3. U-Th-Pb SYSTEMATICS IN ZIRCON AND TITANITE

Robert E. Zartman and Loretta M. Kwak

ABSTRACT

U-Th-Pb isotopic analyses of zircon and titanite were made for two core samples of granite from borehole ATK-1 drilled into the Eye-Dashwa Lakes pluton. One of the samples from near the bottom of the hole (990.97 to 996.78 m) yielded zircon and titanite that was slightly to severely disturbed isotopically. Eight fractions of zircon give an upper concordia intercept age of 2625 ± 16 Ma (MSWD = 34), which, based on an evaluation of the more concordant data points and on other geochronological results, is interpreted as being slightly too young. The time of crystallization is probably better approximated by the $^{206}Pb/^{206}Pb$ age of 2665 Ma determined on a slightly (~8%) discordant titanite.

The other sample from near the surface (3.85 to 9.61 m) generally revealed even more severely disturbed isotopic systematics for both zircon and titanite. The complex nature of the disturbance(s) probably resulted from the penetration of meteoritic water into rock already modified by post-crystallization hydrothermal alteration. Nuclide migration occurred in both minerals—during the Middle or Late Proterozoic for the zircon and during the modern weathering cycle for the titanite. Material balance calculations are used to demonstrate a recent relative gain of radiogenic Pb and/or loss of Th and U from the freshest-looking, least-altered titanite by exchange with altered, leucoxene-bearing titanite.

1. INTRODUCTION

Two intervals of the core from borehole ATK-1, one from near the surface (3.85 to 9.61 m) and the other from near the bottom of the hole (990.97 to 996.78 m), were selected for measurement of U-Th-Pb isotopic systematics in zircon and titanite. Both sampled intervals consisted of medium- to coarse-grained granite representative of the main phase of the Eye-Dashwa Lakes pluton; however, the near-surface rock was pervasively fractured and altered to a pink color in contrast to the fresh, gray rock at depth. The petrography, mineralogy, and geochemistry of this core are described elsewhere (Kamineni and Stone, 1990, and references therein). Other papers included in this report, by Peterman et al. and Doe and Peterman, deal more broadly with the Rb-Sr and U-Th-Pb isotopic systematics of the whole rock and constituent minerals.

The purpose of undertaking the study was twofold:

(1) to date as precisely as possible the Eye-Dashwa Lakes pluton, and
(2) to gain some insight into the post-crystallization migration of U, Th, and Pb in the zircon and titanite.
However, in pursuing the first objective, sample selection favoring less-altered material has introduced a bias against the second objective, which prevented a rigorous quantitative treatment of open-system behavior. Our most precise age for the pluton is 2625 ± 16 Ma (MSWD = 34), based on the upper concordia intercept of a linear fit to eight analyzed fractions of zircon from the deep-core sample. However, the extremely high MSWD and skewness of the less-discordant analyses to the overall linear array suggest that this intercept age may be slightly low. A better estimate of the time of crystallization might be the $^{207}\text{Pb} / ^{206}\text{Pb}$ age of 2665 Ma determined on co-existing titanite.

Neither the zircon nor the titanite from the near-surface sample provides additional definitive constraints on the age of the pluton. Both minerals show the effect of major post-crystallization disturbances of their isotopic systematics. Especially complex discordance patterns are encountered in titanite partially altered to leucoxene, which occurs within fractured rock of the near-surface sample.

2. **ANALYTICAL PROCEDURE**

Approximately 50 kg of rock from each of the two core samples was crushed and pulverized to -100-mesh size. Aliquots of the pulverized samples were removed for Rb-Sr and U-Th-Pb whole-rock analyses before further processing (Peterman et al., 1990; Doe and Peterman, 1990). Heavy minerals were then recovered from a Wilfley table, and the final zircon and titanite concentrates were obtained by standard heavy liquid and magnetic separation techniques. Each mineral was further divided into a number of size and crystal morphology fractions in order to elucidate discordance patterns. In two instances, splits of a zircon fraction were subjected to pneumatic abrasion to remove external surfaces and metamict domains that may have responded preferentially to post-crystallization disturbances.

