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Abstract: Understanding the relationship between accessory mineral growth and the evolution of silicate mineral assemblages along the entirety of a P-T-t path is a critical step in developing models for evolving tectonic systems. Here we combine U-Pb age data (for zircon and monazite), rare earth element (REE) data and compositionally specific phase diagrams (P-T pseudosections) for the rocks of the Palghat Cauvery shear system (PCSS), southern India in order to constrain the periodicity of heating /cooling and burial/exhumation events during the Ediacaran/Cambrian amalgamation of Gondwana. HREE data from zircon is consistent with zircon growth at 672-724 °C during the breakdown of garnet in the kyanite stability field at  $535.0 \pm 4.9$  Ma. This represents a cooling that punctuates the P-T-t path. Subsequent monazite growth and symplectite formation occurred at 920 °C and 7.5 kbar, ~10 Ma after zircon growth which reflects a period of reheating

and decompression related to delamination and the collapse of the East African orogen. The REE chemistry of the monazite is consistent with the system having undergone partial melting prior to monazite growth, thereby altering the bulk rock chemistry. The periodicity of the heating and cooling cycles (~10 Ma) from this study are consistent with recently proposed tectonic switching models for the formation of granulite metamorphism in accretionary/collisional tectonic settings. The elevated heat flows required to generate the UHT metamorphism are achievable in the proposed back-arc setting for the PCSS during Gondwana amalgamation.

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**The *P-T-t* architecture of a Gondwanan suture: REE, U-Pb and Ti-in-zircon thermometric constraints from the Palghat Cauvery shear system, South India**

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1 **Abstract**

2 Understanding the relationship between accessory mineral growth and the evolution  
3 of silicate mineral assemblages along the entirety of a *P-T-t* path is a critical step in  
4 developing models for evolving tectonic systems. Here we combine U-Pb age data  
5 (for zircon and monazite), rare earth element (REE) data and compositionally specific  
6 phase diagrams (*P-T* pseudosections) for the rocks of the Palghat Cauvery shear  
7 system (PCSS), southern India in order to constrain the periodicity of heating /cooling  
8 and burial/exhumation events during the Ediacaran/Cambrian amalgamation of  
9 Gondwana. HREE data from zircon is consistent with zircon growth at 672-724 °C  
10 during the breakdown of garnet in the kyanite stability field at  $535.0 \pm 4.9$  Ma. This  
11 represents a cooling that punctuates the P-T-t path. Subsequent monazite growth and  
12 symplectite formation occurred at 920 °C and 7.5 kbar, ~10 Ma after zircon growth  
13 which reflects a period of reheating and decompression related to delamination and  
14 the collapse of the East African orogen. The REE chemistry of the monazite is  
15 consistent with the system having undergone partial melting prior to monazite growth,  
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17 cycles (~10 Ma) from this study are consistent with recently proposed tectonic  
18 switching models for the formation of granulite metamorphism in  
19 accretionary/collisional tectonic settings. The elevated heat flows required to generate  
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21 during Gondwana amalgamation.

22

23 *Keywords:* Gondwana; UHT metamorphism; Monazite; Zircon; Garnet;  
24 THERMOCALC

25

## 1 **Introduction**

2 The integration of the textural and chemical characteristics of accessory and silicate  
3 minerals provides invaluable information when investigating the metamorphic and  
4 tectonic history of a terrane (e.g. Buick et al., 2006; Hermann and Rubatto, 2003;  
5 Kelsey et al., 2007; Rubatto, 2002; Rubatto and Hermann, 2007; Rubatto et al., 2006;  
6 Rubatto et al., 2001; Whitehouse and Platt, 2003). In particular, the information  
7 extracted from mineral assemblages can be used to great effect in making inferences  
8 about poorly understood processes such as those involved in the generation,  
9 preservation and tectonic significance of ultrahigh temperature (UHT) metamorphic  
10 assemblages (Harley, 1998a; Harley, 1998b; Harley and Kelly, 2007; Kelly and  
11 Harley, 2005). Coupling these observations with calculated metamorphic phase  
12 diagrams for specific equilibrium bulk rock compositions ( $P$ - $T$  pseudosections) allows  
13 a clearer picture of the whole  $P$ - $T$ - $t$  evolution of a terrane to be reconstructed (e.g.  
14 Clark et al 2007; Kelsey et al., 2007). This approach is especially important in  
15 terranes that have undergone UHT metamorphism due to the uncertainty surrounding  
16 the ability of geochronometers to record the timing of peak metamorphism (Fraser et  
17 al., 1997; Harley, 2004; Kelsey et al., 2008; Roberts and Finger, 1997; Tomkins et al.,  
18 2005). This uncertainty reflects (1) the lack of absolute knowledge regarding closure  
19 temperature and rates of elemental diffusion in key geochronometers such as zircon  
20 and monazite and (2) the lack of certainty as to the exact controls on the growth of  
21 zircon and monazite and how it relates to mineral reactions above and below the  
22 solidus. Recent advances in the application of accessory phase thermometry (e.g.  
23 Watson and Harrison, 2005; Watson et al., 2006; Ferry and Watson, 2007) allows  
24 constraints to be placed on the temperatures at which accessory phase growth  
25 occurred. This information can then be incorporated with the metamorphic forward

1 models allowing a detailed event chronology, linking textural, temporal and thermal  
2 observations, to be constructed. It is only when this information is gathered that  
3 insights into the tectonic processes that created the metamorphism are generated and  
4 the significance of the nature and timing of metamorphism for plate-tectonic global  
5 reconstructions (e.g. Boger and Wilson, 2005; Collins and Pisarevsky, 2005; Li et al.,  
6 2007) can be addressed.

7

8 In this paper we investigate the major and trace element compositions of garnet,  
9 zircon and monazite in order to constrain the timing and rates of processes in the  
10 Palghat Cauvery shear system (PCSS) in southern India (Fig. 1). This region  
11 preserves a distinctive record of high-grade metamorphism coupled with accessory  
12 mineral development and is a key area in understanding the tectonic scenarios that  
13 may lead to the generation of ultra-high temperature crustal metamorphism. There is  
14 also a recent debate surrounding the report of eclogite facies rocks from this area  
15 (Kelsey et al., 2006; Shimpo et al., 2006; Tsunogae and Santosh, 2006; Kanazawa et  
16 al., 2009) and the significance that these rocks have in defining the location of major  
17 suture/collision zones during the amalgamation of Gondwana (Collins et al., 2007b;  
18 Collins and Pisarevsky, 2005).

19

## 20 **Regional Geology**

21 The PCSS is an approximately 70 km by 400 km E-W zone characterised by an  
22 anastomosing network of mainly dextral shear zones, typically 1-10km wide,  
23 separating the Dharwar Craton from the Southern Granulite Terrane (SGT) in  
24 southern India. (Chetty et al., 2003; Tomson et al., 2006) (Fig.1). The lithologies  
25 within the PCSS consist of deformed Neoproterozoic rocks; variably retrograded

1 charnockitic gneisses associated with biotite and hornblende-bearing migmatitic  
2 gneisses intercalated with supracrustal rocks that include, metapelites, calc-silicate  
3 marbles and quartzites (Bhaskar Rao et al., 1996; Chetty and Bhaskar Rao, 2006).

4

5 A number of previous studies have found significant differences in the structural style,  
6 lithological units, Nd model ages, Rb-Sr mineral ages and metamorphic *P-T*  
7 conditions of the lithologies within the PCSS when compared to the Dharwar Craton  
8 and SGT (Bartlett et al., 1998; Ghosh et al., 2004; Harris et al., 1994b; Meissner et al.,  
9 2002; Santosh et al., 2005; Santosh et al., 2003). As a result the PCSS has been  
10 proposed to represent a major structural feature within southern India. The PCSS has  
11 been interpreted as (1) a dextral transcurrent shear belt (Drury et al., 1984); (2) a  
12 suture zone (Bhaskar Rao et al., 2003; Meissner et al., 2002); (3) an Archaean-  
13 Palaeoproterozoic terrane boundary (Harris et al., 1994b); (4) a collapsed marginal  
14 basin (Drury and Holt, 1980) and (5) a zone of Palaeoproterozoic and Neoproterozoic  
15 re-working of Archaean crust (Bhaskar Rao et al., 1996; Chetty et al., 2003; Ghosh et  
16 al., 2004; Harris et al., 1994b; Santosh et al., 2003; Tomson et al., 2006). The notion  
17 that the PCSS represents the Archaean-Proterozoic or Neoproterozoic terrane  
18 boundary has been contested, based on new U-Pb zircon age data and Sm-Nd model  
19 ages for charnockitic and migmatitic gneisses (Bhaskar Rao et al., 2003; Ghosh et al.,  
20 2004). These studies suggest that the Archaean crust may extend south of the PCSZ  
21 up to Karur-Kamban-Painavu-Trichur (KKPT) shear zone (Ghosh et al., 2004) (Fig.  
22 1).

