Quaternary, possibly including a pre-Late Jurassic metasedimentary terrain. The track-length distributions characterized by relatively long means is a significant feature of the AFTA data, particularly given that the apatite grains were eroded from mixed sources of a broad age range. The AFTA data provide evidence, therefore, that the source terrains cooled moderately quickly from paleotemperatures of at least 110°C . Sediment input from the plutonic source (which is areally dominant onshore; e.g., Forsythe and Nelson, 1985) argues against derivation of all the apatite grains from rapidly cooled volcanic or high-level intrusive rocks. Furthermore, we attribute the moderately rapid cooling to uplift and erosion of the source area; however, a rapid decline in heat flow (e.g., cooling of the host rock after intrusion) cannot be ruled out. Following erosion, detrital apatite grains were transported and deposited at the drill sites.

Figure 3. Histograms of confined track length measurements for samples from Leg 141 holes. Number of tracks measured (n) and mean track length in micrometers (arrows) is indicated for each sample.

Timing of Thermal Events

The two AFTA samples from each site are at present downhole temperatures that probably differ by only 1°C because of the close sample spacing (Tables 1 and 2). For this reason, data generated from the two samples from each site were combined to improve the statistical analysis of the individual single grain ages. These combined samples consisting of 40 single grains are referred to by their drill site number (Table 3).

The chi-squared statistics for each composited sample show that there is significant variability in the single-grain ages within the samples (Table 3). To evaluate real differences in the single-grain ages, we make use of radial diagrams (Galbraith, 1988), which are useful for graphically representing trends in the single-grain age data (Fig. 4). All points on a straight line from the origin of each plot define a single value of fission track age, and the distance along the x -axis represents the corresponding precision of each single-grain determination. Therefore, precise individual grain ages fall to the right of the plot, which allows easy identification of young, precise grains. Although there is some scatter in the data (Fig. 4), broad trends can be seen in each of the three plots, particularly for younger ages for which more precise grains exist.

Table 2. Summary of AFTA data for Leg 141 samples.

Sample number	Hole	Depth (mbsf)	Present temp. ($^{\circ}\text{C}$) ^{a,h}	No. of grains	Stratigraphic age (Ma) ^c	AFTA age (Ma) ^d	Mean track length (mm)	Standard deviation (μm)	No. of confined tracks measured
RD30-6	859B	264.57	29	20	3.4–1.6	8.8 ± 1.2	13.3 ± 0.3	1.8	41
RD30-5	859B	269.47	29	20	3.4–1.6	14.2 ± 2.9	13.8 ± 0.3	1.7	53
RD30-1	860B	39.50	8	20	3.4–1.6	17.6 ± 3.0	14.2 ± 0.2	1.8	100
RD30-2	860B	47.47	9	20	3.4–1.6	6.7 ± 0.9	13.9 ± 0.1	1.3	103
RD30-3	862A	1.92	2	20	1.6–0? ^b	17.8 ± 3.1	14.1 ± 0.2	1.4	61
RD30-4	862A	14.92 ^e	3	20	1.6–0?	16.7 ± 2.9	13.9 ± 0.2	1.5	101

^a Present temperatures for Holes 859B and 862A calculated using a thermal gradient of $100^{\circ}\text{C}/\text{km}$ and a surface temperature of 2°C .

Hole 860B calculated using a thermal gradient of $140^{\circ}\text{C}/\text{km}$ and surface temperature of 2°C .

^b Slight revision of stratigraphic ages or present temperatures will not affect our thermal history interpretation.

^c Uses the geologic time scale of Harland et al. (1990).

^d Central age used, except RD30-6, which uses the pooled age.

^e Maximum depth (see Table 1).

Table 3. AFTA data for composite samples.