Chemistry and mass spectrometry procedures observed in this study were documented by Zartman et al. (1986). The analytical precision and accuracy described by those authors are generally valid for this study. A more complete treatment of error assignment to U-Th-Pb isotopic data is given by Ludwig (1980). Because of the possibility that the titanite was giving spurious concentration values because of incomplete equilibration with the spike, an alternative dissolution procedure, using borax fluxing, was employed in some analyses to confirm the validity of our results. Results observed by the two methods were consistently in good agreement, which leads us to conclude that no serious problems exist in the determination of U, Th, and Pb concentrations of that mineral. The analytical results obtained for samples ATK-1(990.97-996.78 m) and ATK-1(3.85-9.61 m) are presented in Table 1 and are shown plotted on concordia diagrams in Figures 1 and 2, respectively.
## Table 1

### U-Th-Pb Isotopic Ages of Zircon and Titanite from Eye-Dashwa Lakes Pluton

<table>
<thead>
<tr>
<th>Mesh size</th>
<th>Weight (ng)</th>
<th>Concentration (ppm)</th>
<th>Isotopic composition of lead (at.%)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>U  Th Pb 204Pb 206Pb 207Pb 208Pb</td>
<td>206Pb 207Pb 207Pb 208Pb</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>238U 235U 206Pb 232Th</td>
<td></td>
</tr>
<tr>
<td>Zircon</td>
<td></td>
<td></td>
<td></td>
<td>----------</td>
</tr>
<tr>
<td>+100</td>
<td>5.53</td>
<td>556.1</td>
<td>246.0 236.9</td>
<td>0.2178   66.74 13.38 19.66</td>
</tr>
<tr>
<td>+100A</td>
<td>1.52</td>
<td>500.1</td>
<td>238.6 213.2</td>
<td>0.1976   66.71 13.24 19.85</td>
</tr>
<tr>
<td>-100</td>
<td>3.81</td>
<td>876.9</td>
<td>527.7 391.1</td>
<td>0.1879   66.80 12.95 20.07</td>
</tr>
<tr>
<td>Titanite</td>
<td></td>
<td></td>
<td></td>
<td>----------</td>
</tr>
<tr>
<td>total</td>
<td>8.33</td>
<td>92.9</td>
<td>489.7 239.3</td>
<td>0.6895   32.67 14.37 52.27</td>
</tr>
<tr>
<td>unalt'd I</td>
<td>7.63</td>
<td>82.3</td>
<td>338.2 225.4</td>
<td>0.6165   33.28 13.62 52.49</td>
</tr>
<tr>
<td>unalt'd II</td>
<td>4.76</td>
<td>82.4</td>
<td>354.7 213.6</td>
<td>0.6186   32.87 13.55 52.97</td>
</tr>
<tr>
<td>alt'd I</td>
<td>4.52</td>
<td>198.8</td>
<td>355.2 410.3</td>
<td>0.8263   31.21 15.71 52.25</td>
</tr>
<tr>
<td>alt'd II</td>
<td>1.93</td>
<td>127.9</td>
<td>367.6 n.d.</td>
<td>--       -- -- -- -- --</td>
</tr>
</tbody>
</table>

### ATK-1 (3.85-9.61 m)

<table>
<thead>
<tr>
<th>Zircon</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+80</td>
<td>3.40</td>
<td>160.6</td>
<td>99.7 89.7</td>
<td>0.0176   72.47 13.15 14.36</td>
</tr>
<tr>
<td>-80 + 100</td>
<td>2.84</td>
<td>247.4</td>
<td>153.2 135.1</td>
<td>0.0564   70.63 13.08 16.24</td>
</tr>
<tr>
<td>-100 + 200</td>
<td>4.70</td>
<td>346.2</td>
<td>219.3 184.4</td>
<td>0.0355   71.57 13.00 15.40</td>
</tr>
<tr>
<td>-100 + 200’</td>
<td>3.84</td>
<td>251.7</td>
<td>189.3 135.6</td>
<td>0.0166   71.54 12.93 15.51</td>
</tr>
<tr>
<td>-100 + 200**</td>
<td>1.07</td>
<td>149.8</td>
<td>109.3 86.1</td>
<td>0.0408   70.47 13.05 16.43</td>
</tr>
<tr>
<td>-100 + 200***</td>
<td>1.41</td>
<td>378.8</td>
<td>250.9 202.9</td>
<td>0.0423   71.11 13.00 15.85</td>
</tr>
<tr>
<td>-200 + 325</td>
<td>2.39</td>
<td>523.1</td>
<td>337.5 226.4</td>
<td>0.0352   71.29 12.74 15.93</td>
</tr>
<tr>
<td>-325</td>
<td>1.72</td>
<td>749.2</td>
<td>533.0 150.6</td>
<td>0.0339   70.13 12.22 17.62</td>
</tr>
</tbody>
</table>