23

24 In tight-fit reconstructions of Gondwana, southern India is juxtaposed against  
25 Madagascar and East Antarctica (Reeves and de Wit, 2000), where the major suture

1 zones of the amalgamation of eastern Gondwana have been identified and correlated  
2 through adjoining crustal blocks (Boger and Miller, 2004; Collins et al., 2007b;  
3 Collins and Pisarevsky, 2005; Fitzsimons, 2000; Meert, 2003; Meert and Van der  
4 Voo, 1997; Shaju et al., 1998). A number of different microcontinents have been  
5 identified within the models of the amalgamation of eastern Gondwana; the most  
6 significant of which, in the context of southern India, is Azania – a microcontinent  
7 consisting of central Madagascar, part of eastern Africa and the Al-Mafid Block in  
8 Yemen (Collins and Pisarevsky, 2005; Collins et al., 2007a). Prior to the formation of  
9 Gondwana, the Mozambique Ocean was located between Azania and India. The  
10 closure of the Mozambique Ocean formed the ~550-510 Ma Malagasy Orogeny  
11 (Collins and Pisarevsky, 2005). The site of this closure has been identified in eastern  
12 Madagascar as the Betsimisaraka suture (Collins, 2006; Collins and Windley, 2002),  
13 but its southern continuation is contentious. Recent work has demonstrated that the  
14 PCSS marks an isotopic boundary between the Northern Granulite and Southern  
15 Granulite terranes (Clark et al., 2009; Fig 1), contains discontinuous ultramafic bodies  
16 that are coincident with crust penetrating shear zones that offset the Moho (Collins et  
17 al., 2007b; Meissner et al., 2002) and may contain evidence of Neoproterozoic UHP  
18 metamorphism (Shimpo et al., 2006) and therefore is a likely candidate for the  
19 continuation of the Betsimisaraka suture into southern India.

20

## 21 **Results**

### 22 *Petrography*

#### 23 *Sample description*

24 The petrology of the various units that occur in the Panagad area have been  
25 investigated in detail by Kanazawa et al. (2009) and this study we have focussed on



1 one lithology type a garnet-kyanite-biotite gneiss, sample I05-54. I05-54 is from an  
2 Mg-Al rich granulite from Panangad within the PCSS (Fig. 1b). This Mg-Al rich unit  
3 occurs as a 10 to 50 metre wide unit that is discordant with the migmatitic layering in  
4 the host mafic gneisses. The unit shows a general north-easterly trend with a steep  
5 ( $>75^\circ$ ) northwest dip and a near vertical lineation defined by alignment of kyanite  
6 (Fig 2a). The unit has a variable mineralogy with garnet, kyanite, biotite, gedrite,  
7 sapphirine and cordierite all visible in within the unit (see Kanawazaet al., (in press)  
8 for further details). Sample I05-54 is composed of coarse-grained garnet, kyanite and  
9 biotite with sapphirine is observed rimming the kyanite blades whereas cordierite and  
10 gedrite are not visible in hand sample (Fig. 2b).

11

12 In thin section, I05-54 displays three distinct petrographic relationships: (1) an  
13 inclusion rich garnet core (Fig. 2c); (2) a coarse grained garnet, kyanite and biotite  
14 assemblage, and (3); symplectite development between the coarse-grained minerals  
15 (Fig. 2d).

16

### 17 *Inclusion assemblage*

18 Coarse grained garnets contain a zone rich in inclusions (Fig 2c). Inclusions are  
19 restricted to the core of the garnets and are completely enclosed by a clean inclusion  
20 free garnet rim. The inclusions are dominantly gedrite, sillimanite, and quartz (Fig.  
21 2e) with minor plagioclase observed in some inclusions. The stability of this inclusion  
22 assemblage with garnet is difficult to assess. Vernon (1976) suggests that in general  
23 most inclusions belong to the same metamorphic assemblage as the porphyroblast.  
24 However, the inclusion assemblage may have formed prior to garnet growth as gedrite  
25 and quartz are only found as inclusions within garnet and not elsewhere in the rock

1 (Vernon et al., 2008). Accessory minerals observed in the garnet cores are rutile,  
2 zircon, monazite and apatite. Zircon within the garnet is dominantly oscillatory zoned  
3 with overgrowths either narrow or absent. Zircon occurs as oscillatory-zoned grains  
4 with an absence of any discernable rim or overgrowth material visible under  
5 cathodoluminescence (CL). Collins et al. (2007b) analysed the oscillatory zoned zircon  
6 from this sample and found that the age of oscillatory zoned zircon was ~2500 Ma.  
7 This population is interpreted to be of igneous origin and inherited from the source  
8 material that makes up the bulk of the gneisses in the PCSS. Monazite from within the  
9 core of the garnets is small with grain sizes generally less than 20  $\mu\text{m}$ .

10

11 *Coarse-grained assemblage*

12 I05-54 is dominated by porphyroblastic garnet, kyanite and biotite. As mentioned  
13 above, garnet is characterised by an inclusion-rich core and an inclusion-free rim.  
14 Biotite is coarse grained and contains rare inclusions of zircon, the zircons have well  
15 developed overgrowths on oscillatory zoned cores. Kyanite blades are partly  
16 pseudomorphed by sillimanite with kyanite remaining in the core and more highly  
17 birefringent sillimanite forming on the rims. Kyanite contains inclusions of both rutile  
18 and zircon (Fig. 2f) with zircon having well-developed overgrowths. A single  
19 xenotime crystal was observed in the otherwise inclusion free garnet rim (Fig. 3g)

20

21 *Symplectites*

22 Sapphirine-cordierite and spinel-cordierite symplectites are observed growing  
23 between garnet and kyanite porphyroblasts with cordierite separating garnet from  
24 sapphirine and spinel (Fig. 2g). In places sapphirine-spinel-cordierite symplectites  
25 have developed between the porphyroblastic kyanite and biotite. Additionally a

1 narrow cordierite corona separates the garnet from the biotite without the additional  
2 growth of sapphirine or spinel. Where garnet, kyanite and biotite are all proximal, a  
3 cordierite-spinel-sapphirine-biotite symplectite is formed with the biotite being fine-  
4 grained, bladed and in contact with the garnet (Fig. 2h). The dominant accessory  
5 phase observed in the symplectites is monazite, which is intergrown with both the  
6 sapphirine-cordierite and the spinel-cordierite symplectites (Fig. 2i). In contrast to the  
7 monazite found in the cores of the garnet, the monazite in the symplectite is typically  
8 large ( $>50\ \mu\text{m}$ ). Smaller grains of xenotime are also found in the symplectites (Fig.  
9 3g).

10

### 11 ***Mineral chemistry***

12 Mineral compositions were analysed using the Cameca SX-51 electron microprobe at  
13 Adelaide Microscopy at The University of Adelaide. Quantitative analyses for mineral  
14 chemistry were acquired at 15 kV and 20 nA and a beam diameter of 2-3  $\mu\text{m}$ ,  
15 Compositional maps were acquired at 15 kV and 100 nA for major elements (Figs. 3a-  
16 d) and 150 nA for trace elements (Figs. 3e-g) with a 'dwell time' of 195 ms and a  
17 step-size of 2  $\mu\text{m}$  in both the x and y directions. A summary of the analyses can be  
18 found in Tables 1 and 2.

19

### 20 ***Garnet***

21 Porphyroblastic garnet is in generally a solid solution of almandine and pyrope with  
22  $X_{\text{Mg}}$  (=Mg/Fe+Mg) in the range of 0.51-0.62 (Table 1) with low contents of grossular  
23 ( $<3\ \text{mol}\ \%$ ) and spessartine ( $<1.15\ \text{mol}\%$ ). Garnet has shows a pyrope rich core  
24 ( $\text{Alm}_{36-39}\ \text{Pyr}_{58-61}\ \text{Sps}_1\ \text{Grs}_{1-3}$ ) relative to the rim ( $\text{Alm}_{42-44}\ \text{Pyr}_{49-51}\ \text{Sps}_1\ \text{Grs}_{1-3}$ )  
25 consistent with retrograde diffusion and the occurrence of the cordierite coronae

1 around the garnet (Table 1; Fig 3a-d). The compositional zoning of the major  
2 elements is also evident in the electron microprobe traverse presented in Figure 4a.

3

4 *Biotite*

5 Biotite is Mg rich ( $X_{Mg}=0.80-0.81$ ) and contains approximately 2 wt%  $TiO_2$  (Table 2).  
6 Both the coarse grained and symplectitic biotite have similar compositions.

7

8 *Cordierite*

9 All cordierite analyses have a uniform magnesian composition with  $X_{Mg}$  in the range  
10 0.89-0.91 (Table 2).

11

12 *Sapphirine*

13 The symplectitic sapphirine is less magnesian ( $X_{Mg}= 0.76-0.78$ , Table 2) compared to  
14 other studies from the PCSS (Koshimoto et al., 2004; Santosh and Sajeev, 2006;  
15 Santosh et al., 2004; Shimpo et al., 2006). Other components apart from  $SiO_2$  (11.7-  
16 12.3 wt%) and  $Al_2O_3$  (61.1-62.5 wt%) total less than 1 wt%.

17

18 *Gedrite*

19 As previously mentioned gedrite only occurs as inclusions within the cores of the  
20 porphyroblastic garnet and is associated with quartz and sillimanite. The gedrite  
21 inclusions preserve an  $X_{Mg}$  range of 0.77-0.78. The  $Na_2O$  content ranges from 1.28-  
22 1.62 wt% and  $TiO_2$  show a range of 0.26-0.46 wt%.

23

24 *Spinel*

1 Symplectitic spinel occurs in association with cordierite is principally a solid solution  
2 of hercynite and Mg-spinel with consistent  $X_{Mg}$  values of 0.46-0.47 (Table S2). Spinel  
3 also contains a small amount of  $Cr_2O_3$  (0.33-0.51 wt%) and ZnO (0.80-1.20 wt%).

