In situ monazite (U–Th)–Pb ages from the Southern Brasília Belt, Brazil: constraints on the high-temperature retrograde evolution of HP granulites

B. L. RENO,1* P. M. PICCOLI,1 M. BROWN1 AND R. A. J. TROUW2
1Laboratory for Crustal Petrology, Department of Geology, University of Maryland, College Park, MD 20742-4211, USA (mbrown@umd.edu)
2Department of Geology, Federal University of Rio de Janeiro, Ilha do Fundão, CEP 21949-900, Rio de Janeiro, Brazil

ABSTRACT In the southern sector of the Southern Brasilia Belt, late Neoproterozoic arc–passive margin collision resulted in juxtaposition of an arc-derived nappe (the Socorro–Guaxupê Nappe) over a stack of passive margin-derived nappes (the Andrelândia Nappe Complex) that lies on top of autochthonous basement of the São Francisco Craton. (U–Th)–Pb monazite ages are reported from the high-grade nappes of the Andrelândia Nappe Complex to better constrain the high-temperature retrograde evolution. For residual HP granulites from the uppermost Três Pontas–Varginha Nappe, (U–Th)–Pb ages of c. 662 and 655 Ma from low yttrium monazite inclusions in the rims of, or associated with garnet are interpreted to date the late-stage close-to-peak prograde evolution, whereas an age of c. 648 Ma from a similar low yttrium monazite inclusion is interpreted to record post-peak recrystallization with melt via fractures in garnet. For the same nappe, ages of 640–631 Ma retrieved from higher yttrium areas or cores in monazite grains that occur both as inclusions in garnet and in the matrix are interpreted to record growth of monazite either by local breakdown of garnet (± older monazite) and mass exchange with a matrix melt reservoir along cracks or growth from residual melt in the matrix as it crystallized during high-pressure, close-to-isobaric cooling close to the solidus, the temperature of which, at a given pressure, varies with bulk composition of the residual granulites. (U–Th)–Pb ages in the range 620–588 Ma from lower yttrium areas in these monazite grains and from matrix-hosted patchy monazite are interpreted to date exhumation, as recorded by close-to-isothermal decompression and subsequent close-to-isobaric cooling. Older monazite ages in this group are interpreted to record late-stage interaction with melt close to the solidus whereas younger monazite ages are interpreted to record recrystallization of monazite by dissolution–reprecipitation owing to ingress of alkali fluid from the Carmo da Cachoeira Nappe beneath as fluid was released by crystallization of in-source melt at the solidus. In the underlying Carmo da Cachoeira Nappe, higher yttrium areas in monazite and one single domain monazite yield chemical ages of 619–616 Ma, which are interpreted to date growth as in-source melt crystallized close to the solidus along the high-pressure, close-to-isobaric segment of the retrograde P–T evolution. Younger (U–Th)–Pb ages of 600–595 Ma retrieved from lower yttrium areas and one single domain monazite are interpreted to record recrystallization of monazite by dissolution–reprecipitation owing to release of fluid at the solidus during exhumation of this nappe. Monazite from the Carvalhos Klippe, interpreted to be correlative with the uppermost nappe, yields a wide range of (U–Th)–Pb ages: for two zoned grains, c. 619 and c. 614 Ma from higher yttrium cores, and c. 583 and c. 595 Ma from lower yttrium rims; and, 592–580 Ma from single domain grains in one sample, and ages of c. 593 and c. 563 Ma from monazite in a second sample. Ages younger than 605 Ma are interpreted to date a fluid-induced response to the early stages of orogenic loading associated with terrane accretion in the Ribeira Belt to the southeast. The results reported here demonstrate that ages retrieved from monazite that grew close to the solidus in residual granulites from a single tectonic unit will vary from sample to sample according to differences in the solidus temperatures. Further, we show that monazite inclusions may yield ages that are younger than the host mineral and confirm the propensity of monazite to record evidence of tectonic events that are not always registered by other high-temperature mineral chronometers.

Key words: Brasília Belt; Brazil; HP granulite; monazite chronology; pseudosection; Ribeira Belt; (U–Th)–Pb monazite dating.

*Present address: Institute for Geography & Geology, University of Copenhagen, Øster Voldgade 10, 1350 København K, Denmark

© 2011 Blackwell Publishing Ltd
INTRODUCTION

Modern studies of metamorphic rocks integrate petrographic, thermobarometric and geochronological data to provide information about the depth and rate of burial of these rocks, their thermal history, the timing and time-scale of metamorphism, and rates of exhumation. These studies have been enabled by advances during the last decade in: thermobarometry and the characterization of P–T paths, particularly via the calibration and application of accessory phase thermometers and through the use of pseudosections (Baldwin et al., 2007; Powell & Holland, 2008); the interpretation of ages retrieved from high-temperature accessory phase chronometers, particularly using microstructural setting and chemical composition (Harley et al., 2007; Williams et al., 2007); and, understanding zircon and monazite dissolution and crystallization in relation to these P–T paths (Kelsey et al., 2008). As a result, the combination of reliable pressure, temperature and time information has enabled better parameterization of the high-temperature evolution of orogenic belts, such as the southern sector of the Southern Brasilia Belt (Baldwin & Brown, 2008; Reno et al., 2009).

In this contribution, P–T path information and a suite of new (U–Th)–Pb monazite ages are presented for high-pressure granulites from the southern sector of the Southern Brasilia Belt to further constrain the timing of events during the high-temperature, suprasolidus-to-subsolidus retrograde evolution of these rocks. In addition, the cooling history of these high-pressure granulites during exhumation is retrieved by combining these new monazite age results with published age data for zircon and biotite (Reno et al., 2009, 2010). For melt-bearing rocks we find that ages of monazite crystallization vary from sample to sample within a single tectonic unit due to differences in the solidus temperatures, which varies according to how residual the granulites have become after melt loss or whether the sample is leucosome. This finding suggests that for high-temperature metamorphic rocks caution is required in the interpretation of ages that appear to be inconsistent with each other, as variation in the ages retrieved may be expected in a regional study of partially melted rocks. Our results also demonstrate that monazite may yield ages that are younger than the host mineral in which it appears to be enclosed as inclusions, and furthermore it may record evidence of events that are not always registered by other high-temperature mineral chronometers.

REGIONAL GEOLOGY

The Neoproterozoic–Cambrian assembly of Gondwanan elements in southern Brazil (Fig. 1a) involved closure of oceans to both the west and the east of the São Francisco Craton. To the west, this involved closure of the Brazilide Ocean and suturing of the Paranapanema Block and several intervening arcs (e.g. Arenópolis Arc, Socorro–Guaxupé Arc) in the south (older), and suturing of the Goiás Massif and the Mara Rosa Arc in the north (younger) to the western margin (present co-ordinates) of the São Francisco Craton, creating the Southern and Northern arms of the Brasília Belt respectively (Campos Neto & Caby, 1999, 2000; Junges et al., 2002; Pimentel et al., 2004; Valeriano et al., 2004, 2008). To the east, the Ediacaran–Cambrian closure of the Adamastor Ocean, a restricted southward-opening ocean between the São Francisco craton and the western margin of the Congo craton, involved accretion of Palaeoproterozoic basement terranes and at least one intervening arc system (the Rio Negro Magmatic Arc) to the eastern margin of the São Francisco craton (e.g. Machado et al., 1996; Heilbron & Machado, 2003; Schmitt et al., 2004, 2008; Alkmin et al., 2006; Heilbron et al., 2008). The Araçuai and Ribeira Belts along the South American coast and the West Congo and Kaoko Belts along the African coast are the result of this closure. Finally, further to the northwest, the Amazon Craton was sutured to the São Francisco craton by the Cambrian closure of the Clymene Ocean along the Araguaia Belt (Trindade et al., 2006).

The southern sector of the Southern Brasilia Belt (Figs 1b & 2) comprises a stack of flat-lying nappes – the Socorro–Guaxupé Nappe and the underlying Andrelândia Nappe Complex – transported east-north-east onto the São Francisco Craton. The Socorro–Guaxupé Nappe represents part of the magmatic arc from the hangingwall plate, whereas the nappes of the Andrelândia Nappe Complex beneath are composed of metasedimentary rocks originally deposited along a passive margin on the western side (present co-ordinates) of the São Francisco Craton prior to subduction, terminal arc collision and exhumation (e.g. Ribeiro et al., 1995; Campos Neto & Caby, 1999; Paciullo et al., 2000; Reno et al., 2009, 2010). The lower grade nappes (Figs 2 & 3) record the lowest pressures but are structurally deeper in the nappe stack, whereas the higher grade Carmo da Cachoeira/Andrelândia, Lambari/Liberdade and Três Pontas–Varginha Nappes (Figs 2 & 3) record higher pressures and occur structurally higher in the nappe stack (Campos Neto & Caby, 1999, 2000; Garcia & Campos Neto, 2003; Reno et al., 2009). Klippen of high-pressure granulate facies rocks in the southernmost portion of the Brasilia Belt (Figs 2 & 3) are correlated with the Três Pontas–Varginha Nappe (Campos Neto et al., 2010).

A recent study by Reno et al. (2009) has shown that metamorphism in the Andrelândia Nappe Complex began as early as c. 678 Ma, based on a SIMS 206Pb/238U age from zircon included in garnet and in a symplectic aggregate of plagioclase and clinopyroxene in a block of retrograded eclogite located along a nappe contact (Table 1), whereas post-peak, high-temperature crystallization of zircon in leucosome in residual HP
granulite occurred at c. 648 Ma (Table 1). Immediately to the north, in HP amphibolite-to-granulite facies metasedimentary rocks of the Passos Nappe Complex zircon ages of c. 655 Ma likely date the same event (ID-TIMS lower intercept ages; Valeriano et al., 2004). Further north again, in the Anápolis–Itaucu Complex in the northern sector of the Southern Brasília Belt, high-precision TIMS U–Pb zircon ages from four widely spaced samples constrain the timing of UHT granulite metamorphism to the interval 649–634 Ma (Baldwin & Brown, 2008).

Rb–Sr isochron ages of c. 590 Ma reported by Reno et al. (2009) were related to the main retrograde foliation-forming event during high-temperature exhumation to mid-crustal depths. Recently, Nebel et al. (2010) have re-evaluated the $^{87}$Rb decay constant and found it to be 2% lower than the recommended one. This requires that earlier Rb–Sr isochron ages be revised upward by 2%, in this case to c. 602 Ma (the new age for sample 04-6-21A is 601.5 ± 3.7 Ma and for sample 04-6-21B is 603 ± 13 Ma); the revised age will be used throughout this article.

For the overlying arc-related Socorro–Guaxupé Nappe a SIMS $^{206}$Pb/$^{238}$U zircon age of c. 622 Ma from HP granulite (Table 1) was interpreted by Reno et al. (2009) to record immediate post-peak temperature cooling during the juxtaposition of this nappe against the stack of passive margin-derived nappes. Further to the west in the Socorro–Guaxupé Nappe, in migmatites formed at a shallower structural level than the granulites, (U–Th)–Pb ages in the range 640–606 Ma were interpreted by Martins et al. (2009) to record monazite generation at different stages during prograde-to-peak anatexis and the subsequent retrograde crystallization of melt.

The Ribeira Belt is a northeast-trending orogenic system that affected eastern Brazil during the Ediacaran to Cambrian Periods. It comprises several tectono-stratigraphic terranes (e.g. Machado et al., 1996; Heilbron et al., 2000, 2008; Schmitt et al., 2004, 2008). From northwest to southeast these are (Fig. 1b): the Occidental terrane, which represents the reworked passive margin of the São Francisco craton and which preserves a metamorphic record of subsequent terrane
amalgamation events; the Paraíba do Sul–Embu composite terrane, which comprises Palaeoproterozoic basement and a metasedimentary cover sequence sutured to the craton in the interval 605–580 Ma; the Oriental terrane, which includes the Rio Negro Magmatic Arc and associated migmatitic granulites, sutured to the margin in the interval 580–550 Ma; and the Cabo Frio terrane, which comprises Palaeoproterozoic basement and a high-grade supracrustal succession inferred to have formed in a back-arc basin related to the Rio Negro magmatic arc, and sutured to the margin in the interval 530–510 Ma.