### ATK-1 (990.97-996.78 m)

<table>
<thead>
<tr>
<th>Zircon</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>+80</td>
<td>3.32</td>
<td>124.6</td>
<td>400.5 108.4</td>
<td>0.0709   47.04 9.393 43.50</td>
</tr>
</tbody>
</table>

Decay constants: $^{238}$U = $1.55125 \times 10^{-10}$ a$^{-1}$; $^{235}$U = $9.8485 \times 10^{-10}$ a$^{-1}$; $^{232}$Th = $4.9375 \times 10^{-11}$ a$^{-1}$; $^{238}$U/$^{235}$U = 137.88.

Isotopic composition of common lead assumed to be that of coexisting K-feldspar (Doe and Peterman, 1990):

$^{204}$Pb: $^{206}$Pb: $^{207}$Pb: $^{208}$Pb = 1:13.57:14.66:33.40

* abraded fraction
** clear, euhedral crystals;
*** elongate crystals.

Estimated leucoxene contents of titanites are * 3%; b 0%; c 35%; d 15%; analyses of unaltered II and altered II fractions of titanite by borax fluxing.

n.d., not determined.
FIGURE 1: Concordia Diagram for ATK-1(990.97-996.78 m). Open circle - zircon; solid circle - titanite.

FIGURE 2: Concordia Diagram for ATK-1(3.85-9.61 m). Open circle - zircon; solid circle - titanite.


3. DISCUSSION

3.1 ATK-l(990.97-996.78 m)

The most precise age obtained in this study for the Eye-Dashwa Lakes pluton derives from the deep-core sample, ATK-l(990.97-996.78 m). This sample, from near the bottom of the borehole, was chosen for its extremely fresh appearance and freedom from fractures, although zones of intense erosion and fracturing do occur locally at this depth in the pluton (Kamineni and Dugal, 1982; Kerrich and Kamineni, 1988). The fresh rock is a gray, medium- to coarse-grained granite consisting of oligoclase, microcline, quartz, and biotite with accessory magnetite, apatite, titanite, and zircon. U-Th-Pb isotopic analyses of eight size and morphological fractions of zircon and of a composite titanite provide the basis for geochronological interpretation.

The upper concordia intercept of a linear fit to all eight analyzed fractions of zircon is 2625 ± 16 Ma (MSWD = 34), which is in good agreement with the Rb-Sr whole-rock age of 2637 ± 33 Ma (Peterman et al., 1990), but distinguishably younger than the U-Pb whole-rock concordia intercept age of 2684 ± 25 Ma (Doe and Peterman, 1990). The extremely high MSWD of the zircon concordia intercept age, however, clearly reveals a dispersion in the linearity of the data beyond that expected solely from the analytical uncertainty. Furthermore, upon closer examination of the less-discordant and larger-grain-size fractions of zircon, we note an inverse correlation between uranium content and $^{207}\text{Pb}/^{206}\text{Pb}$ age, which introduces a skewness to the linear array and accounts for much of the excess MSWD.

This skewness is even more accentuated if the single titanite analysis from this sample is included in a regression from which the -200 + 325 and -325 mesh fractions of zircon are omitted. It is probably unwarranted, however, to assume that a simple projection of the skewed array to its intersection with concordia would yield a better age for the pluton, especially when considering the morphological heterogeneity and mixture of mineral species comprising the array. More likely, some complex relationship exists between the response of the zircon to disturbances in its U-Pb isotopic systematics and degradation of lattice domains in the crystal by radioactivity. The lower uranium content, slightly reduced discordance, and significantly increased $^{207}\text{Pb}/^{206}\text{Pb}$ age of the abraded -100 + 200 mesh fraction compared to the unabraded counterpart lend support to such an interpretation of the zircon population.