4

#### 5 ***Zircon and Monazite geochronology***

6 Equipment and operating conditions for monazite analysis are identical to those  
7 reported by Payne et al (2008). U-Pb acquisition used a 15  $\mu m$  beam diameter for  
8 monazite, run at a repetition rate of 5 Hz. Monazite ages were calculated using the  
9 MADEL monazite standard to correct for U-Pb fractionation (TIMS normalization  
10 data  $^{207}Pb/^{206}Pb = 490.7$  Ma,  $^{206}Pb/^{238}U = 514.8$  Ma and  $^{207}Pb/^{235}U = 510.4$  Ma), and  
11 the GLITTER software for data reduction. Over the duration of this study the  
12 reported average normalised ages for MADEL are  $493.0 \pm 8.3$ ,  $514.3 \pm 2.4$  and  
13  $511.2 \pm 2.0$  Ma for the  $^{207}Pb/^{206}Pb$ ,  $^{206}Pb/^{238}U$  and  $^{207}Pb/^{235}U$  ratios, respectively ( $n =$   
14 32). Accuracy was monitored by repeat analyses of the in-house internal monazite  
15 standard (94-222/Bruna-NW,  $^{206}Pb/^{238}U = 447$  Ma). Over the duration of this study  
16 the reported average  $^{206}Pb/^{238}U$  age for the internal standard was  $446.9 \pm 3.1$  ( $n = 15$ ).  
17 Analytical data for the analyses can be found in Tables 6.

18

19 Zircon and monazite were separated from crushed rock samples by conventional  
20 magnetic and methylene iodide liquid separation methods. Grains were handpicked  
21 and mounted in epoxy resin discs. No grains of monazite less than 50  $\mu m$  in diameter  
22 analysed in an attempt to avoid the analysis of the monazite inclusions from the garnet  
23 cores. The grains were cathodoluminescence (CL) imaged (zircon) or backscatter  
24 electron (BSE) imaged (monazite) to assess compositional and textural zoning in  
25 individual grains prior to analysis. Multi-faceted equant zircon crystals (Fig. 5a) and

1 large brightly luminescent CL rims (Fig. 5b-d) yielded a precise  $^{206}\text{Pb}/^{238}\text{U}$  age of  
2  $535.0 \pm 4.9$  Ma ( $2\sigma$ , MSWD = 1.4, Fig. 5e) and Th/U ratios from these analyses are  
3  $<0.22$ , characteristic of metamorphic zircon. The details of these data are presented in  
4 Collins et al. (2007) The LA-ICPMS analyses of monazite yielded two statistically  
5 distinct ages, the cores (Fig.6a) of monazite yielded a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $525.7 \pm 3.9$   
6 Ma ( $2\sigma$ , MSWD = 0.17, Fig. 6b, Table 3) whereas overgrowths (Fig. 6a) on the  
7 monazite cores gave a  $^{206}\text{Pb}/^{238}\text{U}$  age of  $515.7 \pm 4.7$  ( $2\sigma$ , MSWD = 0.20, Fig 6c, Table  
8 3).

9

#### 10 ***Garnet, zircon, monazite trace element chemistry***

11 Rare Earth Element (REE) compositions of minerals (Table 4, 5 and 6) were  
12 performed by laser ablation inductively coupled mass-spectrometry (LA-ICPMS) on  
13 block mounted mineral separates at The University of Adelaide using a Agilent  
14 7500cs ICPMS equipped with a New Wave 213 nm Nd-YAG laser. Beam diameter  
15 was set at  $65\mu\text{m}$  using a repetition rate of 5 Hz which produced a laser power density  
16 of  $\sim 14\text{-}16$  J  $\text{cm}^{-2}$ . Data was collected using time-resolved data acquisition in fast peak-  
17 jumping mode and processed using the GLITTER software (Van Achterbergh et al.,  
18 2001). Total acquisition time per analysis was 120 seconds; 60 seconds background  
19 measurement followed by 60 seconds of sample ablation. Calibration was performed  
20 against the NIST 612 standard glass using the coefficients of Pearce et al. (1997).  
21 NIST was run 4 times at the beginning and end of a run, interspersed by two analyses  
22 of BCR-2 and ten analyses of unknowns.  $^{43}\text{Ca}$  was used as the internal standard for  
23 garnet and monazite and Si for zircon, applying previously determined values from  
24 microprobe analysis. Precision based on repeated analyses of standards is

1 approximately  $\pm 10\%$  for concentrations  $< 10$  ppm. Typical detection limits for REE in  
2 this study ranged from 0.04-0.6 ppm.

3

4 Ti in zircon was measured in the same analytical run as the REE analyses. The less  
5 abundant  $^{49}\text{Ti}$  isotope (5.41%) was analysed in preference to the more abundant  $^{48}\text{Ti}$   
6 isotope (73.72%) to avoid the interference with  $^{96}\text{Zr}$ . Individual temperature errors  
7 (Table 5) are a function of counting statistics, standard calibration and the uncertainty  
8 in the thermometer calibration and were calculated via propagation of the  $2\sigma$  errors of  
9 the counting statistics and the standard calibration through the Ti in zircon  
10 thermometer of Watson and Harrison (2006).

11

### 12 *Garnet*

13 The trace element distribution in garnet from I05-54 was analysed by a LA-ICPMS  
14 traverse (Fig. 4a) and electron probe compositional mapping (Fig. 3e-g). The LA-  
15 ICPMS traverse consisted of 17 spot analyses across a garnet with a diameter of  
16 approximately 6000  $\mu\text{m}$  (Fig. 3a). Zoning is observed in a number of the trace  
17 elements with a few different patterns being recognised. As described earlier, the  
18 garnet consists of two main zones, the inclusion rich core and the inclusion free rim,  
19 and most of the elemental zoning patterns observed in the maps and the LA-ICPMS  
20 traverse reflect a change associated with the transition between the two garnet types.

21

22 Garnet maps show zoning in P (Fig 3f) with the garnet core more depleted (6-70 ppm)  
23 relative to the rim (159-266 ppm) with a step increase at the transition between the  
24 core and rim. This pattern is similar to the patterns observed for Zr and Hf (Table 4).  
25 The core of the garnet is contains 43-85 ppm Y, 3-11 ppm Yb and .3-1.3 ppm Lu. The

1 HREE-poor core then transitions in to an intermediate domain with Y contents 105-  
2 135 ppm, 16-32 ppm Yb and and 2.2-6 ppm Lu with a corresponding increases in the  
3 other HREE, Co, and Ni. The beginning of the intermediate Y rich zone also  
4 represents the largest drop in Sc, Ti and V (184-223 ppm Sc, 69-77 ppm Ti and 67-74  
5 ppm V in the core), which then gradually decrease rimward (61-158 ppm Sc, 32-55 Ti  
6 ppm and 24-49 ppm V from the intermediate zone to rim) in there abundances. Y, Co,  
7 Ni and the HREE then show a decrease in their relative elemental abundances back to  
8 those measured in the core moving towards the rim of the garnet.

9

10 In summary three main zoning styles are observed in the trace elements of the garnets.

11 These are:

12 (1) A bell shaped zoning pattern in the Sc, Ti and V with a step decrease in abundance  
13 that corresponds with the petrographically observed core/rim transition in the garnet;

14 (2) A W-shaped trend in P, Zr and Hf with core and rims relatively enriched in these  
15 elements relative to the intermediate area, although the elements are much more  
16 strongly enriched in the rims than in the core, and;

17 (3) A zoning pattern that consists of a low abundance flat core, near symmetric peaks  
18 corresponding with the petrographically observed core/rim transition that drop off  
19 toward the rims. This pattern is observed in Co, Ni, Y and the HREE from Gd to Lu  
20 with the pattern becoming more pronounced moving from Gd to Lu.

21

22 Garnet chondrite-normalised REE patterns for sample I05-54 show similar features  
23 that are common to high-grade garnet in granulite terranes (Degeling et al., 2001;  
24 Harley and Kelly, 2007; Harley et al., 2007; Hermann and Rubatto, 2003; Kelly and  
25 Harley, 2005; Whitehouse and Platt, 2003) with one major exception. This exception



1 is that there is no significant Eu anomaly ( $\text{Eu}/\text{Eu}^* 0.80\text{-}1.05$ ) associated with the  
2 garnet in any of the textural zones described earlier. However, the garnet displays a  
3 consistent depletion in the LREE with all well below chondrite values and enrichment  
4 in the HREE relative to chondrite. Variation in the relative HREE enrichment in the  
5 textural domains is observed across the garnet (Fig. 4c). The garnet core is more  
6 depleted (Fig. 4,  $\text{Lu}/\text{Gd} 0.09\text{-}0.19$ ) relative to a more enriched intermediate zone (Fig.  
7 4,  $\text{Lu}/\text{Gd} >1.0$ ) that corresponds to the interface between the core and rim of the  
8 garnet. The HREE content is depleted from this more enriched zone towards the rim  
9 (Fig. 4,  $\text{Lu}/\text{Gd} 0.17\text{-}0.65$ ). The relative abundance of the LREEs remains constant  
10 across the garnet.