Composite sample	Original sample numbers (strat. age, Ma)	Age limits of younger population Ma ^a (maximum likelihood value)	Age limits of older population Ma ^a (maximum likelihood value)	P (chi-squared) statistic ^b
859	RD30-5 and -6 (3.4–1.6)	6.2–10.2 (7.9)	19.1–41.4 (23.1)	<0.1%
860	RD30-1 and -2 (3.4–1.6)	4.2–7.3 (5.6)	15.4–26.7 (20.2)	<0.1%
862	RD30-3 and -4 (1.6–0?)	7.3–11.2 (9.1)	24.3–38.1 (30.5)	<0.1%

^a Lower and upper 95% confidence limits.

^b Definition of the P (chi-squared) statistic is given in the Appendix.

It is possible to quantify these broad trends by statistically analyzing for the separation of different age populations in each combined sample. Using the techniques of Galbraith (1988), we observed that the data from each sample show significant structure in individual grain ages, and two distinct age groups can be identified in each sample within 95% confidence limits (Table 3). At Site 859, the younger population gives a fission track age of 7.9 Ma with lower and upper 95% confidence limits of 6.2 and 10.2 Ma, respectively. The lower and upper confidence limits of this population from Sites 860 and 862 are 4.2 to 7.3 Ma and 7.3 to 11.2 Ma, respectively. There is remarkable consistency in the age of this population between samples, which is approximately 7 ± 2 Ma (Table 3). This pattern of single-grain ages, together with the track-length distributions, suggests that the samples (or grains in this case) cooled from paleotemperatures of $\sim 110^{\circ}\text{C}$ or more near the time given by the age range of the youngest group (i.e., ~ 7 Ma). Correcting the measured age for the modest amount of annealing recorded by the track lengths suggests that cooling may have commenced somewhat earlier, but not before 7.5 Ma within the errors discussed above.

Similarly, lower and upper confidence limits were calculated for the older population identified in each sample (Table 3) and the ranges show an overlap at 24.3–26.7 Ma for the three samples. These grains may be richer in chlorine and therefore retain their fission tracks formed prior to the ~ 7 Ma event (see Green et al., 1985 for a discussion of the effects of chlorine content), or alternatively, the older grains were derived from a distinct terrain which did not experience cooling at ~ 7 Ma. In conclusion, the AFTA data are compatible with a thermal model that consists of two events (at ~ 7 and ~ 25 Ma) that are both associated with rapid cooling.

IMPLICATIONS FOR TECTONIC EVOLUTION OF THE FOREARC AND ARC REGION

The AFTA parameters are clearly dominated by inheritance: that is, they exhibit characteristics from their source rather than the post-

depositional thermal environment. The shapes of the track-length distributions and long mean track lengths suggest that all samples cooled quickly through $\sim 110^{\circ}\text{C}$, which we relate to uplift and erosion of the source area.

Two distinct age populations can be recognized in the upper Pliocene-Quaternary composite sediment samples from Sites 859, 860, and 862. The younger group indicates that relatively rapid cooling of the source area occurred around 7 ± 2 Ma, which seemingly postdates the time of initial collision at 15 Ma in the Tierra del Fuego region ~ 130 km to the south ($\sim 55^{\circ}\text{S}$). Detailed geophysical studies of the southern Chile margin have enabled reconstruction of plate geometries through the Cenozoic, which together with calculated convergence rates have been used to determine the timing of collision (e.g., Herron et al., 1981; Cande et al., 1987). These reconstructions also show that the first ridge segment which was about 700 km long, was not fully subducted until ~ 10 Ma at latitude 48°S (Forsythe and Nelson, 1985), and that three shorter ridge segments, separated by transform fault zones, have subsequently collided at 5–6 Ma, 2.5–4 Ma, and 0.1 Ma (Herron et al., 1981; Forsythe and Nelson, 1985; Forsythe et al., 1986; Cande et al., 1987).