The high angle between the strike of the Ribeira and Brasília belts (Fig. 1b) resulted in an interference zone where deformation and metamorphism associated with the Ribeira Belt was superimposed on the southern part of the Brasília Belt (Trouw et al., 2000, 2006). In the southern portion of the study area, sillimanite, which occurs as pseudomorphs after kyanite as well as in the matrix, is interpreted to record overprinting related to terrane accretion in the Ribeira Belt (Trouw et al., 2006; Heilbron et al., 2008). The metamorphic map of the study area (Fig. 3) shows an east–west-trending sillimanite-in isograd that crosscuts the northeast–southwest-trending isograds related to the Brasília metamorphism; this is the petrographic evidence for the overprint. Klippen associated with the Três Pontas–Varginha Nappe occur within this overprint zone, whereas the main outcrop of the Três Pontas–Varginha and Carmo da Cachoeira Nappes is located to the north of the overprint zone.

**ANALYTICAL METHODS**

**X-ray mapping**

Wavelength dispersive X-ray element composition maps were collected using a JEOL JXA-8900R electron probe microanalyzer at the University of Maryland to identify homogenous compositional domains. An accelerating voltage of 15 kV and a focused beam (≈1 μm diameter) with a cup current of 250 nA were utilized to collect X-ray maps of U, Th, Pb and Y. The crystals, X-ray lines and detectors used during map collection are given in Appendix S1. A peak search using the relevant crystal and X-ray line were optimized prior to mapping. The step size between adjacent points on a map varied from 0.5 to 1 μm, with a count time for each point of between 200 and 500 ms. These two parameters were adjusted according to the size of each individual monazite grain, primarily to adjust collection time for an individual map. Thus, a larger distance between points was used for larger grains.

**(U–Th)–Pb monazite dating**

Monazite chemical compositions were determined using the JEOL JXA-8900R electron probe microanalyzer (EPMA) at the University of Maryland following a protocol modified from that suggested by Pyle et al. (2005; J. Pyle, personal communication, 2006) to
ensure efficiency in collection of X-ray counts while maintaining accuracy in analysis. An accelerating voltage of 15 kV, a cup current of 200 nA and a beam diameter of 3–5 μm were used for both standardization and analysis. During quantitative analysis Si, Y, P, Ce and Ca were measured in addition to the Th, U and Pb necessary for calculating an age. Standardization for Th, Si, U and Pb was done on ThSiO₄, UO₂ and PbCO₃, respectively, standardization for Y and P, and Ce was done on synthetic YPO₄ and CePO₄, respectively, and standardization for Ca was done on a garnet standard (12442/USGS GTAL). Each monazite analysis took ~9 min, with the measurement time being primarily a function of the count time for Pb; for a typical analysis, lead was counted for 240 s plus 120 s on each background position. A more detailed description of the analytical methods and conditions used at the University of Maryland is presented in Appendix S1.

**Age, error and Pb isotope calculations**

In this article, an individual determination of time calculated from a single high-precision chemical analysis is referred to as a date, whereas an age is calculated from a close-to-normally distributed, statistically representative population of dates that is interpreted to record a growth or recrystallization event (cf. Martin et al., 2007; Baldwin & Brown, 2008). A quantitative assessment of the normality of each data set is determined by analysing the kurtosis (a measure of the peakedness or flatness of the data set compared to a normal distribution) and the skewness (a measure of the asymmetry of the data set compared to a normal distribution), and by constructing probability plots. The values of kurtosis and skewness are a function of sample size, and values of kurtosis and skewness are described as low if they are within two standard errors of zero and high if they are not within two standard errors of zero. These statistical measures are discussed further in Appendix S1. Monazite (U–Th)-Pb ages reported here are mean ages with uncertainty quoted as twice the standard deviation of the mean (2σm).

**Reference monazite** In this work, the GSC-8153 reference monazite was analysed during each analytical session and the Trebilcock reference monazite was analysed during most analytical sessions as quality control checks (see Appendix S1).

**Mineral equilibria modelling**

Mineral equilibria modelling reported in this article was undertaken using THERMOCALC 3.26 (Powell et al., 1998; updated August 2007) and the internally consistent data set of Holland & Powell (1998: data set teds55, created in November 2003). The calculations were done in the chemical system Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–Fe₂O₃ (NCKFMASHTO) using the following a-x models: biotite and melt (White et al., 2007), orthopyroxene and spinel-magnetite (White et al., 2002), garnet (Dienet et al., 2008), cordierite (Holland & Powell, 1998), K-feldspar and plagioclase (Holland & Powell, 2003), white mica (Coggon & Holland, 2002), and ilmenite–hematite (White et al., 2000). The aluminosilicates, quartz and aqueous fluid (H₂O) are taken to be pure end-member phases. The modelling does not include minor components, such as F or Cl in biotite or Cr₂O₃ in magnetite, which will affect the stability of these phases. However, the NCKFMASHTO system is currently the most realistic approximation of rock compositions within which modelling may be undertaken (White et al., 2003, 2007).

**SAMPLES**

Monazite was analysed in nine samples from the Três Pontas–Varginha Nappe, five samples from the Caminho da Cachoeira Nappe and two samples from the Carvalhos Klippe. Sample locations are listed in Table 2 and sample descriptions are given in the Appendix.

**METAMORPHIC HISTORY**

**Três Pontas–Varginha Nappe**

The metamorphic history of the Três Pontas–Varginha Nappe is discussed in detail by Reno et al. (2009) and only a brief summary of the main details is included here. In Fig. 4, a schematic P–T path for the Três Pontas–Varginha Nappe (Reno et al., 2009) has been superimposed on four representative P–T pseudosections, one for a sample from the lower part of the nappe close to the top (04-6-21), two from the middle of the nappe (04-6-2 & 04-6-11) and the fourth for a sample from the upper part of the nappe close to the top (05b-6-31B). The peak phase assemblage fields for the four samples are as follows...
(Fig. 4, all + Qtz): sample 04-6-21, garnet–K-feldspar–plagioclase–ilmenite–silicate melt; sample 04-6-11, garnet–biotite–K-feldspar–plagioclase–ilmenite–silicate melt; sample 04-6-2, garnet–K-feldspar–plagioclase–ilmenite–silicate melt; and, sample 05-6-31B, garnet–K-feldspar–kyanite–ilmenite–plagioclase–silicate melt.

The post-peak retrograde $P$–$T$ path is stepped, comprising a high-pressure–high-temperature close-to-isobaric segment, a close-to-isothermal segment $\sim$750°C and a low-pressure close-to-isobaric segment $\sim$0.65 GPa. The solidus at high-pressure–high-temperature is different in each of the three pseudo-sections for residual HP granulites (Fig. 4a,b,d), varying from $\sim$850 to $\sim$780 °C, but occurs at a much lower temperature for the leucosome sample (Fig. 4c). The high-temperature decompression step is consistent with: the occurrence of primary kyanite throughout the nappe, the occurrence of foliation-forming sillimanite in mylonitic gneisses close to the base and top of the nappe, and the Ti-in-quartz temperatures retrieved from quartz in the mylonitic fabric (Reno et al., 2009). The reader is referred to Reno et al. (2009) for further details of the mineral equilibria modelling of samples from the Três Pontas–Varginha Nappe and for additional specific petrographic information supporting the retrograde $P$–$T$ path.

**Carvalhos Klippe**

$P$–$T$ pseudosections were constructed for samples 05b-5-23, 04-5-6 and 04-5-8 using the H$_2$O contents determined by loss on ignition (LOI). K-feldspar, which is not present in the samples, was present across the $P$–$T$ range in all three phase diagrams, and the observed peak assemblages, which do not include K-feldspar, were not represented in these pseudosections. This is interpreted to be an artefact of the low H$_2$O content determined by LOI in comparison with the H$_2$O content originally present at the solidus in the natural samples (cf. Carrington & Watt, 1995; Korhonen et al., 2011). Thus, to obtain $P$–$T$ pseudosections with the observed peak assemblage for the Carmo da Cachoeira samples it was necessary to adjust the amount of H$_2$O present.

To estimate an appropriate H$_2$O content, $T$–$X$(H$_2$O) diagrams were constructed at a pressure of 1.4 GPa, where the pressure was assessed from the $P$–$T$ pseudosections calculated with H$_2$O contents determined by LOI, for a range of H$_2$O contents between the LOI values and 10 mol.% H$_2$O. H$_2$O contents were chosen from the $T$–$X$(H$_2$O) diagrams based on the point where the observed peak assemblage field was stable at temperatures above the solidus. The revised $P$–$T$ pseudosections constructed using the higher H$_2$O contents are shown in Fig. 5. In Fig. 6, simplified pseudosections are contoured for mole proportion of garnet, biotite, silicate melt and H$_2$O. Also, $P$–$T$ paths consistent with the petrography are superimposed on the pseudosections in this figure.

In thin section, the strong foliation in all samples from the Carmo da Cachoeira Nappe means that any microstructures consistent with the presence of a silicate melt likely have been overprinted. However, irregular polymineralic quartz-feldspathic aggregates preserved as inclusions in garnet are interpreted to have crystallized from former melt inclusions, and the peak mineral assemblage is inferred to have been in equilibrium with silicate melt. Thus, the assemblage observed in thin section for these samples is represented by the phase assemblage field quartz–biotite–garnet–plagioclase–kyanite–ilmenite–silicate melt–rutile (Fig. 5).

Considering all three samples, these assemblages constrain the metamorphic conditions to pressures between 1.1 and 1.35 GPa and temperatures between 700 and 820 °C (ignoring the minor modal amount of rutile included in garnet and ilmenite in 05b-5-23). However, the peak temperature may have been higher,
Fig. 4. Simplified $P$–$T$ pseudosections for four representative samples from the Três Pontas–Varginha Nappe to show the high-temperature retrograde $P$–$T$ evolution of this nappe (modified from Reno et al., 2009). The interpreted high-temperature retrograde $P$–$T$ path from Reno et al. (2009) is superimposed (it is shown as a 0.15 GPa wide arrow, which corresponds to an estimated nappe thickness of 5 km (Campos Neto & Caby, 2000)). The peak phase assemblage field for the samples are: 04-6-21, garnet–quartz–K-feldspar–plagioclase–ilmenite–silicate melt; 04-6-2, garnet–K-feldspar–plagioclase–quartz–ilmenite–silicate melt; 04-6-11, garnet–biotite–quartz–K-feldspar–plagioclase–ilmenite–silicate melt; and, 05-6-31B, garnet–K-feldspar–kyanite–ilmenite–plagioclase–quartz–silicate melt. Phase abbreviations follow Kretz (1983).
corresponding to the phase assemblage field quartz–
ilmenite–silicate melt for samples 04-5-6 and 04-5-8
(Fig. 5), as the possibility that K-feldspar was present
and was consumed to form biotite along the early part
of the retrograde $P$–$T$ path cannot be ruled out. For
sample 05b-5-23, this would be consistent with the
peak phase assemblage field including rutile (Fig. 4a,
field 3), which is stable up to 900 °C at 1.35 GPa.
Depending on the specific sample, the mole
portion of biotite increases from <12 to >21 mol.% at
the expense of garnet as a function of decreasing
temperature across the phase stability field corresponding to
the assemblage seen in thin section (Fig. 6).