11

## 12 *Zircon*

13 All zircon analysed from the sample occurred as either multi-faceted equant zircon  
14 crystals (Fig.5a) or as wide, brightly luminescent, under CL, overgrowths on  
15 oscillatory-zoned cores (Fig. 5b-d). Once again the patterns are similar to those found  
16 in zircons from high-grade metamorphic rocks, particularly those inferred to have  
17 formed in sub-solidus conditions (Hoskin and Schaltegger, 2003; Rubatto, 2002), with  
18 flat to slightly negative HREE patterns ( $\text{Lu}/\text{Gd} 0.11\text{-}0.18$ ) positive Ce anomalies  
19 ( $\text{Ce}/\text{Ce}^* 12\text{-}74$ ), and no negative Eu anomalies ( $\text{Eu}/\text{Eu}^* 0.89\text{-}1.01$ ). The LREE  
20 elements are close to, or below, chondrite values. The Th/U ratios obtained from the  
21 analysed zircon were in the range 0.09-0.22 (Collins et al., 2007), this is consistent  
22 with the zircon growth occurring during metamorphism (Corfu et al., 2003; Williams  
23 and Claesson, 1987). The REE composition of the oscillatory zoned cores that yielded  
24 Archaean ages was analysed and found to have distinctly different chondrite

1 normalised REE patterns (Fig. 5g) with much steeped HREE slopes than the unzoned  
2 c. 535 Ma population.

3  
4 The Ti contents of the zircons were also analysed in order to constrain the temperature  
5 at which the zircons grew. Due to the large beam size of the laser and the relative  
6 width of zircon overgrowths no trends in the data was able to be detected, i.e. zoning  
7 from high temperature early growth to low temperature later rim growth, was able to  
8 be detected. The measured Ti values ranged between 4.3-11.7 ppm (Table 5) which  
9 corresponds to a temperature range of 672-724 °C using the Ti in zircon thermometer  
10 (Fig. 4f; Watson and Harrison, 2005; Watson et al., 2006). The application of the Ti in  
11 zircon thermometer is dependent on the growth of zircon in equilibrium with a  
12 suitable buffering assemblage of quartz and rutile (Ferry and Watson, 2007), while  
13 these minerals are present in the rock it cannot be assumed that they are in  
14 equilibrium. The reasons why they are believed to be in equilibrium will be discussed  
15 in the next section.

16  
17 *Monazite*

18 Monazite data for sample I05-54 are plotted on Fig 6d and presented in Table 6. Due  
19 to the analytical spot size (65 µm) only the core regions of monazite was analysed as  
20 the overgrowths were too narrow. The trace element pattern, when normalised against  
21 chondrite, shows a strong relative enrichment in the LREE (232 000- 540 000 times  
22 chondrite for La) with a smooth decrease in the normalised abundance towards the  
23 HREE (Fig. 6d). The monazite from I05-54 displays a small negative Eu anomaly  
24 ( $\text{Eu}/\text{Eu}^* 0.60-0.78$ ) (Fig 6d).

25

1 **Discussion**

2 *Garnet zoning and zircon chemistry*

3 The notion that the trace element composition of zircon and garnet can be used to  
4 correlate growth events between these minerals is well established in both  
5 experimental (Rubatto and Hermann, 2007) and high-grade metamorphic rock  
6 systems (Buick et al., 2006; Harley, 2001; Hermann and Rubatto, 2003; Kelly and  
7 Harley, 2005; Rubatto and Hermann, 2003; Rubatto, 2002; Rubatto et al., 2006). The  
8 ability to examine the timing of zircon growth with respect to the growth of a  
9 petrologically sensitive mineral such as garnet can greatly improve the veracity of the  
10 interpreted *P-T-t* evolution of rock systems. This is particularly relevant to high-grade  
11 metamorphic terranes where the timing of zircon growth may not necessarily record  
12 the timing of peak metamorphism (Fraser et al., 1997; Kelsey et al., 2008). Although  
13 there is still some debate as to the most appropriate HREE distribution coefficients for  
14 application to these systems (Buick et al., 2006; Kelly and Harley, 2005; Rubatto,  
15 2002; Rubatto and Hermann, 2007; Rubatto et al., 2006) this technique can be readily  
16 applied to the rocks of the PCSS.

17

18 One feature is immediately apparent when looking at the HREE and Y profiles across  
19 the garnet (Fig 4a), that there is a zone of low HREE and Y abundance that  
20 corresponds with the core of the garnet and it is mantled by a strongly enriched zone  
21 that then decreases rimward. This profile is interpreted to reflect two stages of garnet  
22 growth separated by a period of garnet breakdown and the development of a HREE  
23 and Y annulus that separates the core from the rim of the garnet. The interpretation of  
24 two stages of garnet growth is consistent with the petrographic observation that the  
25 garnet has an inclusion rich core and an inclusion free rim.

1  
2 When relating the timing of zircon growth relative to that of the silicate mineral  
3 assemblage it is useful to establish whether the zircon grew in equilibrium with garnet  
4 (e.g. Hermann and Rubatto, 2003; Rubatto, 2002; Rubatto and Hermann, 2003;  
5 Whitehouse and Platt, 2003). From the normalised patterns presented in Fig 4c it can  
6 be seen that both zircon and garnet display flat to slightly negative Gd to Lu slopes  
7 consistent with equilibrium growth. However, when the  $D_{\text{REE}}(\text{zrc/grt})$  studies of  
8 previous workers from natural rock samples (Fig 7a) and experimental studies  
9 (Fig.7b) (Harley et al., 2001; Whitehouse and Platt, 2001; Rubatto, 2002; Rubatto  
10 and Hermann, 2007; Taylor and Harley, unpubl. data) are compared to the relative  
11 abundances of MREE and HREE in the garnet and zircon of this study it is apparent  
12 that the zircon analysed was not in equilibrium with garnet of any composition in  
13 sample I05-54, regardless of which  $D_{\text{REE}}(\text{zrc/grt})$  is used. Calculated  $D_{\text{REE}}(\text{zrc/grt})$   
14 values decrease slightly from Sm to Gd in all zones of the garnet. The core/rim  
15 boundary (CRB) and rim analyses then show a steady decline in  $D_{\text{REE}}(\text{zrc/grt})$  values  
16 from Tb to Lu (CRB: Tb = 2.04 to Lu = 0.44; rim Tb = 3.71 to Lu = 1.22), whereas the  
17 core shows a slight increase (Tb = 2.69 to Lu = 3.56). These patterns and  
18  $D_{\text{REE}}(\text{zrc/grt})$  values are significantly different when compared to the results from the  
19 study of natural studies (Figure 7a). The absolute  $D_{\text{REE}}(\text{zrc/grt})$  values in the CRB and  
20 rim are favoured in zircon over garnet by a factor of 2-3 times the published range in  
21 studies from Harley (2001) and Whitehouse and Platt (2001). The study of Rubatto  
22 (2002), which yielded different results to the other previous studies, shows a steady  
23 increase in  $D_{\text{REE}}(\text{zrc/grt})$  values from Tb to Lu this is again in contrast to the decrease  
24 (CRB and rim) or minor increase (core) observed in this study. When compared to  
25 recent experimental studies of zircon-garnet REE partitioning the  $D_{\text{REE}}(\text{zrc/grt})$

1 patterns are again inconsistent with the zircon and garnet in sample I05-54 being in  
2 equilibrium. Rubatto and Hermann (2007) again show a steady increase in the  $D_{\text{REE}}$   
3 values from Dy to Lu (Figure 7b). I05-54 also shows the MREEs being favoured in  
4 the zircon over garnet by a factor of 2.

5

6 A second diagnostic feature recorded by the REE contents of the zircon in sample  
7 I05-54 is the lack of a pronounced negative Eu anomaly. This feature suggests that  
8 zircon did not grow in the presence of an anatectic melt phase (Hoskin and  
9 Schaltegger, 2003). When coupled with the distinctive flat chondrite-normalised  
10 HREE profile and high HREE contents relative to garnet these observations suggest  
11 that zircon grew during metamorphism, prior to the onset of partial melting and not  
12 during the growth of garnet. The flat HREE patterns observe suggest that zircon was  
13 competing with another phase that incorporates HREE and as discussed above this  
14 phase is unlikely to be garnet. Rare inclusions of xenotime are observed in the garnet  
15 rims (Fig. 3g) and this may be competing with zircon resulting in the observed flat  
16 HREE patterns in zircon. Xenotime growth could have been the result of apatite  
17 and/or monazite breakdown during cooling releasing the required P.

18

19 The temperature of zircon growth can be constrained to be between 672-724 °C via  
20 the application of the Ti in zircon thermometer (Watson and Harrison, 2005; Watson  
21 et al., 2006). The application of this thermometer is dependent upon the growth of  
22 zircon in equilibrium with quartz and rutile. The knowledge of the  $a_{\text{TiO}_2}$  and  $a_{\text{SiO}_2}$  at  
23 the time of zircon growth are fundamental to the accuracy of the Ti in zircon  
24 thermometer (Ferry and Watson, 2007). Sample I05-54 contains rutile and quartz  
25 suggesting that there is potential for the application of the Ti in zircon thermometer.

1 Rutile occurs as inclusions in the same phases as zircon and seems to be in textural  
2 equilibrium with zircon suggesting  $a_{\text{TiO}_2} = 1$ . However, quartz only occurs in the  
3 inclusion assemblage and is not necessarily in equilibrium with zircon and rutile. As  
4 previously discussed, zircon growth occurs prior to partial melting and this is  
5 suggestive of the growth of zircon in a rock that has not undergone modification of  
6 its bulk composition due to the loss of partial melt. We therefore contend that quartz  
7 was likely to be part of the assemblage ( $a_{\text{SiO}_2} = 1$ ) during zircon growth and the Ti in  
8 zircon thermometer being applicable in this case.