The ~ 7 Ma event indicated by the AFTA data records moderately rapid cooling of the source area in the late Miocene, possibly in response to collision of the first and/or second segment of the Chile ridge in the Golfo de Penas area. Unconformities of inferred Pliocene-Miocene age are recognized in the sedimentary record, and have been attributed to uplift and erosion during ridge collision, together with other manifestations of collision such as Miocene plutons and volcanic centers and widespread faulting (Forsythe and Nelson, 1985). Similar effects of uplift and magmatism in the forearc region during the Pliocene have been documented in previous studies of the margin, and are interpreted to have occurred in response to collision of a third ridge segment in the Taitao area at ~ 3 Ma (Cande and Leslie, 1986; Forsythe et al., 1986). The distance between the drill sites, and the distance between the collision zone at ~ 10 –7 Ma and these drill sites implies regional uplift of the Chile margin. Dickinson and Snyder

(1979) proposed that uplift in this zone was the result of asthenospheric upwelling in the slab-free zone beneath the forearc and arc at the site of collision.

The older age population around 25 Ma (late Oligocene) predates collision in the Golfo de Penas region; however, the distinct grouping of the data in the samples suggests that the 25 ± 5 Ma age records another discrete cooling event. A period of uplift and erosion at this time is consistent with recorded unconformities and overlying conglomerates in shelf basins to the north of the present-day triple junction (Cande and Leslie, 1986) and on the Taitao Peninsula to the south (Forsythe and Nelson, 1985). Although timing is not well constrained, the age controls suggest that erosion related to these unconformities occurred in the Oligocene to Miocene (Cande and Leslie, 1986; Forsythe and Nelson, 1985). Therefore, the AFTA data can be interpreted in terms of denudation of the source area.

Plate reconstructions show that at 25 million years ago, highly oblique convergence was occurring along the southern Chile margin, and had been since ~40 Ma, with associated development of strike-slip faulting (Cande and Leslie, 1986). The north-south striking Liquine-Ofqui fault zone is a major crustal fault zone which lies adjacent to the Andean volcanic chain (Forsythe and Nelson 1985), and has a mapped strike length of approximately 1000 km until it trends offshore at the Golfo de Penas (Fig. 1). Both normal and dextral strike-slip movements have been documented; however, timing relationships are poorly constrained. Radiometric ages from the fault zone indicate a maximum age of 30 Ma (Forsythe and Nelson, 1985), and it may be that the 25 Ma event reflects moderately rapid cooling due to deformation along the Liquine-Ofqui fault zone, or a similar fault zone, as a function of oblique subduction at that time.

CONCLUSIONS

The fission track data from detrital apatites in core recovered from Sites 859, 860, and 862 provide some useful results with which to interpret the tectonic evolution of the forearc and arc region of the southern Chile subduction zone. The main conclusions from analysis of individual fission track ages, track-length distributions and mean track lengths include the following:

1. There is no evidence for significant postdepositional heating of the sediments, that is, the sediments have remained at temperatures less than 60°C since deposition.

2. Two distinct age populations occur in all the samples analyzed: a younger age group centered on $\sim 7 \pm 2$ Ma; and an older group at $\sim 25 \pm 5$ Ma. Moderately rapid cooling, due to uplift and erosion of the source terrains through $\sim 110^\circ\text{C}$ is the most likely interpretation of the AFTA data given the mixed sources represented in the sediments. However, cooling due to a rapid decline in heat flow cannot be ruled out with the present data.

3. The late Miocene event revealed by the AFTA data provides evidence for moderately rapid uplift and erosion of the source area and coincides with one or more collisions of ridge segments since initial collision of the Chile spreading ridge and the Chile trench 15 m.y. ago. Late Miocene uplift and magmatism associated with early episodes of ridge collision is analogous to the Pliocene magmatism and uplift documented by field and geophysical studies in this region when the third ridge segment collided.

4. The older age group found in the AFTA data may also indicate a cooling event, but clearly predates collision, and is probably related to deformation and denudation of the arc region as a consequence of highly oblique subduction. More specifically, it may relate to tectonism initiated along the Liquine-Ofqui fault zone at about 25–30 Ma.