The occurrence of muscovite in these samples con-
strains the high-temperature retrograde path to be
close-to-isobaric crossing the solidus in a muscovite-
bearing mineral assemblage field (Fig. 6). The
replacement of garnet by biotite is interpreted to have
occurred along this close-to-isobaric cooling segment of
the $P$–$T$ path, and most of the biotite in this sample
is interpreted to have grown at pressures >1.0 GPa
over a temperature range from 830 to 675 °C (Fig. 6).
The subsequent $P$–$T$ evolution of this nappe is less well
constrained, but must be consistent with the absence of
both sillimanite and cordierite, and the microstructure
of the foliation, which suggests subsolidus deformation
at the stage when it was imposed. The $P$–$T$ path is
interpreted to follow a largely subsolidus close-to-
isothermal decompression segment of ~670 °C and a
low-pressure close-to-isobaric cooling segment of
~0.6 GPa similar to that in the overlying Três Pontas–
Varginha Nappe.

**The Carvalhos Klippe**

The Carvalhos Klippe is interpreted to be part of the
Três Pontas–Varginha Nappe now isolated in the
southernmost portion of the Southern Brasília Belt.
Based on the mineral assemblages and thermobar-
ometry, the granulites in the Klippe are inferred to have
experienced peak metamorphic conditions similar to
the Três Pontas–Varginha Nappe (825 °C & 1.2 GPa;
Campos Neto *et al.*, 2010). Terrane accretion events
associated with development of the Ribeira Belt, par-

cularly accretion of the Paraíba do Sul terrane in the
interval 605–580 Ma, led to a tectonothermal over-
printing recorded by sillimanite in the Carvalhos
Klippe (Fig. 3; Heilbron *et al.*, 2008).

**Lower grade Nappes**

Trouw *et al.* (2006) interpreted the Andrelândia Nappe
to be the tectonic equivalent of the Carmo da
Cachoeira Nappe. Campos Neto & Caby (1999) cal-
culated peak $P$–$T$ conditions of ~1.3 GPa and
~665 °C for the Andrelândia Nappe. These conditions
are lower temperature than the conditions estimated
above for the Carmo da Cachoeira Nappe, which may
be related in part to the use of different thermobar-
ometric methods and the reliance on Fe–Mg exchange
thermometry in association with the GRAIL and
GRIPS barometers.

**MONAZITE CHRONOLOGY**

All chemical composition data for monazite grains
analysed in this study are presented in Table S1. X-ray
element composition maps for yttrium and thorium
concentrations for representative monazite grains from
each sample are presented in Fig. 7. From these maps
it is clear that many of the monazite grains analysed in
this study are multi-domain and chemically zoned,
which sometimes is only poorly defined or patchy, and
from Table S1 it is clear that the absolute values and
range in $Y_2O_3$ and $ThO_2$ contents are variable from
sample to sample. In addition to using the X-ray ele-
ment composition maps, plots of $Y_2O_3$, $ThO_2$ and
$Y_2O_3/ThO_2$ v. date and $Y_2O_3$ v. $ThO_2$ were used to
assess whether dates from a sample represent a single
population or whether multiple populations are
present (e.g. Fig. 8).

To calculate ages, a single population of dates from
monazite grains that do not display clearly differenti-
ated differences in chemistry (referred to as single
domain grains) is used or alternatively several popu-
lations of dates that have been grouped based on
clearly differentiated differences in chemistry are used.
Sometimes separate populations of dates from grains
that show compositional zoning in X-ray element
composition maps produce statistically distinct ages,
but other times they do not. Where populations of
dates grouped on the basis of chemical composition
produce statistically indistinguishable ages, events
represented by the differences in chemistry are inferred
to have been close enough in time that they cannot be
distinguished using the (U–Th)–Pb dating method.
Therefore, from a statistical standpoint, these data sets
are treated as a single age population and the age
derived from the composite data set is considered to have
geological meaning. For monazite grains where the
populations of dates grouped on the basis of chemical
composition produce statistically distinct ages, each of
these ages is considered to have geological meaning.

Monazite (U–Th)–Pb ages are presented in Table 3,
together with values for kurtosis and skewness for each
population of dates, and shown in Fig. 9. In presenting
the results below, only values for kurtosis and skew-
ness for populations of dates that are greater than two
standard errors away from zero are discussed, as these
suggest a non-normal distribution of the data.
Two-sample $t$-tests were performed to calculate
the probability that ages are statistically identical.
A $P$-value <0.05 indicates with 95% confidence that
two ages are distinct, whereas a $P$-value >0.05 indicates
that two ages cannot be statistically distinguished.
Tests were conducted for all possible combinations,
and $P$-values are listed in Table 4, where the data are
Fig. 5. P–T pseudosections to show the phase assemblage fields for three representative samples from the Carmo da Cachoeira Nappe. The assemblage observed in thin section for these samples is represented by the phase assemblage field quartz–biotite–garnet–plagioclase–kyanite–ilmenite–silicate melt (05b-5-23) and rutile (04-5-6 & 04-5-8). However, the peak temperature may have been higher, corresponding to the phase assemblage field quartz–biotite–garnet–K-feldspar–plagioclase–kyanite–rutile–ilmenite–silicate melt for samples 04-5-6 and 04-5-8, which is still consistent with the peak phase assemblage field for sample 05b-5-23, as the possibility that K-feldspar was present in these two samples and was consumed to form biotite along the early part of the retrograde P–T path cannot be ruled out. Phase abbreviations follow Kretz (1983).
Fig. 6. Simplified $P$–$T$ pseudosections from Fig. 5 with isopleths for mol.% Grt, Bt, L and $H_2O$ to show the high-temperature retrograde $P$–$T$ evolution for samples from the Carmo da Cachoeira Nappe, as explained in the text. The interpreted high-temperature retrograde $P$–$T$ path is superimposed (it is shown as a 0.15 GPa wide arrow, similar to that for the overlying Três Pontas–Varginha Nappe). Phase abbreviations follow Kretz (1983).
listed from the oldest to the youngest age by tectonic unit.

**Dissolution–reprecipitation of monazite**

In principle, multi-domain monazite, such as core–rim overgrowths, may be used to date points or segments along a P–T path. Observations from natural systems and recent experimental work indicate that in some cases the overgrowth may represent fluid-aided partial replacement of pre-existing monazite owing to a coupled dissolution–reprecipitation process (Seydoux-Guillaume et al., 2002; Mahan et al., 2006; Harlov & Hetherington, 2010; Hetherington et al., 2010; Harlov et al., 2011; Williams et al., 2011). In these cases, the age recovered will date a fluid event such as the exsolution of fluid from crystallizing melt or the ingress of fluid from another source. For monazite inclusions in peritectic phases such as garnet, ingress of fluid and mobilization of calcium from the host may promote dissolution–reprecipitation of monazite inclusions to produce younger rims with irregular internal boundaries and, commonly, enrichment in less-soluble thorium (cf. DeWolf et al., 1993; Braun et al., 1998; Crowley & Ghent, 1999; Montel et al., 2000).

**Três Pontas–Varginha Nappe**

In sample 05b-6-108, monazite up to 450 μm in size occurs along grain boundaries in the quartzofeldspathic matrix. One monazite grain was dated. It exhibits a small slightly higher yttrium/slightly lower thorium island within monazite characterized by slightly lower yttrium concentrations in X-ray element composition maps (Fig. 7a), and narrow lower yttrium/slightly higher thorium tips, although absolute differences are very small (Table S1). Uranium contents are in the range 1000–1400 ppm and Th/U ratios are 43–54 (Table S1); there is no correlation with age. The residual zoning in yttrium and thorium suggests complexity in the history of monazite crystallization in this sample. However, separate populations cannot be distinguished on the basis of chemistry, so the data are treated as a single age population. An age of 588 ± 4 Ma was calculated from the 35 dates retrieved from this sample (Table 3, Fig. 9).

In sample 04-6-21B, monazite grains up to 210 μm in size occur as inclusions in the rims of garnet and in the matrix either immediately adjacent to garnet or included in biotite. In X-ray element composition maps some monazite grains have off-centre domains with higher yttrium/lower thorium concentrations within wide lower yttrium/higher thorium mantles (e.g. Fig. 7b), whereas other monazite grains lack clearly differentiated variations in chemistry and are treated as single domains; some grains have thin discontinuous high yttrium/low-thorium rinds along their edges. Six monazite grains were analysed (Fig. 8a,b), including one zoned grain (Fig. 7b). For monazite included in garnet, 41 dates combined from one single domain grain with low Y2O3 contents and the low Y2O3 mantle of the zoned grain yield an age of 652 ± 6 Ma (Table 3, Fig. 9), whereas 54 dates from two single domain grains with low Y2O3 contents in the matrix, one in contact with garnet and another included in biotite, yield an age of 638 ± 5 Ma (Table 3, Fig. 9). It is possible to separate the dates retrieved from monazite included in garnet into two groups based on ThO2 (Fig. 8b). Nine dates from areas with lower ThO2 from the mantle of the zoned grain and one date from the single domain grain generate an age of 662 ± 9 Ma (Table 3, Fig. 9), whereas 31 dates combined from areas with higher ThO2 from the mantle of the zoned grain and the single domain grain return an age of 648 ± 7 Ma (Table 3, Fig. 9). These two ages have small uncertainties and are statistically distinct; they are preferred to the single age of 652 ± 6 Ma. The remaining data from the higher Y domain in the zoned grain (Fig. 7b) and from one grain immediately adjacent to garnet have Y2O3 contents correlated with the individual dates and do not form well-defined groups (Fig. 8a); accordingly we do not present ages for these two data sets. In addition, this monazite (Table S1) generally has high uranium, > 2000 ppm and up to ~7500 ppm, and low Th/U, < 35 and down to ~5, both correlated with decreasing age. In comparison, the dated monazite generally has low uranium, < 2000 ppm, and moderate Th/U, 29–37 for the older age group, 30–45 for the intermediate age group and 19–44 for the younger age group; there is no correlation between Y2O3 contents and the individual dates in these three data sets.

In sample 04-6-19, monazite grains up to 170 μm in size are located in the matrix. Three monazite grains were dated. In X-ray element composition maps (e.g. Fig. 7c), monazite commonly has patchy, slightly higher yttrium/lower thorium cores inside lower yttrium/higher thorium rims, although absolute differences are small (Table S1). Uranium contents are high (2700–9200 ppm) and Th/U ratios are low (3–18); there is no correlation with age. The yttrium/thorium zoning suggests more than one event in the history of the monazite in this sample, but separate populations cannot be distinguished on the basis of chemistry. Outliers present in date vs. oxide plots have been removed from the final data set (Table S1), which is treated as a single age population. An age of 603 ± 5 Ma was calculated from 38 dates (Table 3, Fig. 9).

In sample 05b-6-29, monazite grains are generally < 50 μm in size, although they may be up to 350 μm; they are located in the matrix. Two monazite grains were dated. In X-ray element composition maps, monazite has higher yttrium patches in some grains and gradational change in yttrium concentration in other grains (e.g. Fig. 7d), whereas thorium commonly shows zoning from higher to lower concentrations with discordant low-thorium embayments and narrow high
Fig. 7. Yttrium and thorium X-ray element composition maps of representative monazite grains used in this study. The colour scale reflects relative count intensity, with warmer colours representing higher counts (for the colour version of this figure see the online edition). (a–j) Monazite grains from the Três Pontas–Varginha Nappe, (k–q) monazite grains from the Carmo da Cachoeira Nappe, and (r–t) monazite grains from the Carvalhos Klippe.
Fig. 7. (Continued)
thorium partial rims (e.g. Fig. 7d). Plots of Y$_2$O$_3$ vs. ThO$_2$ confirm a clearly differentiated separation into two populations based on chemistry (Fig. 8c,d), which is also partially reflected in uranium contents and Th/U ratios. Higher yttrium areas, which generally have uranium in the range 3000–5000 ppm and Th/U of 10–14 (Table S1), generate an age of 608 ± 5 Ma derived from 49 dates, although a high kurtosis of 2.14 suggests the data set is peaked. Lower yttrium areas, which generally have uranium in the range 2000–4500 ppm and Th/U of 11–30 (Table S1), return an age of 593 ± 7 Ma based on 33 dates (Table 3, Fig. 9).