9

### 10 ***Monazite chemistry***

11 Less is understood about the relationship of monazite growth to major silicate mineral  
12 phases, especially during high-grade metamorphic events such as those experienced  
13 by the samples used in this study (Kelsey et al., 2008). The occurrence of large  
14 monazite grains restricted to the symplectitic overgrowths on the coarse garnet and  
15 kyanite assemblage suggests a relationship between symplectite formation and  
16 monazite growth. However this observation alone is not enough to conclude that the  
17 monazite ages from this study constrain the timing of symplectite formation. The  
18 chondrite normalised REE patterns in sample I05-54 have a pronounced negative Eu  
19 anomaly. A negative Eu anomaly in these rocks could be generated in a couple of  
20 ways, monazite could inherit the negative Eu anomaly from the source rocks, or form  
21 from a rock composition that has undergone partial melting where  $\text{Eu}^{2+}$  has been  
22 incorporated into plagioclase in place of Ca (e.g. Nagy et al., 2002). The presence of a  
23 negative Eu anomaly is a common feature of monazite in high-grade metamorphic  
24 rocks that have undergone partial melting (e.g. Bea and Montero, 1999; Buick et al.,  
25 2006; Hermann and Rubatto, 2003; Rubatto et al., 2006) and in the case of monazite

1 in sample I05-54 the partial melting process is the most likely mechanism to generate  
2 the observed Eu anomaly. Partial melting is preferred to the inheritance of the REE  
3 pattern from the host rock because no negative Eu anomaly is recorded in the zircon  
4 and garnet from the sample, which would be expected if the original host rock had a  
5 negative Eu anomaly (e.g. Schulz et al., 2006).

6

7 *A composite P-T evolution of PCSS*

8

9 It is difficult to reconstruct the early prograde path of the rocks from the Panangad  
10 area but some first order observations can be made based on the petrographic  
11 evidence preserved as inclusions in the porphyroblastic garnet and the trace element  
12 zoning of the garnet. The early prograde evolution of sample I05-54 led to the  
13 formation of the inclusion assemblage of gedrite-sillimanite-quartz possibly in  
14 equilibrium with garnet. It is near impossible to constrain the bulk rock chemistry  
15 relevant for the inclusion assemblage as it has been substantially modified by partial  
16 melting and associated melt-loss. This makes the calculation of a P-T pseudosection  
17 for this early evolution quite difficult to do and therefore quantitative P-T constraints  
18 on this early assemblage nearly impossible to reconstruct. However, the inclusion  
19 assemblage of gedrite-sillimanite-quartz  $\pm$  garnet suggest the initial prograde path  
20 experienced by I05-54 did not exceed temperatures greater than 700-780 °C as the  
21 prograde FMASH gedrite + garnet = cordierite + orthopyroxene reaction was not  
22 crossed (grey shaded area on Fig. 8a; Diener et al., 2008). The presence of sillimanite  
23 also places an upper pressure limit of 8 kbars on the inclusion assemblage.

24

1 Sample I05-54 developed the coarse-grained mineral assemblage garnet-kyanite-  
2 biotite subsequent to the formation of the inclusion assemblage. The formation of this  
3 assemblage was most likely related to the formation of the Y annulus in the garnet  
4 that represents a period of garnet breakdown and Y resorption by the garnet. To  
5 achieve the garnet breakdown and the formation of kyanite in sample I05-54 would  
6 either have to move up pressure or down temperature from the conditions experienced  
7 during the inclusion assemblage formation. An up-pressure evolution, while  
8 consistent with the formation of kyanite, is inconsistent with the breakdown of garnet  
9 and generation of the observed Y annulus. For this reason we prefer an episode of  
10 cooling subsequent to the formation of the gedrite-sillimanite-quartz-garnet  
11 assemblage. The breakdown of garnet during this cooling event would liberate  
12 zirconium (e.g. Degeling et al., 2001; Fraser et al., 1997) and trigger the sub-solidus  
13 growth of zircon. The chemistry of zircon analysed in this study is consistent with this  
14 scenario for two reasons. Firstly, the  $D_{\text{REE}}(\text{zrc}/\text{grt})$  of the sample indicates that zircon  
15 and garnet did not grow in equilibrium. Secondly, the Ti in zircon thermometer  
16 indicates that metamorphic zircon grew at temperatures between 672-724 °C,  
17 consistent with cooling from the conditions related to the growth of gedrite-  
18 sillimanite-quartz-garnet.

19

20 After cooling, I05-54 underwent a period of reheating that drove the rock through the  
21 solidus resulting in partial melting, melt loss and the generation and preservation of  
22 the coarse grained mineral assemblages, symplectite and the growth of monazite. A  
23 metamorphic forward model for a specific rock bulk compositions ( $P$ - $T$   
24 pseudosection) is presented in Figures 8b. Figure 8b was calculated from a  
25 composition determined by XRF analysis of sample I05-54. The  $P$ - $T$  pseudosection



1 was calculated using THERMOCALC v3.31i (Powell and Holland, 1988). The K<sub>2</sub>O-  
2 FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O (KFMASH) including the minerals garnet (g) (Holland  
3 and Powell, 1998), orthopyroxene (opx) (Powell and Holland, 1999), cordierite (cd)  
4 (Holland and Powell, 1998), spinel (sp), aluminosilicate (and/ky/sill), biotite (bi)  
5 (White et al., 2007), K-feldspar (ksp), quartz (q), sapphirine (sa) (Kelsey et al., 2004;  
6 White et al., 2001), osumilite (osm) (Holland et al., 1996), corundum (crn), silicate  
7 liquid (liq) (White et al., 2007) and H<sub>2</sub>O-fluid the pseudosection was calculated using  
8 the 5.5s update to enable the incorporation of sapphirine into the model (Kelsey et al.,  
9 2004).

10

11 The pseudosection shown in Figure 8b constrains the peak conditions experienced at  
12 this time from the symplectite assemblage cordierite-sapphirine-spinel-garnet-  
13 sillimanite-melt that are ~ 7.5 kbar and 920 °C (Fig. 7b). The reheating is consistent  
14 with the growth of a second stage of inclusion-free garnet and subsequent  
15 decompression to form the cordierite-sapphirine-spinel symplectites and the related  
16 growth of monazite. The presence of the negative Eu anomaly displayed by the  
17 monazite is consistent with growth from a partially melted rock, the Eu being  
18 removed from the bulk rock composition via the removal of plagioclase, during high-  
19 grade metamorphism (e.g. Buick et al., 2006; Rubatto et al., 2006).

20

### 21 *A regional tectonic scenario*

22 The mineral parageneses outlined above describes an initial prograde evolution that  
23 generated the gedrite-sillimanite-quartz-garnet assemblage, which was followed by a  
24 period of cooling, garnet resorption, and kyanite and zircon growth at ~535 Ma. A

1 subsequent episode of heating (second stage garnet growth), followed by  
2 decompression (symplectite formation and monazite growth) occurred at ~525 Ma.  
3  
4 This sequence of events is consistent with the initial thickening of a hot crust (Fig. 9a)  
5 that is then subsequently cooled towards a normal geotherm (Fig. 9b). Cooling is then  
6 followed by crustal thickening and an up-pressure evolution (Fig. 9c). A second  
7 thermal pulse, approximately 10 Ma later, heats the crust to ~920 °C and is associated  
8 with decompression (Fig. 9d). We interpret this second heating/decompression pulse  
9 to be due to delamination of the sub-continental lithospheric mantle after continental  
10 collision. This is consistent with reflection seismic images that show a shallowing in  
11 Moho depth beneath the PCSS (Rajendra-Prasad et al. 2006).

12 Such a scenario of repeated pulsative heating and cooling related to extensional and  
13 contractional events on a subduction margin (tectonic switching) has been previously  
14 proposed for the generation of granulite terranes on an evolving collisional continental  
15 margin (Collins, 2002a; Collins, 2002b) in both ancient (Lachlan and New England  
16 Orogens, Australia) and modern (Taupo Volcanic Zone, New Zealand) settings. In this  
17 scenario, transient rollback of a subducting slab induces extension in the overriding  
18 plate and the formation of back-arc basins and the production and emplacement of  
19 basaltic magmas via advection from the decompressed asthenosphere resulting in  
20 thermally anomalous crustal conditions. The arrival of more buoyant oceanic plateaus  
21 induces a period of flat subduction that drives compression focussed into the  
22 thermally softened back arc and the formation of a narrow hot orogenic belt (Collins,  
23 2002a). A back-arc setting for metamorphism associated with the PCSS is consistent  
24 with recent observations made by Brown (2006; 2007) who suggests that Ediacaran-  
25 Cambrian (Pan-African) mobile belts show similarities to inverted, thickened back-arc

1 basins. With the high heat flow at these sites (Hyndman et al., 2005) being able to  
2 account for the generation of the observed UHT mineral assemblages in the inverted  
3 and eroded back-arc settings.

4

5 The tectonic switching model of Collins (2002a) is consistent with a number of first  
6 order observations about the setting of the PCSS: 1) The PCSS is situated close to the  
7 continental margin during the Neoproterozoic amalgamation of Gondwana (Collins  
8 and Pisarevsky, 2005); 2) there is a two stage heating process; the first of which is  
9 associated with crustal thickening and is separated from the second by a stage of  
10 cooling, the second thermal pulse being related to delamination of the lithospheric  
11 mantle and upwelling asthenosphere; 3) The rate of this change in subduction style in  
12 eastern Australia has been proposed to be in the order of ~10 Ma, this is consistent  
13 with the age data of the cooling and reheating events presented in this paper. Previous  
14 workers have interpreted the PCSS as a suture zone between Neoproterozoic India  
15 and Azania (Collins et al., 2007b; Shimpou et al., 2006; Santosh et al., 2009). We  
16 concur that the PCSS was proximal to an Ediacaran-Cambrian active margin, but  
17 suggest that data presented here are consistent with the Panangad being the northern  
18 part of the Madurai Block (Fig. 1)—a part of the Neoproterozoic continent Azania—  
19 to the present day south of the proposed suture zone within a continental back-arc  
20 setting.