This preliminary study highlights the usefulness of apatite fission track analysis for investigating the uplift history of source terrains in which the sediments derived from these sources lack a postdepositional thermal overprint. Further AFTA work on the onshore rocks of

Figure 4. Radial plots (after Galbraith, 1988) for each of the three composite samples from Leg 141 holes. Ages in millions of years are shown around the top and right side of the plot, with open squares representing the fission track age of individual apatite grains. Stippled zone shows the range in stratigraphic age of the sample. Dashed lines indicate the younger and older age populations identified in each sample. The younger population for all samples is compatible with an age of ~7 Ma, whereas the older population can be represented by an age of ~25 Ma. See text for discussion and explanation of the radial plots. Uncertainties on each data point are $\pm 2\sigma$.

the southern Chile margin, both north and south of the present triple junction, would be extremely useful to compare with the data presented here for provenance studies and to further constrain the timing of events in this very active tectonic region.

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* Abbreviations for names of organizations and publications in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

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APPENDIX

Fission Track Age Data

Definitions of terms used as column headings

Ns = number of spontaneous tracks counted; Ni = number of induced tracks counted; Na = number of microscope grid units in which tracks were counted, where the area of basic unit = $6.293 \times 10^{-7} \text{ cm}^2$; Ratio = ratio of spontaneous tracks to induced tracks counted (Ns/Ni); RHOs = density of spontaneous tracks (tracks/cm²); RHOi = density of induced tracks (tracks/cm²); Age = single grain fission track age $\pm 1\sigma$ error in millions of years.

Definitions of terms given below the tables

Chi squared = χ^2 , used to assess variation of single grain ages within the sample. P (chi squared) = probability of obtaining observed χ^2 value for the relevant number of degrees of freedom. If all the grains belong to a single population then $P(\chi^2) > 5\%$. Correlation Coefficient = correlation coefficient between Ns and Ni. Age dispersion = % variation in single grain ages.

Values used in age calculation

Zeta calibration factor = calibration constant determined empirically for the observer. RhoD = density of tracks from uranium standard glass. ND = total number of tracks counted for determining track density. Pooled age = fission track age calculated from pooled ratio Ns/Ni, which is valid only when $P(\chi^2) > 5\%$. Central age = alternative to pooled age when $P(\chi^2) < 5\%$.

Appendix Table 1. Analytical data for sample RD30-1 (Hole 860B).

Grain	Ns	Ni	Na	Ratio	U (ppm)	RHOs	RHOi	Age (Ma)
1	5	40	16	0.125	35.6	4.966E + 05	3.973E + 06	32.1 $\pm$ 15.2
2	7	204	30	0.034	97.0	3.708E + 05	1.081E + 07	8.8 $\pm$ 3.4
3	5	176	28	0.028	89.6	2.838E + 05	9.988E + 06	7.3 $\pm$ 3.3
4	3	66	42	0.045	22.4	1.135E + 05	2.497E + 06	11.7 $\pm$ 6.9
5	3	21	21	0.143	14.3	2.270E + 05	1.589E + 06	36.7 $\pm$ 22.7
6	4	20	20	0.200	14.3	3.178E + 05	1.589E + 06	51.3 $\pm$ 28.1
7	4	53	25	0.075	30.2	2.542E + 05	3.369E + 06	19.4 $\pm$ 10.1
8	6	271	40	0.022	96.6	2.384E + 05	1.077E + 07	5.7 $\pm$ 2.4
9	0	35	20	0.000	25.0	0.000E + 00	2.781E + 06	0.0 $\pm$ 0.0
10	13	183	20	0.071	130.5	1.033E + 06	1.454E + 07	18.3 $\pm$ 5.3
11	5	78	20	0.064	55.6	3.973E + 05	6.197E + 06	16.5 $\pm$ 7.6
12	0	82	32	0.000	36.5	0.000E + 00	4.072E + 06	0.0 $\pm$ 0.0
13	2	57	28	0.035	29.0	1.13 5E + 06	3.235E + 06	9.0 $\pm$ 6.5
14	0	24	28	0.000	12.2	0.000E + 00	1.362E + 06	0.0 $\pm$ 0.0
15	6	76	24	0.079	45.2	3.973E + 05	5.032E + 06	20.3 $\pm$ 8.6
16	3	39	50	0.077	11.1	9.534E + 04	1.239E + 06	19.8 $\pm$ 11.9
17	6	16	21	0.375	10.9	4.540E + 05	1.211E + 06	95.8 $\pm$ 45.9
18	7	77	20	0.091	54.9	5.562E + 05	6.118E + 06	23.4 $\pm$ 9.2
19	17	125	50	0.136	35.6	5.403E + 05	3.973E + 06	34.9 $\pm$ 9.1
20	13	197	28	0.066	100.3	7.378E + 05	1.118E + 07	17.0 $\pm$ 4.9
109	1840				46.6	3.077E + 05	5.193E + 06	15.2 $\pm$ 1.6