The general response of titanite to accumulating radioactive damage is poorly known, but evidence presented below for isotopically severely disturbed titanite from the near-surface core sample suggests that migration of U, Th, and Pb was a rather young event. If we regard the $^{207}\text{Pb}/^{206}\text{Pb}$ age of the ATK-l(990.97-996.78 m) titanite, which is just ~8% discordant, as essentially equal to, or only slightly less than, that of crystallization, then agreement with the U-Pb whole-rock concordia intercept age is considerably improved. A perusal of Table 1 reveals a still higher $^{208}\text{Pb}/^{232}\text{Th}$ age of 2690 Ma for the -80 + 100 mesh fraction of zircon. We
do not place much confidence in this single analysis, however, especially
in the light of the decrease in $^{208}\text{Pb}/^{232}\text{Th}$ age experienced after abraison
of the -100 + 200 mesh fraction. Our data show that the U-Pb and Th-Pb
systems must be at least partially decoupled within the zircon population,
and neither of them are apt to behave as a precisely closed system.

3.2 ATK-1(3.85-9.61 m)

The near-surface core sample, ATK-1(3.85-9.61 m), contributes little to
determining an exact age for the Eye-Dashwa Lakes pluton. Moderate to
extensive hydrothermal alteration of the granite, presumably associated
with the final stages of crystallization, occurs pervasively in the upper
100 m of the borehole, and adjacent to many of the major fracture zones
intersected throughout the total length of the core (Kamineni and Dugal,
1982). This alteration, which is mostly manifested by the pink to red
color imparted to the granite, is accompanied by an albitionization of the
plagioclase, chloritization of the biotite and/or hornblende, and the
introduction of zoisite veinlets crosscutting the rock. A peculiar
leucoxene mottling\(^1\) of the titanite, observed only in the near-surface core
sample, is closely associated with the zoisite veinlets and appears also to
be a product of the hydrothermal activity. Although it is tempting to
relate the more pervasive discoloration of the upper part of the core to
superimposed modern weathering, unequivocal macroscopic methods by which to
distinguish between the effects of original hydrothermal activity and the
subsequent circulation of meteoric water are not readily obvious. Kerrich
and Kamineni (1988) give stable isotope evidence for infiltration of
surface waters into reactivated fractures to depths of 200 m, but otherwise
relate fracturing and alteration of the granite to initial devolatilization
and thermal contraction of the cooling rock. Interestingly, although the
isotopic systematics of the titanite record a disturbance that correlates
with the amount of leucoxene alteration (see below), the postulated accom-
panying redistribution of lead is clearly a more recent event. Evidently,
the disrupted U-Th-Pb isotopic systematics result from the combined effects
of hydrothermal alteration and modern weathering.

Figure 2 reveals that the zircon and the titanite display open-system
behavior documenting severe disturbance of their U-Pb isotopic systematics.
The three zircon analyses plot too close together on a concordia diagram to
define any meaningful linear array, and it is not obvious how they may
relate to those analyses obtained for the deep core sample, ATK-1(990.97-
996.78 m). The greater discordance of equivalent-size zircon from the
near-surface compared to the deep part of the core correlates with a consi-
derably higher uranium content and may be accentuated by greater access to
meteoric water accompanying incipient weathering of the rock. Also, the
peculiarly low $^{206}\text{Pb}/^{204}\text{Pb}$ of the near-surface zircon can best be explained
by the post-crystallization introduction of common lead. However, the
significant reduction in $^{207}\text{Pb}/^{206}\text{Pb}$ ages of the zircon occurring near the
surface suggests that the U-Pb isotopic systematics record additional

\(^1\) The dull, white-to-yellow, patchy leucoxene was identified by SEM and X-
ray diffraction analysis, and found to consist of fine-grained anatase
$(\text{TiO}_2)$ and an unidentified calcium-iron aluminosilicate.
disturbance at times other than today, such as during the Middle or Late Proterozoic. Although with diminished effect, a similar disturbance may offer an explanation for the skewed array observed in the more concordant fractions of zircon from the deep core samples. Unfortunately, the available data do not permit us to place with much confidence a useful constraint on the intermediate history of the rock.²

Attempts to date the titanite recovered from the near-surface core sample produced a discordancy pattern that presents special problems in interpretation. The initial analysis of the titanite was performed on the total mineral separate, which consisted of -60 + 200 mesh resinous, wedge-shaped crystals and cleavage fragments ranging in color from light to medium yellowish brown. Although microscopic examination had revealed a mottled appearance of a few grains, no effort was made to upgrade the titanite used for this initial analysis. Subsequent concern about mineral purity did arise when the calculated U-Pb ages were found to be reversely discordant. Eventually, the possibility of spurious concentration values led us to modify the dissolution procedure by including an initial borax fusion step, but the consistency in results from before and after the modification argues against analytical difficulties.