Fig. 8. Y$_2$O$_3$ vs. age and Y$_2$O$_3$ vs. ThO$_2$ plots to show variation in monazite chemistry within single samples and between samples.
Monazite in sample 04-6-2, which is generally <200 μm in size, occurs as inclusions or partial inclusions in the rims of garnet and adjacent to garnet where they are partially included in biotite but still in contact with garnet. In X-ray element composition maps (Fig. 7e), monazite generally has patchy yttrium and thorium concentrations, and may rarely show weak zoning into core and rim. Four monazite grains were dated. Although Y₂O₃ varies continuously from 0.01 to 0.36 wt%, it is possible to separate the dates into two groups based on ThO₂ (Fig. 8e,f). Areas with higher ThO₂ have low Y₂O₃ and low uranium, with Th/U generally in the range 26–40, although most are 26–31 (Table S1); they generate an age of 656 ± 4 Ma.
derived from 63 dates (Table 3, Fig. 9). In contrast, areas with lower ThO₂ have variable Y₂O₃, but have moderate to high uranium and lower Th/U ratios (in the range 4–37, but most 4–10; Table S1); they return an age of 654 ± 7 Ma based on 57 dates (Table 3, Fig. 9). However, these two ages are statistically indistinguishable, suggesting events represented by the differences in ThO₂, uranium and Th were close enough in time that they cannot be separated using the (U–Th)–Pb dating method. Therefore, the dates are treated as a single population, which yields an age of 655 ± 4 Ma derived from the 120 dates.

Monazite grains up to 350 μm in size occur along grain boundaries in leucosome-dominated sample 04-6-11. In X-ray element composition maps (e.g. Fig. 7f,g), some grains show a residual core area with slightly higher yttrium concentrations within a wide lower yttrium mantle (e.g. Fig. 7f), whereas other grains show weak patchy zoning in yttrium concentration; thorium is relatively high and not strongly zoned. Two monazite grains were dated, one with a weak residual core and the other with slightly patchy yttrium concentration. If treated as a single population, then the 73 dates yield an age of 600 ± 5 Ma. Eight of these dates with the highest Y₂O₃ values from the residual core generate an age of 617 ± 15 Ma, which is statistically distinct from an age of 597 ± 5 Ma based on 65 dates combined from the surrounding mantle and the second single domain grain (Table 3, Fig. 9). Although the analyses with the highest Y₂O₃ values have uranium contents at the low end of the range of values, they are not clearly distinguished from the bulk of the data set (Table S1). On balance, taking into account the small size of the high Y₂O₃ group of analyses and the large uncertainty associated with the older age, the age of 600 ± 5 Ma is preferred.

Monazite grains in sample 05b-6-103 are generally <120 μm in size, although they may be up to 250 μm; they occur as inclusions in kyanite and along kyanite grain boundaries in quartz-feldspathic layers. Two
monazite grains were dated. In X-ray element composition maps (e.g. Fig. 7h), one monazite grain contains areas or bands with higher yttrium/lower thorium concentrations alternating with areas or bands with lower yttrium/higher thorium concentrations, whereas the second monazite grain is not clearly zoned. For the zoned grain, higher yttrium areas, which have a more restricted range of uranium contents and Th/U ratios (generally 4000–8000 ppm and 5–13, respectively; Table S1), generate an age of 620 ± 7 Ma derived from 27 dates, whereas lower yttrium areas, which have variable Y2O3 and a wider range of uranium contents and Th/U ratios (generally >1000 but <8000 ppm and 5–24, but mostly <11, respectively; Table S1), return an age of 605 ± 6 Ma based on 31 dates (Table 3, Fig. 9). The second grain, which also has variable Y2O3 with a similar range of absolute values to the lower yttrium areas in the zoned grain and a wide range of uranium contents and Th/U ratios (Table S1), yields an age of 619 ± 4 Ma based on 96 dates (Table 3, Fig. 9).

In sample 05b-6-36, the analysed monazite grains, which are up to 500 μm in size, are located in garnet. In X-ray element composition maps (e.g. Fig. 7i), some monazite shows distinct higher yttrium cores with irregular thorium distributions and lower yttrium rims with generally higher thorium concentrations. Four grains were dated: one with distinct zoning (grain 7), one with patchy zoning (grain 5) and two without clearly differentiated differences in chemistry (Fig. 8g,h). The results are presented separately for each grain. For the two zoned grains, the higher yttrium core in grain 7, which has high uranium contents and low Th/U ratios (generally 5000–6000 ppm and 6–7, respectively; Table S1), yields an age of 640 ± 6 Ma derived from 36 dates, whereas the higher yttrium patches in grain 5, which have a wider range of uranium contents and Th/U ratios than grain 7 (Table S1), yields an age of 620 ± 7 Ma derived from 36 dates (Table 3, Fig. 9). The lower yttrium rim on grain 7, which has a wider range of uranium contents and Th/U ratios than the core (Table S1), yields an age of 610 ± 4 Ma derived from 68 dates, whereas the lower yttrium patches in grain 5, which have a moderate range of uranium contents and Th/U ratios (generally >3000 but <5000 ppm and 8–12, respectively; Table S1), yield an age of 606 ± 7 Ma derived from 45 dates (Table 3, Fig. 9), although a high kurtosis of 1.04
suggests the data set is peaked. One single domain grain with gradational variation in yttrium in the X-ray element composition map and higher Y$_2$O$_3$ and a wide range of uranium contents with Th/U ratios generally in the range 5–11 (Table S1), yields an age of 631 ± 5 Ma based on 61 dates, whereas the second single domain grain, which has lower Y$_2$O$_3$ and generally lower uranium contents and higher Th/U ratios (mostly in the range 10–14), yields an age of 607 ± 5 Ma based on 49 dates (Table 3, Fig. 9).

Monazite grains up to 250 μm in size in sample 05b-6-31B are located in garnet. One monazite grain was dated; it shows three distinct zones in both yttrium and thorium X-ray element composition maps (e.g. Fig. 7). Four outliers may be identified in the oxide plots (Fig. 8i,j) and these four dates have been culled from the data set. Twenty-one dates from higher yttrium areas in the core, and these four dates have been culled from the data set. Outliers may be identified in the oxide plots (Fig. 8i,j) 634 ± 7 Ma (Table 3, Fig. 9). A medium-yttrium mantle composition map and higher Y$_2$O$_3$, and a wide range of uranium contents with Th/U ratios generally lower uranium contents and higher Th/U ratios (mostly in the range 10–14), yields an age of 604 ± 8 Ma (Table 3, Fig. 9).

Carmo da Cachoeira Nappe
For all samples from the Carmo da Cachoeira Nappe (Table S1), uranium contents are high (>4000 ppm) and Th/U ratios are low (<8). As the variation from sample to sample is minimal, these data are not discussed by individual sample below.

Monazite grains up to 250 μm in size in sample 05b-5-23 are included in biotite. Six monazite grains were dated. In X-ray element composition maps (e.g. Fig. 7k), monazite shows lower yttrium contents in the core, which is surrounded by slightly higher yttrium mantles, partially enclosed within discontinuous higher yttrium rims and tips. Although not homogeneous, the variations in chemistry are not
sufficiently distinctive to provide a basis to group the data from this sample (Table S1). An age of 616 ± 6 Ma is calculated from 41 dates (Table 3; Fig. 9); a high kurtosis of 1.75 suggests the data set is peaked. Monazite from this sample was also analysed using the SIMS at UCLA, which yielded a $^{206}\text{Pb}/^{238}\text{U}$ age of 612 ± 10 Ma (Appendix S1, Table 5).

In sample 05b-5-22, monazite grains up to 100 μm in size are located in biotite. Four monazite grains were dated. X-ray element composition maps reveal weak zoning with small slightly higher yttrium/slightly higher thorium patches within grains characterized by generally lower yttrium/lower thorium concentrations (e.g. Fig. 7m). However, the zoning is not sufficiently distinct to provide a basis to group the data from this sample. An age of 617 ± 6 Ma is calculated from 48 dates (Table 3, Fig. 9). Although more than one event is suggested by the variation in chemistry in the monazite grains, only a single age may be distinguished using the (U–Th)–Pb dating method.

In sample GR-05-4B, monazite grains up to 200 μm in size occur in the quartz-feldspathic matrix. One monazite grain was dated. A complex patchy pattern of zoning is seen in X-ray element composition maps of both yttrium and thorium (e.g. Fig. 7n), but there is no clear basis to group dates in this sample using composition (Table S1). Therefore, all dates are taken to represent a single growth or recrystallization event. An age of 595 ± 5 Ma was calculated from 42 dates (Table 3, Fig. 9).

Monazite grains up to 60 μm in size in sample 04-5-6 are included in biotite or located along multi-mineral grain boundaries. Four monazite grains were dated. X-ray element composition maps (e.g. Fig. 7o) reveal lower yttrium areas, commonly extending from one edge to the central part of a grain that are partially surrounded by distinct higher yttrium mantles within which there may be small high yttrium patches. The grains are not strongly zoned in thorium (e.g. Fig. 7o). Statistically distinct ages were retrieved from two groups of dates based on yttrium zoning in this sample. Seventy dates from the higher yttrium areas generate an age of 619 ± 6 Ma, although a kurtosis of 1.25 suggests that the data are peaked, whereas 20 dates from the lower yttrium areas yield an age of 600 ± 8 Ma (Table 3, Fig. 9).

The Carvalhos Klippe

In sample 05b-10-102, the grains of monazite are up to 150 μm across, with one inclusion in garnet 250 μm across. Six monazite grains were dated, five associated with biotite and kyanite in the quartz-feldspathic matrix and one inclusion in garnet. In X-ray element composition maps (e.g. Fig. 7r,s), monazite commonly has distinct cores with higher yttrium/higher thorium concentrations within wide mostly lower yttrium/lower thorium rims; some monazite in this sample has an additional narrow high yttrium rim outside a lower yttrium mantle. In contrast to other samples in this study, all monazite cores and rims and single domain grains from this sample show distinctive compositions in Y$_2$O$_3$ v. ThO$_2$ and Y$_2$O$_3$ and ThO$_2$ oxide v. date plots (Fig. 8k,l); for this reason the results are presented separately for each grain.

For two-zoned grains, the higher yttrium/lower thorium part of grain 2, which has uranium contents in the range 3000–6000 ppm and Th/U of 4–10 (Table S1), yields an age of 619 ± 11 Ma derived from 15 dates, whereas the residual higher yttrium/lower thorium domains occurring on one side and as discontinuous patches along the outer edges of grain 6, which have uranium contents in the range 3000–6500 ppm and Th/U mostly in the range 7–10 (Table S1), yield an age of 614 ± 9 Ma derived from 28 dates (Table 3, Fig. 9). In contrast, the area with patchy yttrium and thorium zoning in grain 2, which has higher uranium contents in the range 6000–12 000 ppm and a range of Th/U of 6–17 (Table S1), produces an age of 583 ± 4 Ma derived from 19 dates, whereas the lower yttrium central area in grain 6, which has uranium contents in the range 2000–5000 ppm and Th/U of 4–7 (Table S1), yields an age of 595 ± 8 Ma derived from 47 dates (Table 3, Fig. 9). Four single domain grains yield ages of (Table 3, Fig. 9): 592 ± 5 Ma based on 15 dates (grain 3; U contents of 13 000–18 000 ppm and Th/U of 4–7; Table S1); 585 ± 5 Ma based on 37 dates (grain 5; U contents of 1000–5000 ppm and Th/U of 8–28; Table S1); 582 ± 18 Ma based on 17 dates (grain 1; U contents of <3000 ppm and Th/U of 4–7; Table S1); and, 580 ± 7 Ma based on 26 dates (grain 4; U contents generally in the range 2000–8000 ppm and Th/U of 7–18; Table S1).