21

22 **Summary**

23 The coupled accessory phase, major silicate mineral parageneses, trace element  
24 geochemistry, geochronology and *P-T* pseudosections presented in this paper allow a

1 relatively complete *P-T-t* evolution and tectonic setting for the rocks of the PCSS to  
2 be deduced.

3

4 1. HREE data from zircon is consistent with zircon growth during the breakdown  
5 of garnet at between 672-755 °C in the kyanite stability field at  $535.0 \pm 4.9$   
6 Ma.

7

8 2. Monazite growth and symplectite formation occurred at 920 °C and 7.5 kbar,  
9 ~10 Ma after zircon growth and reflects a period of reheating and  
10 decompression related to delamination. The REE chemistry of the monazite is  
11 consistent with the rock having undergone partial melting prior to monazite  
12 growth, thereby altering the bulk rock chemistry.

13

14 3. The periodicity of the heating and cooling cycles (~10 Ma) from this study are  
15 consistent with recently proposed tectonic switching models for the formation  
16 of granulite metamorphism in accretionary/collisional tectonic settings  
17 (Collins, 2002a). The elevated heat flows required to generate the UHT  
18 metamorphism are achievable in the proposed back-arc setting for the  
19 Pannangad locality within the PCSS during Gondwana amalgamation (e.g.  
20 Brown, 2007; Hyndman et al., 2005).

21

1 **References**

- 2 Bartlett J. M., Dougherty-Page J. S., Harris N. B. W., Hawkesworth C. J., Santosh M.,  
3 1998. The application of single zircon evaporation and model Nd ages to the  
4 interpretation of polymetamorphic terrains: an example from the Proterozoic  
5 mobile belt of south India. *Contributions to Mineralogy and Petrology*. 131,  
6 181-195
- 7 Bea F., Montero P., 1999. Behavior of accessory phases and redistribution of Zr,  
8 REE, Y, Th, and U during metamorphism and partial melting of metapelites  
9 in the lower crust: An example from the Kinzigite Formation of Ivrea-  
10 Verbano, NW Italy. *Geochimica et Cosmochimica Acta*. 63, 1133-1153
- 11 Bhaskar Rao Y. J., Chetty T. R. K., Janardhan A. S., Gopalan K., 1996. Sm-Nd and  
12 Rb-Sr ages and P-T history of the Archean Sittampundi and Bhavani layered  
13 meta-anorthosite complexes in Cauvery shear zone, South India: evidence  
14 for Neoproterozoic reworking of Archean crust. *Contributions to Mineralogy  
15 and Petrology*. 125, 237-250
- 16 Bhaskar Rao Y. J., Janardhan A. S., Vijaya Kumar T., Narayana B. L., Dayal A. M.,  
17 Taylor P. N., Chetty T. R. K., 2003. Sm-Nd Model Ages and Rb-Sr Isotopic  
18 Systematics of Charnockites and Gneisses across the Cauvery Shear Zone,  
19 Southern India: Implications for the Archaean - Neoproterozoic Terrane  
20 Boundary in the Southern Granulite Terrain. *Memoir Geological Society of  
21 India*. 50, 297-317
- 22 Boger S. D., Miller J. M., 2004. Terminal suturing of Gondwana and the onset of the  
23 Ross-Delamerian Orogeny: the cause and effect of an Early Cambrian  
24 reconfiguration of plate motions. *Earth and Planetary Science Letters*. 219,  
25 35-48
- 26 Boger S. D., Wilson C. J. L., 2005. Early Cambrian crustal shortening and a  
27 clockwise P-T-t path from the southern Prince Charles Mountains, East  
28 Antarctica: implications for the formation of Gondwana. *Journal of  
29 Metamorphic Geology*. 23, 603-623
- 30 Brown M., 2006. Duality of thermal regimes is the distinctive characteristic of plate  
31 tectonics since the Neoproterozoic. *Geology*. 34, 961-964
- 32 Brown M., 2007. Metamorphic conditions in orogenic belts: A record of secular  
33 change. *International Geology Review*. 49, 193-234

- 1 Buick I. S., Hermann J., Williams I. S., Gibson R. L., Rubatto D., 2006. A SHRIMP  
2 U-Pb and LA-ICP-MS trace element study of the petrogenesis of garnet-  
3 cordierite-orthoamphibole gneisses from the Central Zone of the Limpopo  
4 Belt, South Africa. *Lithos.* 88, 150-172
- 5 Chetty T. R. K., Bhaskar Rao Y. J., 2006. The Cauvery Shear Zone, Southern  
6 Granulite Terrain, India: A crustal-scale flower structure. *Gondwana  
7 Research.* 10, 77-85
- 8 Chetty T. R. K., Bhaskar Rao Y. J., Narayana B. L., 2003. A Structural cross section  
9 along Krishnagiri-Palani Corridor, Southern Granulite Terrain of India.  
10 *Memoir Geological Society of India.* 50, 255-277
- 11 Clark, C., Collins, A.S., Kinny, P.D., Timms, N.E., Chetty, T.R.K., 2008 SHRIMP U-  
12 Pb age constraints on the age of charnockite magmatism and metamorphism  
13 in the Salem Block, southern India. *Gondwana Research.* doi:  
14 10.1016/j.gr.2008.11.001
- 15 Clark, C., Hand, M., Kelsey, D.E., Goscombe, B., 2007. Linking crustal reworking to  
16 terrane accretion. *Journal of the Geological Society, London.* 164, 937-940
- 17 Collins A. S., 2006. Madagascar and the amalgamation of Central Gondwana.  
18 *Gondwana Research.* 9, 3-16
- 19 Collins, A.S., Santosh, M., Braun, I., Clark, C., 2007a. Age and sedimentary  
20 provenance of the Southern Granulites, South India. U-Th-Pb SHRIMP  
21 secondary ion mass spectrometry. *Precambrian Research.* 155, 125-138.
- 22 Collins A. S., Clark C., Sajeev K., Santosh M., Kelsey D. E., Hand M., 2007b.  
23 Passage through India: the Mozambique Ocean suture, high-pressure  
24 granulites and the Palghat-Cauvery shear zone system. *Terra Nova.* 19, 141-  
25 147
- 26 Collins A. S., Pisarevsky S. A., 2005. Amalgamating eastern Gondwana: The  
27 evolution of the Circum-Indian Orogens. *Earth-Science Reviews.* 71, 229-  
28 270
- 29 Collins A. S., Windley B. F., 2002. The tectonic evolution of central and northern  
30 Madagascar and its place in the final assembly of Gondwana. *Journal of  
31 Geology.* 110, 325-339
- 32 Collins W. J., 2002a. Hot orogens, tectonic switching, and creation of continental  
33 crust. *Geology.* 30, 535-538
- 34 Collins W. J., 2002b. Nature of extensional accretionary orogens. *Tectonics.* 21,

- 1 Corfu F., Hanchar J. M., Hoskin P. W. O., Kinny P. D., 2003. Atlas of zircon textures.  
2 In: Hanchar J. M., Hoskin P. W. O. (eds) Zircon, vol 53. Mineralogical  
3 Society of America, Reviews in Mineralogy and Geochemistry, Washington,  
4 D.C., pp 468-500
- 5 Degeling H., Eggins S., Ellis D. J., 2001. Zr budgets for metamorphic reactions, and  
6 the formation of zircon from garnet breakdown. *Mineralogical Magazine*. 65,  
7 749-758
- 8 Diener J. F. A., Powell R., White R. W., Holland T. J. B., 2007. A new  
9 thermodynamic model for clino- and orthoamphiboles in the system Na<sub>2</sub>O-  
10 CaO-FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O-O. *Journal of Metamorphic Geology*. 25,  
11 631-656
- 12 Drury S. A., Harris N. B. W., Holt R. W., Reeves-Smith G. W., Wightman R. T.,  
13 1984. Precambrian tectonics and crustal evolution in south India. *Journal of*  
14 *Geology*. 92, 1-20

- 1 Drury S. A., Holt R. W., 1980. The tectonic framework of the south Indian craton: A  
2 reconnaissance involving Landsat imagery. *Tectonophysics*. 65, T1-T15
- 3 Fitzsimons I. C. W., 2000. A Review of tectonic events in the East Antarctic Shield  
4 and their implications for Gondwana and earlier supercontinents. *Journal of*  
5 *African Earth Sciences*. 31, 3-23
- 6 Fraser G., Ellis D., Eggins S., 1997. Zirconium abundance in granulite-facies  
7 minerals, with implications for zircon geochronology in high-grade rocks.  
8 *Geology*. 27, 607-610
- 9 Ghosh J. G., de Wit M. J., Zartman R. E., 2004. Age and tectonic evolution of  
10 Neoproterozoic ductile shear zones in the Southern Granulite Terrain of  
11 India, with implications for Gondwana studies. *Tectonics*. 23,
- 12 Harley S. L., 1998a. On the occurrence and characterization of ultrahigh-temperature  
13 metamorphism. In: Treloar P. J., O'Brien P. J. (eds) *What Drives*  
14 *Metamorphism and Metamorphic Reactions?*, vol 138. Geological Society of  
15 London, pp 81-107
- 16 Harley S. L., 1998b. Ultrahigh temperature granulite metamorphism (1050 degrees C,  
17 12 kbar) and decompression in garnet (Mg70)-orthopyroxene-sillimanite  
18 gneisses from the Rauer Group, East Antarctica. *Journal of Metamorphic*  
19 *Geology*. 16, 541-562
- 20 Harley S. L., 2004. Extending our understanding of Ultrahigh temperature crustal  
21 metamorphism. *Journal of Mineralogical and Petrological Sciences*. 99, 140-  
22 158
- 23 Harley S. L., Kelly N. M., 2007. The impact of zircon-garnet REE distribution data on  
24 the interpretation of zircon U-Pb ages in complex high-grade terrains: An  
25 example from the Rauer Islands, East Antarctica. *Chemical Geology*. 241,  
26 62-87
- 27 Harley S. L., Kelly N. M., Moller A., 2007. Zircon behaviour and the thermal  
28 histories of mountain chains. *Elements*. 3, 25-30
- 29 Harris N. B. W., Santosh M., Taylor P. N., 1994b. Crustal Evolution in South India:  
30 Constraints from Nd Isotopes. *The Journal of Geology*. 102, 139-150
- 31 Hermann J., Rubatto D., 2003. Relating zircon and monazite domains to garnet  
32 growth zones: age and duration of granulite facies metamorphism in the Val  
33 Malenco lower crust. *Journal of Metamorphic Geology*. 21, 833-852