After some of the titanite grains were determined to contain patches of leucoxene (see Figure 3), several fractions of the mineral were hand-picked to accentuate this phenomenon and see what effect it might have on the isotopic systematics. Fractions consisting of 1) the freshest, most translucent, and 2) the most-altered, leucoxene-mottled grains were designated as unaltered I and II, and altered I and II, respectively.

As we had suspected, major redistribution of nuclides was found to correlate with the leucoxene alteration. Unexpectedly, though, the U-Pb systematics in the unaltered grains showed an enhanced reverse discordancy, while the altered grains showed only minor, normal discordancy. Accompanying this pattern in ages was a trend in U and Pb concentration among the analyses, which dropped to slightly lower values in the unaltered separates and increased by about a factor of two in the altered separate. The greater fluctuation in U than Pb and the close similarity in Pb isotopic composition (except for a difference in percent of common lead) suggests that recent lead mobility played an important role in establishing the relative pattern of age discordance; that is, internal homogenization of lead in the titanite would result in progressively older U-Pb ages with decreasing U content.

² For example, a linear regression through all zircon analyses from the near-surface and, except for the -200 + 325 and -325 mesh fractions, the deep-core samples yield upper and lower concordia intercept ages of 2671 ± 23 Ma and 741 ± 94 Ma, respectively. Because the superimposed effect of any modern lead loss is likely to cause counterclockwise rotation of the regression line, the lower intercept age in particular will be reduced and should be considered a minimum value for the intermediate disturbance event.
FIGURE 3: Photomicrograph of Titanite from ATK-1(3.85-9.61 m) Showing Typical Wedge-Shaped Crystals and Two Grains with Leucoxene (L) Mottling. The altered and unaltered fractions were hand-picked to include and exclude, respectively, such grains with obvious patches of leucoxene.

The common lead content of the titanite introduces considerable uncertainty in correcting for the non-radiogenic component of the lead analyses. The isotopic composition used for making the common lead correction is taken to be that of a coexisting K-feldspar reported by Doe and Peterman (1990), but, even so, error propagation alone translates into a maximum precision for the $^{207}\text{Pb}/^{206}\text{Pb}$ ages of about ±25 Ma. Thus, although the upper concordia intercept of a remarkably linear fit to the four fractions of titanite yields a very precise age of 2657 ± 5 Ma (MSWD = 0.44), one cannot ignore the larger common lead uncertainty not included in the regression calculation. Furthermore, the implication for lead mobility even brings into question our assumption that the coexisting K-feldspar can be used to represent the common lead in the titanite.

Nevertheless, the good agreement among all $^{207}\text{Pb}/^{206}\text{Pb}$ ages for the titanite with the presumed emplacement age of the Eye-Dashwa Lakes pluton does put one important constraint on the time of disturbance of the U-Pb isotopic system; that is, the event recorded by the disturbance is rather young (<200 Ma) and probably related to weathering within the near-surface environment. Whether the lower concordia intercept age of 214 ± 39 Ma has geological meaning at the indicated level of precision, however, is open to similar questioning as the upper concordia intercept age. By comparison, the single titanite analysis from the deep-core sample revealed just minor
normal discordancy for both U-Pb and Th-Pb isotopic systems, and only onetenth as much common lead as the near-surface core sample.

If the initial analysis of the total titanite represents a true composite sample, either a preferential loss of thorium and uranium relative to lead or the gain of some extraneous radiogenic lead must have occurred in the titanite-leucoxene system. Figure 4 represents an attempt to model the titanite as a simple two-component mixture of unaltered titanite and leucoxene, which had recently suffered an internal redistribution of U, Th, and Pb. For this purpose, it is instructive to separate the Pb into three fractions—common, uranogenic, and thorogenic—which may have behaved independently during their movement through the rock. As was done previously, the isotopic composition of the K-feldspar is used here to define the common lead of the system, although we recognize the probable oversimplification of this assumption. Except for the anomalously high thorium content of the total analysis, the concentration data do indeed approximate a two-component system. Also, for a mixture of about 68% titanite and 32% leucoxene, a concordant U-Pb age of 2657 Ma would be obtained within

![Graph](image)

**FIGURE 4:** Two-Component Mixing Diagram of Titanite and Leucoxene from ATK-1(3.85-9.61 m). Values along right margin are extrapolated to 100% leucoxene.