In sample 05b-10-65, there are two types of monazite occurring as inclusions in garnet, grains up to 450 μm in size and skeletal grain aggregates; one large monazite grain and monazite in a skeletal grain aggregate were dated. In X-ray element composition maps (e.g. Fig. 7l), the large monazite grain exhibits patches with higher yttrium and thorium along the edges; this grain has higher yttrium contents than the sporadically developed skeletal grain aggregates. Uranium contents are in the range 3000–11 000 ppm.
and Th/U ratios are 5–10 (Table S1). In X-ray element composition maps (not shown), the skeletal monazite exhibits a slight patchy distribution of yttrium and thorium concentrations. U contents are <2000 ppm and Th/U ratios are 16–46 (Table S1). The larger monazite produces an age of 593 ± 4 Ma derived from 80 dates, whereas the skeletal monazite yields an age of 563 ± 21 Ma based on 16 dates (Table 3, Fig. 9). A larger monazite grain from this sample was also analysed using the SHRIMP at Curtin University, which yielded a 206Pb/238U age of 595 ± 12 Ma (Appendix S1, Table 5).

DISCUSSION

The Três Pontas–Varginha Nappe

The Três Pontas–Varginha Nappe lies immediately beneath the arc-derived Socorro–Guaxupé Nappe and represents the uppermost of the supracrustal nappes derived from the subducted passive margin at the western side (present co-ordinates) of the São Francisco Craton during the Brasília Orogeny. This nappe records the highest pressures of metamorphism in the Andrelândia Nappe Complex, with peak pressure of ~1.5 GPa and peak temperature in the range 840–900 °C. It is located north of the sillimanite-in isograd related to the tectonothermal overprint associated with younger terrane accretion events in the Ribeira Belt to the southeast (Fig. 3).

U–Pb zircon ages of 648 ± 12 Ma and 648 ± 8 Ma (SIMS and LA-ICP-MS) and 647 ± 11 Ma (SIMS) for samples 04-6-11 and 05b–6-31B from the middle and upper portions of the nappe (Table 4, Appendix S1, Table 5). For sample 04-6-21B, the solidus at a temperature close to the solidus by reaction between ilmenite during high-pressure close-to-isobaric decompression to mid-crustal temperature, close-to-isothermal decompression to mid-crustal temperature for the 40Ar/39Ar age of 1.4 GPa is at ~850 °C (Fig. 4). Given the consistently low yttrium, high thorium and low uranium contents and moderate to high Th/U ratios in the monazite grains from this sample, the age of c. 638 Ma is interpreted to register recrystallization of old monazite close to the solidus during the high-temperature, close-to-isobaric retrograde evolution. There is no evidence of growth of new monazite with higher yttrium concentrations, which might have been expected given the increase in mol.% biotite at the expense of garnet within 20 °C of the solidus (Fig. 4a). In contrast, for sample 05b-6-31B, the solidus at ~1.3 GPa is at ~780 °C (Fig. 4d). Accordingly, the age of c. 634 Ma from the high yttrium core of a monazite grain in garnet in this sample is interpreted to register growth of monazite in garnet at a temperature close to the solidus by reaction between garnet and melt (discussed further below) during the high-pressure–high-temperature retrograde evolution. Zircon from the same sample yielded an age of 647 ± 11 Ma, which was interpreted by Reno et al. (2009) to date growth at ~800 °C. The difference in age between zircon and monazite is consistent with the

Interpretation of monazite (U–Th)–Pb ages

Monazite ages from the Três Pontas–Varginha Nappe fall into one of three distinct age groups, with the exception of one age that is unique. Most ages in each of the groups are statistically identical, with t-test P-values generally ≥0.05, and ages between these groups are mostly statistically distinct, with t-test P-values generally < 0.05 (Table 4).

The oldest monazite ages of c. 662 and c. 655 Ma come from grains characterized by low yttrium but with variable uranium contents and Th/U ratios. These grains are included in or associated with garnet in samples 04-6-21B and 04-6-2, respectively, from the lower and middle portions of the nappe (Table 4, Fig. 10). The monazite ages are statistically distinct from the U–Pb zircon ages of c. 648 Ma reported by Reno et al. (2009) for other samples from the middle and upper portions of the nappe. Based on the low Y2O3 contents for these monazite grains, the ages are interpreted to date engulfment by the rim of peritectic garnet at a late stage along the prograde evolution close to peak metamorphic conditions. The age of c. 648 Ma from low yttrium monazite also included in the rim of garnet in sample 04-6-21B is distinct from the older age of c. 662 Ma from the same sample and all younger monazite ages. It has a higher thorium content in comparison with the older monazite but a similar uranium content resulting in slightly higher Th/U ratios, and may represent older monazite that recrystallized during high-temperature close-to-isobaric cooling by interaction with melt via cracks in host garnet.

A second group of ages in the range 640–631 Ma includes: single domain low yttrium monazite grains from the matrix of sample 04-6-21B from lower in the nappe; high yttrium cores and patches from inclusions of monazite in garnet in sample 05b-6-36 from the middle portion of the nappe; and, the high yttrium core of a monazite inclusion in garnet from sample 05b-6-31B from the upper part of the nappe (Table 4, Fig. 10). For sample 04-6-21B, the solidus at ~1.4 GPa is at ~850 °C (Fig. 4). Given the consistently low yttrium, high thorium and low uranium contents and moderate to high Th/U ratios in the monazite grains from this sample, the age of c. 638 Ma is interpreted to register recrystallization of older monazite close to the solidus during the high-temperature, close-to-isobaric retrograde evolution. There is no evidence of growth of new monazite with higher yttrium concentrations, which might have been expected given the increase in mol.% biotite at the expense of garnet within 20 °C of the solidus (Fig. 4a). In contrast, for sample 05b-6-31B, the solidus at ~1.3 GPa is at ~780 °C (Fig. 4d). Accordingly, the age of c. 634 Ma from the high yttrium core of a monazite grain included in garnet in this sample is interpreted to register growth of monazite in garnet at a temperature close to the solidus by reaction between garnet and melt (discussed further below) during the high-pressure–high-temperature retrograde evolution. Zircon from the same sample yielded an age of 647 ± 11 Ma, which was interpreted by Reno et al. (2009) to date growth at ~800 °C. The difference in age between zircon and monazite is consistent with the
estimated slow rate of cooling for the high-pressure–
high-temperature retrograde evolution.

The third group comprises ages in the range
620–588 Ma. Older ages come from: higher yttrium
patches and cores of matrix-hosted monazite in sample
04-6-19 (c. 620 Ma) from the lower part of the nappe;
high yttrium areas in one grain and a second single
domain monazite in sample 05b-6-103 (c. 620 Ma)
from the middle portion of the nappe; and, a saddle
cutting across the core of monazite in sample 05b-6-
31B (c. 616 Ma) from the top of the nappe (Table 4,
Fig. 10). The saddle age of c. 616 Ma is interpreted to
date recrystallization owing to interaction with matrix
melt via fractures in the host garnet triggered by an
increase in melt mol.% along the decompression seg-
ment of the retrograde $P$–$T$ evolution (Fig. 4d), and a
similar explanation is possible for the c. 620 Ma ages in
the other two samples. However, the high but variable
uranium contents and moderate Th/U ratios for these
two samples is also consistent with the possibility of
recrystallization of monazite by dissolution–reprecip-
tation owing to interaction with fluid infiltrated from
crystallizing migmatites of the Carmo da Cachoeira
Nappe beneath (see below).

Intermediate ages in the range 610–600 Ma come
from lower yttrium areas and rims on monazite grains

Fig. 10. Summary of ages from the Socorro–Guaxupé Nappe, the Passos Nappe Complex and the Andrelândia Nappe Complex, as
discussed in the text. Uncertainties on monazite (U–Th)–Pb ages are twice the standard deviation of the mean; uncertainties on other
data are those quoted by the authors. For the ages from this study, yellow circles represent (U–Th)–Pb monazite ages whereas yellow
circles with an internal cross represent SIMS or SHRIMP monazite ages (see text; for the colour version of this figure see the online
Varginha Nappe; RE, retro-eclogite; CdC, Carmo da Cachoeira Nappe; CK, Carvalhos Klippe.
of samples 05b-6-103, 05b-6-36 and 05b-6-31B, with one single domain age from a matrix-hosted monazite in sample 04-6-19 and one weakly zoned monazite from leucosome sample 04-6-11 (Table 4, Fig. 10). These intermediate ages are similar to the Rb-Sr isochron ages of c. 602 Ma that Reno et al. (2009) interpreted to date the formation of the sillimanite-bearing penetrative fabric associated with exhumation. The single domain age of c. 600 Ma from monazite grains in the leucosome sample from the middle portion of the nappe is interpreted to register growth close to the solidus at ~640 °C along the low-pressure close-to-isobaric segment of the P–T path (Fig. 4c). Zircon from the same sample yielded an age of 648 ± 12 Ma, which was interpreted by Reno et al. (2009) to date growth at ~800 °C along the high-pressure close-to-isobaric segment of the P–T path (Fig. 4). The difference in age between zircon and monazite is consistent with expectations in crystallizing granite (Kelsey et al., 2008). The age of c. 604 from the low yttrium/high thorium rim on a monazite grain included in garnet from sample 05b-6-31B from the top of the nappe is interpreted to date recrystallization of monazite by dissolution–reprecipitation owing to interaction with exsolved fluid via fractures during final crystallization of the melt at the solidus along the low-pressure segment of the P–T path at ~680 °C. Moderate to high uranium contents and moderate Th/U ratios, and lower yttrium/high thorium concentrations for monazite from the remaining three samples is consistent with recrystallization of monazite by dissolution–reprecipitation owing to interaction with fluid infiltrated from crystallizing migmatites of the Carmo da Cachoeira Nappe beneath (see below).

The oldest (U–Th)–Pb ages come from monazite hosted in and associated with garnet, but their yttrium contents and ages vary from low to high and from c. 662 to c. 631 Ma. Although the older low yttrium monazite is interpreted to be late-stage prograde inclusions in the rims of peritectic garnet, younger ages from high yttrium monazite inclusions are interpreted to represent high-temperature retrograde growth of monazite in garnet. Garnet generally has sufficient concentrations of phosphorus and yttrium (Villaseca et al., 2003, 2007; Kohn & Malloy, 2004), and possibly rare earth elements (McFarlane et al., 2005), so that in the presence of an additional light rare earth element source, such as a pre-existing grain of monazite and/or melt, growth of monazite during garnet breakdown is feasible.

In these HP granulites, biotite (± quartz and plagioclase) has partially replaced garnet owing to high-temperature retrograde reaction with melt during cooling to the solidus (Reno et al., 2009), and the higher yttrium contents in many of these included monazite grains are consistent with them growing during garnet breakdown (e.g. Foster et al., 2002). Monazite grains included in garnet commonly occur adjacent to or transect microcracks in the host (Fig. 11). These microcracks generally abut against matrix minerals at the garnet edge and larger cracks are commonly infilled with matrix minerals, particularly biotite produced by resorption of garnet during reaction with crystallizing melt. Thus, we infer that the cracks predate final crystallization of residual melt at the solidus. In these circumstances, it is reasonable to postulate that partial or complete recrystallization of older monazite or growth of new monazite could have been induced by mass exchange with a cation reservoir exterior to the garnet via melt-mediated diffusion of any necessary additional nutrients to the interior of the garnet.