- 1 Holland T. J. B., Babu E., Waters D. J., 1996. Phase relations of osumilite and  
2 dehydration melting in pelitic rocks: A simple thermodynamic model for the  
3 KFMASH system. *Contributions to Mineralogy and Petrology*. 124, 383-394
- 4 Holland T. J. B., Powell R., 1998. An internally consistent thermodynamic data set for  
5 phases of petrological interest. *Journal of Metamorphic Geology*. 16, 309-  
6 343
- 7 Hoskin P. W. O., Schaltegger U., 2003. The composition of zircon and igneous and  
8 metamorphic petrogenesis. In: Hancher J. M., Hoskin P. W. O. (eds) *Zircon*,  
9 vol. Mineralogical Society of America, *Reviews in Mineralogy &*  
10 *Geochemistry*, Volume 53, Washington, D.C., pp 27-62
- 11 Hyndman R. D., Currie C. A., Mazzotti S., 2005. Subduction zone backarcs, mobile  
12 belts, and orogenic heat. *GSA Today*. 15, 4-10
- 13 Kanazawa, T., Tsunogae, T., Sato, K. & Santosh, M. 2009. The stability and origin of  
14 sodicgedrite in ultrahigh-temperature Mg-Al granulites: a case study from the  
15 Gondwana suture in southern India. *Contributions to Mineralogy and*  
16 *Petrology*. 157, 95-110.
- 17 Kelly N. M., Harley S. L., 2005. An integrated microtextural and chemical approach  
18 to zircon geochronology: refining the Archaean history of the Napier  
19 Complex, east Antarctica. *Contributions to Mineralogy and Petrology*. 149,  
20 57-84
- 21 Kelsey, D.E., Clark, C., Hand, M., 2008. Thermobarometric modeling of zircon and  
22 monazite growth in melt bearing systems. *Journal of Metamorphic Geology*.  
23 26, 199-212.

- 1 Kelsey D. E., Clark C., Hand M., Collins A. S., 2006. Comment on "First report of  
2 garnet-corundum rocks from southern India: Implications for prograde high-  
3 pressure (eclogite-facies?) metamorphism". *Earth and Planetary Science*  
4 *Letters*. 249, 529-534.
- 5 Kelsey D. E., Hand M., Clark C., Wilson C. J. L., 2007. On the application of in situ  
6 monazite chemical geochronology to constraining P-T-t histories in high-  
7 temperature (> 850 degrees C polymetamorphic granulites from Prydz Bay,  
8 East Antarctica. *Journal of the Geological Society*. 164, 667-683.
- 9 Kelsey D. E., White R. W., Holland T. J. B., Powell R., 2004. Calculated phase  
10 equilibria in  $K_2O$ - $FeO$ - $MgO$ - $Al_2O_3$ - $SiO_2$ - $H_2O$  for sapphirine-quartz-bearing  
11 mineral assemblages. *Journal of Metamorphic Geology*. 22, 559-578.
- 12 Koshimoto S., Tsunogae T., Santosh M., 2004. Sapphirine and corundum bearing  
13 ultrahigh temperature rocks from the Palghat-Cauvery Shear System,  
14 southern India. *Journal of Mineralogical and Petrological Sciences*. 99, 298-  
15 310.
- 16 Li Z. X., Bogdanova S. V., Collins A. S., Davidson A., De Waele B., Ernst R. E.,  
17 Fitzsimons I. C. W., Fuck R. A., Gladkochub D. P., Jacobs J., Karlstrom K.  
18 E., Lu S., Natapov L. M., Pease V., Pisarevsky S. A., Thrane K.,  
19 Vernikovsky V., In Press. Assembly, configuration, and break-up history of  
20 Rodinia: A synthesis. *Precambrian Research*. 160, 179-210.
- 21 Meert J. G., 2003. A synopsis of events related to the assembly of eastern Gondwana.  
22 *Tectonophysics*. 362, 1-40
- 23 Meert J. G., Van der Voo R., 1997. The Assembly of Gondwana 800-550 Ma. *Journal*  
24 *of Geodynamics*. 23, 223-235
- 25 Meissner B., Deters P., Srikantappa C., Kohler H., 2002. Geochronological evolution  
26 of the Moyar, Bhavani and Palghat shear zones of southern India:  
27 implications for east Gondwana correlations. *Precambrian Research*. 114,  
28 149-175
- 29 Nagy G., Draganits E., Demeny A., Panto G., Arkai P., 2002. Genesis and  
30 transformations of monazite, florencite and rhabdophane during medium  
31 grade metamorphism: examples from the Sopron Hills, Eastern Alps.  
32 *Chemical Geology*. 191, 25-46
- 33 Payne, J., Hand M., Barovich K., Wade B. P., 2008. Temporal constraints on the  
34 timing of high-grade metamorphism in the northern Gawler Craton:

- 1           implications for assembly of the Australian Proterozoic. *Australian Journal*  
2           of Earth Sciences. 55, 623-640.
- 3   Pearce N. J. G., Perkins W. T., Westgate J. A., Gorton M. P., Jackson S. E., Neal C.  
4           R., Chenery S. P., 1997. A compilation of new and published major and  
5           trace element data for NIST SRM 610 and NIST SRM 612 glass reference  
6           materials. *Geostandards Newsletter-the Journal of Geostandards and*  
7           *Geoanalysis*. 21, 115-144
- 8   Powell R., Holland T. J. B., 1988. An internally consistent thermodynamic dataset  
9           with uncertainties and correlations: 3. Applications to geobarometry, worked  
10          examples and a computer program. *J. Metamorphic Geol.* 6, 173-204
- 11   Powell R., Holland T. J. B., 1999. Relating formulations of the thermodynamics of  
12          mineral solid solutions: activity modelling of pyroxenes, amphiboles and  
13          micas. *American Mineralogist*. 84,
- 14   Reeves C., de Wit M. J., 2000. Making ends meet in Gondwana: retracing the  
15          transforms of the Indian Ocean and reconnecting continental shear zones.  
16          *Terra Nova*. 12, 272-280
- 17   Roberts M. P., Finger F., 1997. Do U-Pb zircon ages from granulites reflect peak  
18          metamorphic conditions? *Geology*. 25, 319-322
- 19   Rubatto D., 2002. Zircon trace element geochemistry: partitioning with garnet and the  
20          link between U-Pb ages and metamorphism. *Chemical Geology*. 184, 123-  
21          138
- 22   Rubatto D., Hermann J., 2003. Zircon formation during fluid circulation in eclogites  
23          (Monviso, Western Alps): Implications for Zr and Hf budget in subduction  
24          zones. *Geochimica et Cosmochimica Acta*. 67, 2173-2187
- 25   Rubatto D., Hermann J., 2007. Experimental zircon/melt and zircon/garnet trace  
26          element partitioning and implications for the geochronology of crustal rocks.  
27          *Chemical Geology*. 241, 38-61
- 28   Rubatto D., Hermann J., Buick I. S., 2006. Temperature and bulk composition control  
29          on the growth of monazite and zircon during low-pressure anatexis (Mount  
30          Stafford, central Australia). *Journal of Petrology*. 47, 1973-1996
- 31   Rubatto D., Williams I. S., Buick I. S., 2001. Zircon and monazite response to  
32          prograde metamorphism in the Reynolds Range, central Australia.  
33          *Contributions to Mineralogy and Petrology*. 140, 458-468.