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1 This single deviation from an otherwise linear mixing array further raises the question of analytical difficulty in the thorium determination. An alternative explanation is that the total fraction contains some minor thorium-enriched phase that has been excluded from the unaltered and altered fractions.
such a binary system. Conceivably, highly altered titanite was preferentially removed during mineral separation, in which case our composite sample may be biased against the leucoxene component. However, other phases of the rock, contributing uranium, thorium, and both common and radiogenic lead, are likely to have participated in the chemical redistribution event, and we have no reason to believe that closed-system behavior actually did prevail between the titanite-leucoxene binary system.

Although the preceding argument implies that a net flux of uranium or lead into, or from, the titanite-leucoxene system is not required, no combination of components can yield concordant Th-Pb ages under the assumptions of the model. Instead, a deficiency in thorium relative to lead—and, except for the noted anomaly in the total analysis, a remarkably uniform thorium content—is found for all combinations of the hypothesized binary system. Either thorogenic Pb has been gained or Th has been lost in the composite titanite-leucoxene. Perhaps most surprisingly, a gain of radiogenic Pb and/or loss of Th and U must have severely affected even the freshest-looking, least-altered titanite.

The highly disturbed condition of the titanite prevents us from making an exact material balance or from retrieving its isotopic systematics prior to disturbance. The binary-mixture model is offered only as an illustration to emphasize the general trend of element redistribution that appears to have caused the reverse discordancy in the unaltered grains. Leaching and abrasion experiments, while not carried out in the present study, could be helpful in distinguishing among different location sites of U, Th, and Pb in the titanite. For example, an easily removed component containing the "excess" thorogenic lead would certainly lend credence to the suggestion that recent introduction of such lead into the titanite has occurred. Also, restricting these experiments to material separated from more specific core intervals might better define migration distances of the labile nuclides, perhaps to a scale commensurate with individual fracture zones.

4. CONCLUSIONS

The analytically best-constrained age for the Eye-Dashwa Lakes pluton calculated from the upper concordia intercept of a linear fit to eight fractions of zircon from the deep-core sample ATK-1(990.97-996.78 m) is 2625 ± 16 Ma. However, the extremely high HSWD, 34, for this array of points and the skewed alignment of the less-discordant analyses suggest a slightly earlier emplacement of the pluton. The $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2665 Ma obtained on a slightly discordant titanite from the same sample perhaps provides a better estimate of a minimum age, which is then brought into closer agreement with the U-Pb whole-rock concordia intercept age of 2684 ± 25 Ma (Doe and Peterman, 1990).

U-Pb isotopic systematics for both zircon and titanite from the near-surface core sample (3.85 to 9.61 m) are significantly more disturbed, presumably as a consequence of the penetration of meteoric water into incipiently weathered rock that was already hydrothermally altered soon after
its crystallization. A higher uranium content of the zircon in comparison to equivalent grain-size fractions from the deep-core sample may have further accentuated the escape of radiogenic lead. Also, evidence exists that at least some of the disturbance of the U-Pb isotopic systematics of the zircon was caused by events at times other than the recent past, such as during the Middle or Late Proterozoic. Disturbance of the isotopic systematics of the titanite, on the other hand, appears to have occurred mainly during the modern weathering cycle by the redistribution of Pb and/or U and Th within the mineral with a relative net gain of radiogenic Pb or loss of Th and, likely, U from the composite material. As a consequence, titanite judged by visual examination to be least altered nonetheless showed too old a Th-Pb age and strong reverse discordance in its U-Pb ages.

ACKNOWLEDGMENTS

We wish to thank Karin Barovich for providing high-quality mineral separates. Our study benefitted particularly from the assistance of Eugene Foord, who performed SEM and X-ray diffraction analyses on the titanite, allowing a better characterization of the leucoxene alteration. Also, we are grateful to Samuel S. Goldich, John N. Aleinikoff, and Randall R. Parrish for thoughtful reviews that improved the original manuscript significantly.

REFERENCES