Appendix Table 2. Analytical data for sample RD30-2 (Hole 860B).

Grain	Ns	Ni	Na	Ratio	U (ppm)	RHOs	RHOi	Age (Ma)
1	3	96	49	0.031	30.2	9.729E + 04	3.113E + 06	7.4 ± 4.4
2	5	240	60	0.021	61.7	1.324E + 05	6.356E + 06	5.0 ± 2.2
3	6	307	48	0.020	98.6	1.986E + 05	1.016E + 07	4.7 ± 1.9
4	3	32	40	0.094	12.3	1.192E + 05	1.271E + 06	22.3 ± 13.5
5	3	37	24	0.081	23.8	1.986E + 05	2.450E + 06	19.3 ± 11.6
6	4	114	70	0.035	25.1	9.080E + 04	2.588E + 06	8.3 ± 4.3
7	3	79	24	0.038	50.8	1.986E + 05	5.231E + 06	9.0 ± 5.3
8	9	189	60	0.048	48.6	2.384E + 05	5.006E + 06	11.3 ± 3.9
9	2	108	80	0.019	20.8	3.973E + 04	2.145E + 06	4.4 ± 3.1
10	4	122	60	0.033	31.4	1.059E + 05	3.231E + 06	7.8 ± 4.0
11	5	55	35	0.091	24.2	2.270E + 05	2.497E + 06	21.6 ± 10.1
12	0	27	48	0.000	8.7	0.000E + 00	8.938E + 05	0.0 ± 0.0
13	7	503	100	0.014	77.6	1.112E + 05	7.993E + 06	3.3 ± 1.3
14	3	201	60	0.015	51.7	7.945E + 04	5.323E + 06	3.6 ± 2.1
15	3	47	18	0.064	40.3	2.648E + 05	4.149E + 06	15.2 ± 9.0
16	8	543	100	0.015	83.7	1.271E + 05	8.629E + 06	3.5 ± 1.3
17	1	19	80	0.053	3.7	1.986E + 04	3.774E + 05	12.5 ± 12.8
18	9	477	100	0.019	73.5	1.430E + 05	7.580E + 06	4.5 ± 1.5
19	3	71	18	0.042	60.8	2.648E + 05	6.268E + 06	10.1 ± 5.9
20	1	42	48	0.024	13.5	3.311E + 04	1.390E + 06	5.7 ± 5.7
82 3309					45.5	1.161E + 05	4.686E + 06	5.9 ± 0.7

Notes: Chi squared = 35.579 for 19 degrees of freedom; P (chi squared) = 1.2%. Correlation coefficient = 0.801; age dispersion = 31.277%. Zeta calibration factor of 352.7 ± 5 for SRM612 reference glass. $\text{RhoD} = 1.350\text{E} + 06 \text{ cm}^{-2}$; ND = 2120. Pooled age = 5.9 ± 0.7 Ma. Central age = 6.7 ± 0.9 Ma.