The occurrence of minerals in hosts that are older than the inclusions themselves is becoming an increasingly recognized phenomenon, for example xenotime inclusions in zircon that are younger than the zircon (Rasmussen et al., 2011), demonstrating that hosts with...
a tendency to develop fractures may have only limited ability to protect inclusions from late-stage events (Whitney, 1996; El-Shazly et al., 2011; Rasmussen et al., 2011). Similarly, Whitney & Dilek (1998) suggested that large biotite inclusions and composite inclusions in garnet from the Niğde metamorphic core complex had grown at the expense of the host garnet. Contrary to the conclusion by DeWolf et al. (1993), Braun et al. (1998) and Montel et al. (2000) that garnet can be an effective shield for monazite against resetting during younger events, the results presented here demonstrate the need for caution in the interpretation that inclusions are older than or synchronous with growth of the host mineral.

Ages in relation to the solidus for the Três Pontas–Varginha Nappe samples

Zircon ages from the Três Pontas–Varginha Nappe are generally older than monazite ages in the same rock, as predicted by the modelling of Kelsey et al. (2008). These authors ascribed this sequence to differences in the temperatures at which zircon and monazite grew rather than differences in closure temperature systematics. Reno et al. (2009) argued that zircon formation in samples from the Três Pontas–Varginha Nappe occurred during cooling from around peak temperature to the solidus, consistent with the high-temperature retrograde $P$–$T$ path deduced from microstructures linked to phase assemblage fields in pseudosections. For monazite ages in this study interpreted to date crystallization close to the solidus, both the ages and the solidus temperatures vary as follows: for sample 04-6-21, ages of c. 648 and c. 638 Ma and a solidus temperature of $\sim$850 °C at $\sim$1.4 GPa; for sample 05-6-31B, an age of c. 634 Ma and a solidus temperature of $\sim$780 °C at $\sim$1.3 GPa; and, for sample 04-6-11 (leucosome), an age of c. 600 Ma and a solidus temperature of $\sim$640 °C at $\sim$0.65 GPa. It is clear that monazite ages correlate with solidus temperature, with a younger age from less residual granulite (sample 05-6-31B) than more residual granulite (sample 04-6-21), and the youngest age from the leucosome. Thus, caution is required in the interpretation of ages from high-temperature metamorphic rocks that appear to be inconsistent with each

---

**Fig. 11.** Backscattered electron images to show representative examples of monazite in or associated with garnet. Monazite grains in garnet are always associated with and extend across cracks in the host that are inferred to have provided fast diffusion pathways to an external melt reservoir that enabled growth or recrystallization of monazite inside the garnet. (a) Sample 04-6-21B, grain 3 (upper left, inside garnet); (b) sample 04-6-21B, grain 7; (c) sample 04-6-21B, grain 12; (d) sample 04-6-2, grain 1 (upper centre, inside garnet); (e) sample 04-6-2, grain 4; (f) sample 05b-6-31B, grain 2 (upper left, inside garnet). Scale bar is 500 µm in all cases.
other as variation in the ages retrieved may to be
expected in a regional study of rocks that exhibit
evidence of melting.

Tectonic implications of the youngest ages
(U–Th)–Pb monazite ages in the third group are
interpreted to date exhumation as recorded by the
close-to-isothermal decompression segment of the P–T
path (Fig. 4), in common with the same interpretation
for the Rb-Sr isochron ages of c. 602 Ma, followed by
close-to-isothermal cooling. These ages overlap in time
with the beginning of accretion of the Paraíba do Sul
terrane during the interval 605–580 Ma against the
southeastern side (present co-ordinates) of the
Andrelândia Nappe Complex and the underlying
basement of the São Francisco Craton during the first
tectonic phase of the Ribeira Orogeny (Heilbron et al.,
2008). Thus, Reno et al. (2010) attributed the decom-
pression event to tectonically driven exhumation
during orogenic collapse of the nappe stack, which
they related to far-field stresses associated with the
growth of the Ribeira Belt to the southeast. In this
interpretation, some of the monazite ages are related to
final crystallization of melt in less residual parts of the
nappe, whereas other ages would be related to recrystal-
zization of monazite by dissolution–precipitation
owing to ingress of fluid (cf. Villa, 2010) released at the
solidus at temperatures of ~670 °C in crystallizing
migmatites of the Carmo da Cachoeira Nappe beneath
(see below). Fluid derived from such a source is likely
to be alkaline in nature and suitable to promote
recrystalization of monazite by dissolution–precipitation
as demonstrated in recent experiments on fluid-
mediated partial alteration of monazite (Hetherington
et al., 2010; Harlov et al., 2011).

The Carmo da Cachoeira Nappe
The Carmo da Cachoeira Nappe lies immediately
beneath the Três Pontas–Varginha Nappe and repre-
sents a second supracrustal nappe derived from the
subducted passive margin at the western side (present
co-ordinates) of the São Francisco Craton during the
Brasilíia Orogeny. It comprises upper amphibolite-to-
granulite facies rocks that achieved peak pressures in
the range 1.1–1.35 GPa and peak temperatures in the
range >820 °C but <900 °C. The Carmo da Cachoeira
Nappe also lies north of the sillimanite-in iso-
grade related to the tectonothermal overprint associated
with younger terrane accretion events in the Ribeira
Belt to the southeast (Fig. 3).

Analysed monazite grains are present as inclusions
in biotite, which is mostly aligned within the foliation,
with only a few larger randomly oriented grains, or
along multi-mineral grain boundaries; much of the
biotite is inferred to have grown along the retrograde
P–T path at the expense of garnet. (U–Th)–Pb mon-
azite ages from the Carmo da Cachoeira Nappe fall

cooling history of the Três Pontas–Varginha and Carmo da
Cachoeira Nappes
Metamorphic temperatures from Figs 4 & 6, and from
Ti-in-zircon and Ti-in-quartz thermometry (Reno
et al., 2009), may be combined with the age informa-
tion (summarized in Fig. 10; Reno et al., 2009, 2010;
this study) and an estimate of the closure temperature
for the \(^{40}\text{Ar}/^{39}\text{Ar}\) system in biotite to derive a cooling
history for each of the Três Pontas–Varginha and
Carmo da Cachoeira Nappes. The maximum rate of
cooling is limited by the rate of heat conduction to the
surface, which can be assessed using the one-
dimensional diffusion or heat conduction equation
(Stiwe, 2007). The time for thermal diffusion to
reduce the temperature at 20–25 km depth (approxi-
mately equivalent to a metamorphic pressure of 0.6–
0.75 GPa) to 300 °C (the closure temperature used by
Reno et al. 2010 for the \(^{40}\text{Ar}/^{39}\text{Ar}\) system in biotite in
these nappes) is likely to be <20 Ma, and the rate of
cooling is likely to be much faster at the beginning of
this period. However, it is possible that the closure
temperature for the \(^{40}\text{Ar}/^{39}\text{Ar}\) system in biotite in ’dry’
granulites (i.e. those with no evidence of subsolidus
disequilibrium, such as chloritization of biotite) is
much higher than 300 °C, possibly as high as 450–
500 °C (Villa, 1998, 2010; Allaz et al., 2011) or even
550 °C (Balogh & Dunkl, 2005). This is an important
but unresolved issue that has a significant impact on
the potential T–t paths. Two T–t paths for each nappe,
drawn to comply with these various constraints, are

© 2011 Blackwell Publishing Ltd
MONAZITE AGES FROM THE SOUTHERN BRASÍLIA BELT

The Carvalhos Klippe

The Carvalhos Klippe is inferred to be part of the Três Pontas–Varginha Nappe now isolated in the southernmost portion of the Southern Brasília Belt (Campos Neto et al., 2010). It is interpreted to have experienced similar peak metamorphic conditions as the Três Pontas–Varginha Nappe with high-temperature growth of monazite close to the solidus at c. 618 Ma (Campos Neto et al., 2010). Loading owing to terrane accretion events within the Ribeira Belt led to a tectonothermal overprint evidenced by growth of sillimanite in the Carvalhos Klippe.

(U–Th)–Pb monazite ages from the Carvalhos Klippe fall into one of two distinct age groups (Table 4), and all are younger than 619 Ma (Fig. 10). Two monazite grains in sample 05b-10-102 yielded core and rim ages. The core ages of c. 619 and 614 Ma are statistically identical and identical to the age of 617.7 ± 1.3 Ma determined by ID-TIMS analysis of monazite from this klippe (Campos Neto et al., 2010). These ages are younger than the oldest two groups of ages but similar to the ages of 620–616 Ma in the youngest group from the Três Pontas–Varginha Nappe (Table 4, Fig. 10). Rim ages and single domain ages from sample 05b-10-102 and ages from monazite included in garnet in sample 05b-10-65 comprise a group of statistically indistinguishable ages in the range 595–563 Ma (Table 4, Fig. 10). If the two ages with large uncertainties are excluded (582 ± 18 & 563 ± 21 Ma), then the remaining ages fall into two statistically distinguishable groups of ages in the ranges 595–592 and 585–580 Ma.

The monazite in sample 05b-10-65 occurs as two morphologically distinct types (larger single grains and smaller skeletal grain aggregates, both in garnet) that record different ages. The age of 593 ± 4 Ma calculated from dates obtained from a larger single grain provides a minimum age for the formation of garnet in this rock. A younger age of 563 ± 21 Ma from the skeletal aggregate of grains is difficult to interpret due to the large uncertainty and the small sample size. In both cases, the low thorium content suggests derivation from garnet.

These ages may indicate that the retrograde P–T path for the Carmo da Cachoeira Nappe could have been closer to constant dP/dT.

The Carvalhos Klippe

The Carvalhos Klippe is inferred to be part of the Três Pontas–Varginha Nappe now isolated in the southernmost portion of the Southern Brasília Belt (Campos Neto et al., 2010). It is interpreted to have experienced similar peak metamorphic conditions as the Três Pontas–Varginha Nappe with high-temperature growth of monazite close to the solidus at c. 618 Ma (Campos Neto et al., 2010). Loading owing to terrane accretion events within the Ribeira Belt led to a tectonothermal overprint evidenced by growth of sillimanite in the Carvalhos Klippe.

(U–Th)–Pb monazite ages from the Carvalhos Klippe fall into one of two distinct age groups (Table 4), and all are younger than 619 Ma (Fig. 10). Two monazite grains in sample 05b-10-102 yielded core and rim ages. The core ages of c. 619 and 614 Ma are statistically identical and identical to the age of 617.7 ± 1.3 Ma determined by ID-TIMS analysis of monazite from this klippe (Campos Neto et al., 2010). These ages are younger than the oldest two groups of ages but similar to the ages of 620–616 Ma in the youngest group from the Três Pontas–Varginha Nappe (Table 4, Fig. 10). Rim ages and single domain ages from sample 05b-10-102 and ages from monazite included in garnet in sample 05b-10-65 comprise a group of statistically indistinguishable ages in the range 595–563 Ma (Table 4, Fig. 10). If the two ages with large uncertainties are excluded (582 ± 18 & 563 ± 21 Ma), then the remaining ages fall into two statistically distinguishable groups of ages in the ranges 595–592 and 585–580 Ma.

The monazite in sample 05b-10-65 occurs as two morphologically distinct types (larger single grains and smaller skeletal grain aggregates, both in garnet) that record different ages. The age of 593 ± 4 Ma calculated from dates obtained from a larger single grain provides a minimum age for the formation of garnet in this rock. A younger age of 563 ± 21 Ma from the skeletal aggregate of grains is difficult to interpret due to the large uncertainty and the small sample size. In both cases, the low thorium content suggests derivation from garnet.

These ages may indicate diachronism in the age of metamorphism for the HP granulites between the Três Pontas–Varginha Nappe and the Carvalhos Klippe or that the correlation with the HP granulites of the Três Pontas–Varginha Nappe is incorrect. Perhaps the Carvalhos Klippe is part of the Occidental terrane, the reworked passive margin of the São Francisco craton, within the Ribeira Belt. In either case, it is likely that the younger monazite ages register overprinting during the early accretion events within the Ribeira Belt. The 595–592 Ma ages overlap in time with accretion in the
interval 605–580 Ma of the Paraiba do Sul terrane against the southeastern side (present co-ordinates) of the Andrelândia Nappe Complex and the underlying basement of the São Francisco Craton during the early stage of formation of the Ribeira Belt. The 585–580 Ma ages overlap in time with the late stage of accretion of the Paraiba do Sul terrane and the beginning of accretion in the interval 580–550 Ma of the Oriental terrane outboard of the Paraiba do Sul terrane in the Ribeira Belt to the southeast (Heilbron et al., 2008). Thus, these monazite (U–Th)–Pb ages could be related to recrystallization of monazite by dissolution–recrystallization owing to ingress of aqueous fluid driven by orogenic loading associated with terrane accretion during the Ribeira Orogeny to the southeast (cf. Ge & Garven, 1992; Garven, 1995; Appold & Garven, 1999). Except for grain 3 from sample 05b-10-102, which has the highest uranium content of all monazite in this study, the generally lower uranium contents and higher Th/U ratios for the monazite yielding younger ages are consistent with this interpretation.

Correlation with the Passos Nappe to the north

The Passos Nappe Complex lies immediately to the north of the Andrelândia Nappe Complex in the southern sector of the Southern Brasilia Belt; it is also composed of rocks derived from the former passive margin along the western edge (present co-ordinates) of the São Francisco Craton. The Passos Nappe comprises metasedimentary rocks of the Araxá Group, which is correlative with the Andrelândia Group of the Andrelândia Nappe Complex to the south. The 4.5 km thick nappe preserves an inverted metamorphic sequence from biotite zone at the base through garnet, staurolite, kyanite and migmatite zones to a thin (~100 m) granulite facies zone at the top (Valeriano et al., 2004).

Valeriano et al. (2004) reported well-defined lower intercept ages of 656 ± 16 Ma (sample 1042) and 655 ± 4 Ma (sample 1130) from zircon separates analysed by ID–TIMS from amphibolite-to-granulite facies rocks at the top of the Passos Nappe and from a tectonic lens of felsic metavolcanic rock along the basal thrust of the nappe. These ages are similar to the SIMS 206Pb/238U zircon ages of 648 ± 12 and 647 ± 11 Ma retrieved from the uppermost passive margin-derived nappe in the Andrelândia Nappe Complex (Fig. 10), which were interpreted by Reno et al. (2009) to record down-temperature crystallization of zircon in leucosome in residual HP granulite. A concordant TIMS 206Pb/238U age of 631 ± 4 Ma (sample 1081) was obtained for monazite from a leucosome vein from close to the top of the Passos Nappe, and a slightly younger sub-concordant TIMS 206Pb/238U age of 622 ± 1/–2 Ma (sample 1042) was retrieved from monazite from the top unit in the Passos Nappe (Valeriano et al., 2004). These ages are similar to the (U–Th)–Pb ages of 640–631 and 620–616 Ma retrieved from the Três Pontas–Varginha Nappe and 619–616 Ma retrieved from the Carmo da Cachoeira Nappe in the Andrelândia Nappe Complex (Fig. 10).

Younger concordant ID-TIMS 206Pb/238U ages of 606 ± 2 Ma (sample 1081) and 604 + 7/–8 Ma (sample 1042) obtained for monazite from close to the top and at the top of the Passos Nappe were interpreted by Valeriano et al. (2004) to relate to exhumation of the Passos Nappe. These ages are similar to (U–Th)–Pb ages of 610–600 and 600–595 Ma retrieved from monazite rims, lower yttrium patches in monazite and single domain monazite in samples from the Três Pontas–Varginha and Carmo da Cachoeira Nappes, respectively, in the Andrelândia Nappe Complex (Fig. 10). These ages are also similar to the Rb–Sr isochron ages of c. 602 Ma reported by Reno et al. (2009) for a sample from close to the base of the Três Pontas–Varginha Nappe that were argued to be related to the main retrograde foliation-forming event during high-temperature exhumation to mid-crustal depths (Fig. 10).

ID-TIMS ages of 595 + 35/–34 Ma (sample 1038-3) and 593 + 12/–13 Ma (sample 1036-1) for rutile from samples of amphibolite from close to the top and at the top of the Passos Nappe were interpreted as cooling ages by Valeriano et al. (2004). These ages are similar to (U–Th)–Pb ages of 593 and 588 Ma retrieved from single domain monazite in samples from close to the bottom of the Três Pontas–Varginha Nappe, and three older 40Ar/39Ar ages of 591–583 Ma retrieved from biotite in samples from lower and middle levels of the Três Pontas–Varginha Nappe, in the Andrelândia Nappe Complex (Fig. 10).

Overall, the published zircon, Rb–Sr and 40Ar/39Ar age data and the new (U–Th)–Pb age data presented here for monazite from the Andrelândia Nappe Complex have a similar age spread and age grouping to age data for zircon, monazite and rutile reported by Valeriano et al. (2004) from the Passos Nappe Complex immediately to the north. This similarity in punctuated temporal evolution suggests that events recorded in both Nappe Complexes are regionally significant.

CONCLUSIONS

In this study, (U–Th)–Pb monazite ages are reported for samples from the passive margin-derived nappes of the Andrelândia Nappe Complex in the southern sector of the Southern Brasilia Belt. The results are interpreted in relation to the post-peak, high-temperature, suprasolidus-to-subsolidus retrograde evolution and exhumation of the nappes, and the possible overprinting effects on the southernmost samples of terrane accretion events associated with the younger Ribeira Belt to the southeast.

The results demonstrate that ages retrieved from monazite that grew close to the solidus in residual granulites and in leucosome will vary from sample to sample according to differences in the solidus temper-
ature, which, for a given pressure, is determined by the bulk composition (a measure of the degree of melt depletion for the residues). Thus, age variation is to be expected in a regional study of formerly suprasolidus rocks with a large data set; the age variation in this case may not be regionally systematic, which should enable distinction from diachronism related to a migrating tectonothermal event. In addition, the results of this study confirm the propensity of monazite to record evidence of tectonic events that are not always registered by other high-temperature mineral chronometers.

Specifically, the conclusions of this study are as follows:

1. For the Três Pontas–Varginha Nappe, the oldest (U–Th)–Pb ages of c. 662 and c. 656 Ma come from low yttrium monazite included in or associated with garnet. These ages are interpreted to record incorporation of monazite into the rims of peritectic with garnet. These ages are interpreted to record evidence of tectonic events that are not always registered by other high-temperature mineral chronometers.

2. For the Três Pontas–Varginha Nappe, (U–Th)–Pb ages of 640–631 Ma retrieved from higher yttrium areas in monazite inclusions in garnet and some matrix monazite grains are interpreted to date the post-peak, high-temperature retrograde growth of monazite at temperatures close to the elevated solidus in these residual granulites. The inclusions are interpreted to be a product of interaction between the host garnet and the residual melt via cracks in the garnet.

3. These results demonstrate the need for caution in the interpretation of inclusions as they may be younger than the host mineral rather than older than or synchronous with growth of the host mineral.

4. For the underlying Carmo da Cachoeira Nappe, older (U–Th)–Pb monazite ages in the range 619–616 Ma are interpreted to date the high-temperature suprasolidus growth of foliation-forming biotite during close-to-isobaric cooling following peak temperatures.

5. For the Três Pontas–Varginha Nappe, the youngest group of (U–Th)–Pb monazite ages, in the range 620–588 Ma, includes ages in the older part of the range that record late-stage interaction with melt close to the solidus in some samples and ages in the younger part of the range that record recrystallization of monazite by dissolution–precipitation owing to ingress of fluid from the Carmo da Cachoeira Nappe beneath as alkaline fluid was released at the solidus.

6. For the Carmo da Cachoeira Nappe, younger (U–Th)–Pb monazite ages in the range 600–595 Ma are interpreted to record recrystallization of monazite by dissolution–precipitation owing to release of fluid at the solidus during the early stage of exhumation of this nappe.

7. For the Três Pontas–Varginha and Carmo da Cachoeira Nappes, the retrograde P–T path involves a high-pressure close-to-isobaric cooling segment, a close to isothermal decompression segment and a second close-to-isobaric cooling segment at low pressure. Using our published data in addition to data in this study yields a T–t evolution in which an initial post-peak period of relatively slow cooling, at an average rate of \( \sim 2^{\circ}\text{C Ma}^{-1} \), is interrupted by a short period of fast cooling, at a rate of \( \sim 80\ ^{\circ}\text{C Ma}^{-1} \), during the first 5 Ma, before a return to extremely slow cooling to the ambient geotherm. However, if the closure temperature for the \({ }^{40}\text{Ar/}^{39}\text{Ar}\) system in biotite is as high as 450–550 \(^{\circ}\text{C} \), then the period of faster cooling and the rate of cooling are reduced for the Três Pontas–Varginha Nappe and the period of faster cooling is eliminated for the Carmo da Cachoeira Nappe.

8. (U–Th)–Pb monazite ages from the Carvalhos Klippe fall into one of three distinct age groups all younger than 619 Ma (Fig. 10). Two monazite grains have core ages of c. 619 and 614 Ma, which could indicate diachronism in the age of metamorphism for the HP granulites in the Três Pontas–Varginha Nappe or that the Carvalhos Klippe is part of the Occidental terrane within the Ribeira Belt. Younger monazite ages of 595–592 and 585–580 Ma likely register overprint ing and dissolution–precipitation of monazite owing to ingress of aqueous fluid driven by orogenic loading associated with terrane accretion in the Ribeira Belt to the southeast.

ACKNOWLEDGEMENTS

The research reported here was supported by the U.S. National Science Foundation (grant EAR-0227553 to Brown and Piccoli), and the University of Maryland, including the Maryland NanoCenter and the Nisp-Lab, which are supported in part by the NSF as a MRSEC Shared Experimental Facility. Use of the ion microprobe facility at UCLA, which is partly supported by a grant from the Instrumentation and Facilities Program of the National Science Foundation, and use of the John de Laeter Centre for Mass Spectrometry at Curtin University, which is a joint research venture incorporating Curtin University, the University of Western Australia, CSIRO and the Geological Survey of Western Australia, is acknowledged. Assistance from M. Grove and A. Schmitt (UCLA), C. Clark (Curtin University) and M. Fogarty (University of Copenhagen) is appreciated; and, helpful discussions with J. Baldwin (University of Montana), F. Korhonen (Curtin University), R. Moraes (University of São Paulo), R. Powell (University of Melbourne) and R. White (University of Mainz) on various topics are acknowledged. This work benefited greatly from enlightening discussions with J. Pyle about (U–Th)–Pb monazite EPMA dating. F. Spear and J. Hanchar are thanked for com-
ments on an earlier version of the paper, additional discussions with Spear about (U–Th)–Pb monazite EPMA dating are acknowledged. J. Allaz and N. Kelly are thanked for constructive reviews of the JMG version of this paper, and D. Robinson is thanked for editorial advice. Nevertheless, any remaining infelicities or misinterpretations remain the responsibility of the authors.

REFERENCES


© 2011 Blackwell Publishing Ltd


SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Method for (U–Th)–Pb monazite dating by EPMA used in this study.

Table S1. All chemical composition data for monazite grains analysed in this study.

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

APPENDIX: SAMPLE DESCRIPTIONS

Três Pontas–Varginha Nappe

Samples were collected from multiple locations through the high-pressure granulite facies Três Pontas–Varginha Nappe. Samples 05b-6-108 and 04-6-21 were taken from the Santo Antônio Quarry in the lower part of the nappe close to the base. Samples 04-6-19 and 05b-6-29 were taken from the Four Level Quarry, which is located between the Santo Antônio and Três Pontas Quarries in the lower part of the nappe. Samples 04-6-2, 04-6-11, 05b-6-103 and 05b-6-36 were taken from the Três Pontas Quarry south of the city of Três Pontas in the middle portion of the nappe. Sample 05b-6-31b was taken from the Lixão (garbage dump in a former quarry) in the city of Varginha, which is located in the upper part of the nappe close to the top. All samples are variably residual granulites with centimetric pods and layers of leucosome separated by melanosome. Representative outcrops from this nappe are shown in Fig. A1a,b.