Appendix Table 3. Analytical data for sample RD30-3 (Hole 862A).

Grain	Ns	Ni	Na	Ratio	U (ppm)	RHOs	RHOi	Age (Ma)
1	2	23	60	0.087	5.5	5.297E + 04	6.091E + 05	22.3 ± 16.5
2	18	62	36	0.290	24.6	7.945E + 05	2.737E + 06	74.3 ± 20.0
3	9	351	80	0.026	62.6	1.788E + 05	6.972E + 06	6.6 ± 2.2
4	5	224	48	0.022	66.5	1.655E + 05	7.416E + 06	5.7 ± 2.6
5	17	167	56	0.102	42.5	4.824E + 05	4.739E + 06	26.2 ± 6.7
6	1	12	50	0.083	3.4	3.178E + 04	3.814E + 05	21.4 ± 22.3
7	2	76	60	0.026	18.1	5.297E + 04	2.013E + 06	6.8 ± 4.9
8	4	100	90	0.040	15.8	7.063E + 04	1.766E + 06	10.3 ± 5.3
9	6	39	25	0.154	22.2	3.814E + 05	2.479E + 06	39.5 ± 17.3
10	5	71	100	0.070	10.1	7.945E + 04	1.128E + 06	18.1 ± 8.4
11	5	63	60	0.079	15.0	1.324E + 05	1.669E + 06	20.4 ± 9.5
12	9	60	56	0.150	15.3	2.554E + 05	1.703E + 06	38.5 ± 13.8
13	14	371	100	0.038	52.9	2.225E + 05	5.895E + 06	9.7 ± 2.7
14	3	80	35	0.038	32.6	1.362E + 05	3.632E + 06	9.6 ± 5.7
15	10	153	70	0.065	31.2	2.270E + 05	3.473E + 06	16.8 ± 5.5
16	11	307	30	0.036	145.9	5.827E + 05	1.626E + 07	9.2 ± 2.8
17	18	181	35	0.099	73.7	8.172E + 05	8.218E + 06	25.6 ± 6.3
18	6	157	36	0.038	62.2	2.648E + 05	6.930E + 06	9.8 ± 4.1
19	6	137	60	0.044	32.6	1.589E + 05	3.628E + 06	11.3 ± 4.7
20	4	91	56	0.044	23.2	1.135E + 05	2.582E + 06	11.3 ± 5.8
155 2725					34.0	2.155E + 05	3.788E + 06	14.6 ± 1.3

Notes: Chi squared = 90.452 for 19 degrees of freedom; P (chi squared) = <0.1%. Correlation coefficient = 0.456; age dispersion = 66.175%. Zeta calibration factor of 352.7 ± 5 for SRM612 reference glass. $\text{RhoD} = 1.460\text{E} + 06 \text{ cm}^{-2}$; ND = 2233. Pooled age = 14.6 ± 1.3 Ma. Central age = 17.8 ± 3.1 Ma.

Appendix Table 4. Analytical data for sample RD30-4 (Hole 862A).

Grain	Ns	Ni	Na	Ratio	U (ppm)	RHOs	RHOi	Age (Ma)
1	14	62	60	0.226	14.7	3.708E + 05	1.624E + 06	57.9 ± 17.2
2	6	45	49	0.133	13.1	1.946E + 05	1.459E + 06	34.2 ± 14.9
3	7	92	25	0.076	52.5	4.449E + 05	5.848E + 06	19.6 ± 7.7
4	7	211	30	0.033	100.3	3.708E + 05	1.118E + 07	8.5 ± 3.3
5	2	58	16	0.034	51.7	1.986E + 05	5.760E + 06	8.9 ± 6.4
6	0	3	35	0.000	1.2	0.000E + 00	1.362E + 05	0.0 ± 0.0
7	5	170	25	0.029	97.0	3.178E + 05	1.081E + 07	7.6 ± 3.4
8	4	94	21	0.043	63.8	3.027E + 05	7.113E + 06	10.9 ± 5.6
9	8	58	100	0.138	8.3	1.271E + 05	9.217E + 05	35.4 ± 13.4
10	20	158	28	0.127	80.5	1.135E + 06	8.967E + 06	32.5 ± 7.8
11	3	324	60	0.009	77.0	7.945E + 04	8.581E + 06	2.4 ± 1.4
12	2	96	48	0.021	28.5	6.621E + 04	3.178E + 06	5.4 ± 3.8
13	4	68	50	0.059	19.4	1.271E + 05	2.161E + 06	15.1 ± 7.8
14	2	42	50	0.048	12.0	6.356E + 04	1.335E + 06	12.2 ± 8.9
15	6	72	16	0.083	64.2	5.959E + 05	7.151E + 06	21.4 ± 9.1
16	13	131	60	0.099	31.1	3.443E + 05	3.469E + 06	25.5 ± 7.4
17	9	273	60	0.033	64.9	2.384E + 05	7.230E + 06	8.5 ± 2.9
18	5	73	35	0.068	29.7	2.270E + 05	3.314E + 06	17.6 ± 8.2
19	0	37	36	0.000	14.7	0.000E + 00	1.633E + 06	0.0 ± 0.0
20	6	108	100	0.056	15.4	9.534E + 04	1.716E + 06	14.3 ± 6.0
123 2175					34.3	2.162E + 05	3.823E + 06	14.5 ± 1.4

Notes: Chi squared = 77.987 for 19 degrees of freedom; P (chi squared) = <0.1%. Correlation coefficient = 0.257; age dispersion = 62.914%. Zeta calibration factor of 352.7 ± 5 for SRM612 reference glass. RhoD = $1.460E + 06 \text{ cm}^{-2}$; ND = 2233. Pooled age = $14.5 \pm 1.4 \text{ Ma}$. Central age = $6.7 \pm 2.9 \text{ Ma}$.

Appendix Table 5. Analytical data for sample RD30-5 (Hole 859B).

Grain	Ns	Ni	Na	Ratio	U (ppm)	RHOs	RHOi	Age (Ma)
1	6	144	16	0.042	128.3	5.959E + 05	1.430E + 07	10.7 ± 4.5
2	2	17	9	0.118	26.9	3.531E + 05	3.002E + 06	30.2 ± 22.6
3	2	93	9	0.022	147.3	3.531E + 05	1.642E + 07	5.5 ± 4.0
4	15	87	20	0.172	62.0	1.192E + 06	6.912E + 06	44.2 ± 12.4
5	2	237	49	0.008	69.0	6.486E + 04	7.686E + 06	2.2 ± 1.5
6	0	8	60	0.000	1.9	0.000E + 00	2.119E + 05	0.0 ± 0.0
7	6	144	30	0.042	68.4	3.178E + 05	7.628E + 06	10.7 ± 4.5
8	3	65	12	0.046	77.2	3.973E + 05	8.607E + 06	11.9 ± 7.0
9	0	76	24	0.000	45.2	0.000E + 00	5.032E + 06	0.0 ± 0.0
10	1	62	30	0.016	29.5	5.297E + 04	3.284E + 06	4.2 ± 4.2
11	3	72	20	0.042	51.3	2.384E + 05	5.721E + 06	10.7 ± 6.3
12	10	77	48	0.130	22.9	3.311E + 05	2.549E + 06	33.4 ± 11.2
13	15	197	49	0.076	57.3	4.864E + 05	6.389E + 06	19.6 ± 5.3
14	3	61	16	0.049	54.4	2.980E + 05	6.058E + 06	12.6 ± 7.5
15	1	71	28	0.014	36.2	5.675E + 04	4.029E + 06	3.6 ± 3.7
16	0	13	24	0.000	7.7	0.000E + 00	8.607E + 05	0.0 ± 0.0
17	7	47	21	0.149	31.9	5.297E + 05	3.556E + 06	38.2 ± 15.5
18	7	211	16	0.033	188.0	6.952E + 05	2.096E + 07	8.5 ± 3.3
19	6	49	9	0.122	77.6	1.059E + 06	8.652E + 06	31.4 ± 13.6
20	1	27	18	0.037	21.4	8.828E + 04	2.384E + 06	9.5 ± 9.7
90 1758					49.3	2.815E + 05	5.499E + 06	13.2 ± 1.5