Sample 05b-6-108 is a garnet–aluminosilicate–K-feldspar–quartz gneiss. Euhedral garnet up to 1 cm in diameter includes quartz, kyanite and biotite. Garnet occurs in a matrix comprising discontinuous ribbons of elongate quartz alternating with layers composed of equant quartz and K-feldspar, and variable amounts of oriented sillimanite and biotite (up to 1 mm long) that together with ilmenite define the foliation. This foliation wraps around garnet and augen of ternary feldspar and quartz; sporadic kyanite grains occur in the augen. Coarser-grained biotite several millimetres across occurs in pressure shadows associated with garnet. Accessory monazite, up to 450 μm in length, occurs along grain boundaries in the quartzo-feldspathic matrix.

Sample 04-6-21B is a quartz–garnet–aluminosilicate–K-feldspar gneiss. It comprises coarse garnet (1–1.5 cm across) and elongated augen of ternary feldspar and quartz with a mosaic microstructure wrapped by a layered foliation comprising discontinuous layers of elongate quartz grains and layers of 1 mm-size K-feldspar and quartz or biotite and sillimanite (± rare kyanite). In addition, biotite occurs as irregular inclusions or as part of polymineralic inclusions with quartz in garnet, and as thin rims replacing the edges of some garnet. Rare plagioclase occurs as interstitial patches with low dihedral angles against quartz and K-feldspar suggesting that it pseudomorphed the last traces of interstitial melt during final crystallization at the solidus (Reno et al., 2009). Accessory monazite, up to ~210 μm in length, occurs as inclusions in the rims of garnet and in biotite in the matrix, and accessory zircon occurs in the matrix. Rh–Sr multi-mineral–whole rock isochrons calculated for two fractions of this sample define an age of c. 590 Ma (now revised to c. 602 Ma) interpreted to date high-temperature subsolidus exhumation (Reno et al., 2009).

Sample 04-6-19 is a quartz-rich garnet granulite. Subhedral garnet up to 5 mm in diameter contains inclusions of kyanite, biotite, quartz and plagioclase, and microstructural relations suggest partial replacement of garnet by biotite. The matrix dominantly comprises quartz, with plagioclase and K-feldspar, rare biotite and kyanite, ruged late muscovite or fine-grained aggregates of muscovite that replace feldspar, and ilmenite and rutile. Monazite up to 170 μm in length occurs along grain boundaries in the matrix.

Sample 05b-6-29 is a garnet–biotite–K-feldspar gneiss. Subhedral garnet up to 6 mm in diameter contains inclusions of kyanite and kyanite, and quartz–K-feldspar aggregates inferred to represent former melt inclusions. Garnet is rimmed by biotite, kyanite, quartz and K-feldspar aggregates. Biotite and kyanite blades are aligned within a coarse foliation defined by biotite-rich and biotite-absent layers composed of quartz, K-feldspar and plagioclase. Accessory monazite, generally < 50 μm but rarely up to 350 μm in length, rutile and ilmenite occur in the quartzo-feldspathic matrix.

Sample 04-6-2 is a quartz–garnet–K-feldspar–kyanite–biotite–muscovite–rutile–ilmenite gneiss. Garnet is associated with layers composed of millimetre-size equant K-feldspar and quartz in a mosaic microstructure separated by larger quartz grains or discontinuous layers of coarse quartz grains defining a crude foliation. Biotite occurs as inclusions in garnet (generally ~5 mm in diameter), as retrograde fringes sporadically around garnet or as interstitial grains moulded on K-feldspar, and...
sometimes as fine grains associated with kyanite (~1 mm long) in the crude foliation. Rare coarse-grained muscovite is unoriented and interstitial between K-feldspar grains and between K-feldspar and quartz grains, and is interpreted to have formed close to the solidus (Reno et al., 2009). Modally minor interstitial plagioclase occurs between euhedral K-feldspar grains and along grain boundaries between euhedral K-feldspar and garnet or quartz grains, and is interpreted to have formed during final crystallization of residual melt (Reno et al., 2009). Accessory monazite, generally < 200 µm in length, is either included in the outer parts of garnet or in contact with, but outside of the garnet rims; accessory rutile occurs as inclusions in garnet and in the matrix with zircon and ilmenite.

Sample 04-6-11 is a leucosome-dominated sample that comprises primarily medium grained (2–4 mm) quartz, plagioclase and K-feldspar, with skeletal clusters of euhedral garnet intergrown with quartz up to 1 cm in diameter, sporadic sub-millimetre grains of biotite interpreted to partially replace garnet, and rare interstitial or patchy retrograde muscovite. Stringers of ilmenite up to 2 mm long occur along K-feldspar–K-feldspar grain boundaries. Aggregates of biotite 2–3 mm in size form melanosome that define the foliation. Monazite up to 350 µm across is present along grain boundaries in the leucosome. The age of zircon growth in this sample is 648 ± 12 Ma (Reno et al., 2009).

Sample 05b-6-103 is a garnet–kyanite–K-feldspar gneiss. Garnet up to 5 mm in diameter contains inclusions of biotite, plagioclase, quartz, monazite and rutile. Kyanite up to 5 mm long associated with ilmenite occurs in thin layers that contrast with less common layers dominated by biotite up to 1 mm in length also associated with ilmenite; they alternate with quartz–K-feldspar–plagioclase layers to define compositional layering.
boundaries and associated with biotite. A foliation that wraps the garnet grains; biotite occurs rarely with layers composed of kyanite blades up to 5 mm in length defining and plagioclase (±K-feldspar and accessory rutile) has thin layers composed of kyanite blades up to 5 mm in length defining a foliation that wraps the garnet grains; biotite occurs rarely with garnet. Monazite grains also occur along garnet–biotite grain boundaries and associated with biotite.

Sample 05b-6-31b is a strongly foliated quartz–garnet–biotite–K-feldspar–plagioclase–alumino-silicate–ilmenite gneiss. Semi-continuous layers of elongate quartz alternate with layers composed predominantly of equant ternary feldspar with a mosaic microstructure, finer-grained rounded quartz and commonly interstitial plagioclase. This layering defines a strong foliation that wraps around garnet (2–5 mm diameter). Kyanite and ilmenite occur as inclusions in the mantle regions of garnet, and ilmenite occurs in the matrix. Biotite (<1 mm) occurs preferentially in layers as sporadic grains associated with and sometimes moulded on plagioclase, as aggregates of grains aligned in the foliation, and as millimetric grains replacing garnet. Minor kyanite and abundant sillimanite grains up to 5 mm in length are oriented in the foliation. Sillimanite also occurs as aggregates of small (<0.5 mm) grains formed along cracks that separate fragments of garnet. Monazite up to 250 μm in diameter occurs as inclusions in garnet, and along garnet grain boundaries. The age of zircon growth in this sample is 647 ± 11 Ma (Reno et al., 2009).

**Carmo da Cachoeira Nappe**

Samples were collected from different sections of the INCOPE working quarry south of the city of Três Corações in the Carmo da Cachoeira Nappe. Representative outcrops from the quarry floor are shown in Fig. A1c,d.

Sample 05b-5-23 is a strongly foliated garnet–kyanite–plagioclase–biotite gneiss. Euhedral garnet up to 5 mm in diameter has inclusions of biotite, plagioclase, quartz, rutile, monazite and irregular polymorphiac quartzo-feldspathic aggregates (± biotite) interpreted to represent crystallization products of former melt. The matrix comprises 3–5 mm long biotite grains defining a strong mylonitic foliation together with kyanite, centimetric plagioclase, strongly internally strained quartz and rare muscovite. The foliation wraps around the garnet. Accessory ilmenite, with rare rutile cores, and tourmaline occur in the matrix. Monazite in garnet is generally tiny, but monazite up to 250 μm in diameter occurs as inclusions in biotite.

Sample 05b-5-22 is a strongly foliated biotite–garnet schist. Subhedral to euhedral garnet up to 2 mm in diameter has inclusions of quartz, plagioclase and rutile. Biotite and kyanite up to 1 mm in length are aligned within the foliation with plagioclase augen and lenticular quartz. Rare muscovite and accessory ilmenite, rutile and tourmaline are present in the matrix. Monazite up to 100 μm in diameter occurs as inclusions in biotite.

Sample GR-05-4B is a strongly foliated biotite–garnet schist. Euhedral garnet up to 7 mm in diameter has inclusions of biotite, quartz, plagioclase and rutile. Biotite 2–4 mm long is aligned within the foliation with plagioclase augen and lenticular quartz. Accessory ilmenite, rutile and tourmaline are present in the matrix. Monazite up to 200 μm in diameter occurs in the quartzo-feldspathic matrix.

Sample 04-5-6 is a strongly foliated plagioclase–biotite gneiss. Layers of dominant biotite with kyanite blades 2–4 mm long and minor muscovite, all of which display internal strain, define the foliation. In some layers, this micaceous foliation wraps centimetric augen of internally strained quartz and coarse-grained plagioclase, whereas in other layers the micaceous foliation alternates with layers composed of millimetric quartz and plagioclase. Rare rounded millimetric garnet contains sparse inclusions of biotite and quartz. Monazite up to 60 μm in length occurs as inclusions in biotite and along multilamellar grain boundaries. Accessory ilmenite and rutile are also present in the matrix.

Sample 04-5-8 is a strongly foliated garnet–plagioclase–biotite gneiss. Layers composed of tabular biotite and muscovite 2–4 mm long and rare kyanite, all of which record internal strain, alternate with layers that comprise quartz and plagioclase defining the foliation. The micaceous layers wrap around sporadic lenses up to 1 cm across composed of internally strained quartz and coarse-grained plagioclase. Rounded subhedral garnet up to 5 mm in diameter contains inclusions of biotite, rutile, quartz, both euhedral and irregular plagioclase, irregular polymorhiac quartzo-feldspathic aggregates interpreted to represent former melt, chlorite and muscovite. Biotite rims garnet and larger biotite grains 2–3 mm across occur in the interiors of some C-shaped garnet due to replacement. Monazite is commonly 30–60 μm across but may be up to 100 μm in length; it occurs as inclusions in biotite and associated with garnet–ilmenite grain boundaries at the edge of garnet. Accessory ilmenite and rutile are present in the matrix.

**Carvalhos Klippe**

Samples 05b-10-102 and 05b-10-65 were both taken from bedrock of a waterfall just north of the city of Carvalhos.

Sample 05b-10-102 has large (1 cm) euhedral garnet that are rimmed by small (<0.1 mm) biotite grains. The garnet includes monazite, rutile and ilmenite. The rock is weakly foliated with biotite and kyanite grains (1–2 mm) in layers that surround lenticular aggregates of quartz and plagioclase. Rare muscovite and accessory ilmenite and rutile occur in the matrix. Monazite up to 150 μm in diameter is associated with biotite and kyanite in the quartzo-feldspathic matrix. One larger grain (250 μm) associated with xenotime was found as an inclusion in garnet.

Sample 03b-10-65 is a coarse-grained garnet–kyanite–K-feldspar gneiss. Garnet up to 1 cm in diameter contains inclusions of ilmenite, biotite and monazite up to 450 μm long. Kyanite grains 5–8 mm long are aligned with millimetric biotite grains in the foliation; kyanite contains inclusions of biotite and monazite (~75 μm diameter). Quartz, plagioclase and K-feldspar form lenticular aggregates and layers in the matrix. Accessory ilmenite is associated with biotite and kyanite in the foliation.

Received 24 June 2010; revision accepted 1 August 2011.