Notes: Chi squared = 65.359 for 19 degrees of freedom; P (chi squared) = <0.1%. Correlation coefficient = 0.421; Age dispersion = 71.009%. Zeta calibration factor of 352.7 ± 5 for SRM612 reference glass. RhoD = $1.460E + 06 \text{ cm}^{-2}$; ND = 2233. Pooled age = $13.2 \pm 1.5 \text{ Ma}$. Central age = $14.2 \pm 2.9 \text{ Ma}$.

Appendix Table 6. Analytical data for sample RD30-6 (Hole 859B).

Grain	Ns	Ni	Na	Ratio	U (ppm)	RHOs	RHOi	Age (Ma)
1	2	168	70	0.012	34.2	4.540E + 04	3.814E + 06	3.1 ± 2.2
2	2	23	24	0.087	13.7	1.324E + 05	1.523E + 06	22.3 ± 16.5
3	11	215	50	0.051	61.3	3.496E + 05	6.833E + 06	13.2 ± 4.1
4	3	19	50	0.158	5.4	9.534E + 04	6.038E + 05	40.5 ± 25.2
5	0	3	16	0.000	2.7	0.000E + 00	2.980E + 05	0.0 ± 0.0
6	9	157	36	0.057	62.2	3.973E + 05	6.930E + 06	14.7 ± 5.1
7	2	120	30	0.017	57.0	1.059E + 05	6.356E + 06	4.3 ± 3.1
8	2	51	12	0.039	60.6	2.648E + 05	6.754E + 06	10.1 ± 7.3
9	3	75	50	0.040	21.4	9.534E + 04	2.384E + 06	10.3 ± 6.1
10	3	75	30	0.040	35.6	1.589E + 05	3.973E + 06	10.3 ± 6.1
11	2	138	60	0.014	32.8	5.297E + 04	3.655E + 06	3.7 ± 2.7
12	2	90	49	0.022	26.2	6.486E + 04	2.919E + 06	5.7 ± 4.1
13	1	9	56	0.111	2.3	2.838E + 04	2.554E + 05	28.5 ± 30.1
14	3	88	28	0.034	44.8	1.703E + 05	4.994E + 06	8.8 ± 5.2
15	0	7	28	0.000	3.6	0.000E + 00	3.973E + 05	0.0 ± 0.0
16	0	15	36	0.000	5.9	0.000E + 00	6.621E + 05	0.0 ± 0.0
17	3	93	56	0.032	23.7	8.513E + 04	2.639E + 06	8.3 ± 4.9
18	4	157	42	0.025	53.3	1.513E + 05	5.940E + 06	6.6 ± 3.3
19	3	36	20	0.083	25.7	2.384E + 05	2.860E + 06	21.4 ± 12.9
20	4	187	60	0.021	44.4	1.059E + 05	4.953E + 06	5.5 ± 2.8
59	1726				30.6	1.168E + 05	3.416E + 06	8.8 ± 1.2

Notes: Chi squared = 24.514 for 19 degrees of freedom; P (chi squared) = 17.7%. Correlation coefficient = 0.705; age dispersion = 19.695%. Zeta calibration factor of 352.7 ± 5 for SRM612 reference glass. $\text{RhoD} = 1.460\text{E} + 06 \text{ cm}^{-3}$; ND = 2233. Pooled age = 8.8 ± 1.2 Ma. Central age = 8.9 ± 1.3 Ma.