- 1 Santosh, M., Maruyama, S. & Sato, K. 2009. Anatomy of a Cambrian suture in  
2 Gondwana: Pacific type orogeny in southern India? *Gondwana Research* doi:  
3 10.1016/j.gr.2008.12.012.
- 4 Santosh M., Sajeew K., 2006. Anticlockwise evolution of ultrahigh-temperature  
5 granulites within continental collision zone in southern India. *Lithos.* 92,  
6 447-464
- 7 Santosh M., Tanaka K., Yokoyama K., Collins A. S., 2005. Late Neoproterozoic-  
8 Cambrian felsic magmatism along transcrustal shear zones in southern India:  
9 U-Pb electron microprobe ages and implications for the amalgamation of the  
10 Gondwana supercontinent. *Gondwana Research.* 8, 31-42
- 11 Santosh M., Tsunogae T., Koshimoto S., 2004. First report of sapphirine-bearing  
12 rocks from the Palghat-Cauvery Shear Zone System, southern India.  
13 *Gondwana Research.* 7, 620-626
- 14 Santosh M., Yokoyama K., Biju-Sekhar S., Rogers J. J. W., 2003. Multiple  
15 tectonothermal events in the granulite blocks of southern India revealed from  
16 EPMA dating: implications on the history of supercontinents. *Gondwana  
17 Research.* 6, 29-63
- 18 Schulz B., Klemd R., Bratz H., 2006. Host rock compositional controls on zircon  
19 trace element signatures in metabasites from the Austroalpine basement.  
20 *Geochimica Et Cosmochimica Acta.* 70, 697-710
- 21 Shaju K. M., Yoshida M., Santosh M., 1998. Shear Zones of Southern India:  
22 Implications for the Proterozoic Tectonics of East Gondwana. *Gondwana  
23 Research.* 1, 420-421
- 24 Shimpo M., Tsunogae T., Santosh M., 2006. First report of garnet-corundum rocks  
25 from southern India: Implications for prograde high-pressure (eclogite-  
26 facies?) metamorphism. *Earth and Planetary Science Letters.* 242, 111-129
- 27 Tomkins H. S., Williams I. S., Ellis D. J., 2005. In situ U-Pb dating of zircon formed  
28 from retrograde garnet breakdown during decompression in Rogaland, SW  
29 Norway. *Journal of Metamorphic Geology.* 23, 201-215
- 30 Tomson J. K., Bhaskar Rao Y. J., Vijaya Kumar T., Mallikharjuna Rao J., 2006.  
31 Charnockite genesis across the Archaean-Proterozoic terrane boundary in the  
32 South Indian Granulite Terrain: Constraints from major-trace element  
33 geochemistry and Sr-Nd isotopic systematics. *Gondwana Research.* 10, 115-  
34 127

- 1 Tsunogae T., Santosh M., 2006. Reply to Comment on "First report of garnet-  
2 corundum rocks from southern India: Implications for prograde high-  
3 pressure (eclogite-facies?) metamorphism" by D.E. Kelsey, C. Clark, M.  
4 Hand, A.S. Collins. *Earth and Planetary Science Letters*. 249, 535-540
- 5 Van Achterbergh E., Ryan C. G., Jackson S. E., Griffin W. L., 2001. Data reduction  
6 software for LA-ICP-MS. In: Sylvester Paul J. (ed) *Laser-ablation-ICPMS in  
7 the earth sciences; principles and applications.*, vol. Mineralogical  
8 Association of Canada. Ottawa, ON, Canada. 2001.,
- 9 Watson E. B., Harrison T. M., 2005. Zircon thermometer reveals minimum melting  
10 conditions on earliest Earth. *Science*. 308, 841-844
- 11 Watson E. B., Wark D. A., Thomas J. B., 2006. Crystallization thermometers for  
12 zircon and rutile. *Contributions to Mineralogy and Petrology*. 151, 413-433
- 13 White R. W., Powell R., 2002. Melt loss and the preservation of granulite facies  
14 mineral assemblages. *Journal of Metamorphic Geology*. 20, 621-632
- 15 White R. W., Powell R., Clarke G. L., 2002. The interpretation of reaction textures in  
16 Fe-rich metapelitic granulites of the Musgrave Block, central Australia:  
17 constraints from mineral equilibria calculations in the system  $K_2O$ -FeO-  
18 MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O-TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>. *Journal of Metamorphic Geology*. 20,  
19 41-55
- 20 White R. W., Powell R., Halpin J. A., 2004. Spatially-focussed melt formation in  
21 aluminous metapelites from Broken Hill, Australia. *Journal of Metamorphic  
22 Geology*. 22, 825-845
- 23 White R. W., Powell R., Holland T. J. B., 2001. Calculation of partial melting  
24 equilibria in the system Na<sub>2</sub>O-CaO-K<sub>2</sub>O-FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O  
25 (NCKFMASH). *Journal of Metamorphic Geology*. 19, 139-153
- 26 White R. W., Powell R., Holland T. J. B., 2007. Progress relating to calculation of  
27 partial melting equilibria for metapelite. *Journal of Metamorphic Geology*.  
28 25, 511-527
- 29 White R. W., Powell R., Holland T. J. B., Worley B., 2000. The effect of TiO<sub>2</sub> and  
30 Fe<sub>2</sub>O<sub>3</sub> on metapelitic assemblages at greenschist and amphibolite facies  
31 conditions: mineral equilibria calculations in the system  $K_2O$ -FeO-MgO-  
32 Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O-TiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>. *Journal of Metamorphic Geology*. 18, 497-  
33 511

- 1 Whitehouse M. J., Platt J. P., 2003. Dating high-grade metamorphism - constraints  
2 from rare-earth elements in zircon and garnet. *Contributions to Mineralogy  
3 and Petrology*. 145, 61-74
- 4 Williams I. S., Claesson S., 1987. Isotopic evidence for the Precambrian provenance  
5 and Caledonian metamorphism of high grade paragneisses from the Seve  
6 Nappes, Scandinavian Caledonides. *Contributions to Mineralogy and  
7 Petrology*. 97, 205-217
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- 9

1                   **Figure Captions**

2  
3  
4   **Figure 1** – (a) Map of southern Indai showing the various protolith ages and major  
5                   structural features. (b) Enlargement of area in (a) showing the location of  
6                   the Panangad sample area.

7  
8   **Figure 2** – (a) Field photograph of a garnet-kyanite-biotite gneiss with kyanite blades  
9                   aligned in the shear plane. Scale bar has 1 cm increments. (b) Field photo  
10                  of garnet-kyanite-biotite gneiss (1cm increment on scale bar). (c)  
11                  Photomicrograph of garnet separated from biotite by a narrow rim of  
12                  cordierite, and the development of a sapphirine + cordierite symplectite  
13                  between the garnet and coarse grained kyanite. The pits from the LA-  
14                  ICPMS traverse are visible running vertically through the garnet (field of  
15                  view = 8000  $\mu\text{m}$ ) (d) Sapphirine + cordierite and sapphirine +spinel  
16                  symplectites separating kyanite (partially pseudomorphed by sillimanite)  
17                  and garnet. Note the monazite in the symplectite (field of view = 3500  
18                   $\mu\text{m}$ ). (e) Gedrite + sillimanite + quartz inclusion in garnet. (f) Zircon and  
19                  rutile in coarse grained kyanite blades. (g) Sapphirine-cordierite and  
20                  spinel-cordierite symplectites between garnet and kyanite porphyroblasts  
21                  with cordierite separating garnet from sapphirine and spinel. (h) Fine  
22                  grained biotite in cordierite, note the monazite in the reaction texture and  
23                  the zircon in the kyanite. (i) monazite intergrown with a sapphirine-  
24                  cordierite symplectite.

1 **Figure 3** – (a-g) Electron probe maps of garnet with characteristic retrograde zoning  
2 pattern, LA-ICPMS analysis spots marked. Location of the electron  
3 microprobe spot analysis traverse across the garnet shown in part (4a) is  
4 shown on (b).

5  
6 **Figure 4** – major and trace element data for garnet. (a) Electron microprobe spot  
7 analysis traverse across the garnet (b) LA-ICPMS traverse for Lu, Yb and  
8 Y as shown in Fig. 3a. (c) Chondrite normalised rare earth element  
9 patterns for the core, intermediate and rim of the garnet.

10  
11 **Figure 5** – (a-d) CL images of zircons showing main textural features. (e) Wetherill  
12 concordia plot of U-Pb analyses from sample I05-54 (after Collins et al.,  
13 2007). (f) Range of temperatures obtained from Ti in zircon thermometry.  
14 Chondrite normalise REE patterns for (g) older oscillatory zoned cores and  
15 (h) zircon rims and new grown metamorphic zircon.

16  
17 **Figure 6** – (a) BSE images of a selection of analysed monazites showing main  
18 textural features and the location of U-Pb spot analyses. (b) Wetherill  
19 concordia plot of U-Pb monazite data from monazite cores for sample I05-  
20 54. (c) Wetherill concordia plot of U-Pb monazite data from monazite rims  
21 for sample I05-54. (d) Chondrite normalised REE patterns for monazite.

22  
23 **Figure 7** – Comparison of the REE distribution patterns between zircon and garnet in  
24 (a) natural samples and (b) experimental studies. (Rubatto'02 = Rubatto



1 (02); W & P '03=Whitehouse and Platt 2003; Harley UHT '01 = Harley,  
2 2001; RH07 = Rubatto and Hermann, 2007).

3  
4 **Figure 8** – (a) Schematic phase diagram showing possible maximum temperatures  
5 and pressure experienced during the early metamorphic evolution of  
6 sample I05-54. The  $\text{oam} + \text{grt} = \text{crd} + \text{opx}$  FMASH reaction line is from  
7 Diener et al., 2008). (b) Pseudosections calculated for a bulk composition  
8 determined by XRF analysis of sample I05-54. Bulk rock compositions are  
9 in molecular weight percent.

10  
11 **Figure 9** – Cartoon showing the tectonic evolution of the region around the PCSS  
12 from immediately prior to collision of the Dharwar craton at 540 Ma and  
13 final amalgamation at 525 Ma.

1 **Table Captions**

2

3 **Table 1** – Electron microprobe garnet compositions.

4

5 **Table 2** - Spinel, sapphirine gedrite, cordierite, and two generations of biotite electron  
6 microprobe compositions.

7

8 **Table 3** –U-Pb monazite age data from LA-ICPMS.

9

10 **Table 4** – LA-ICPMS garnet trace element compositions.

11

12 **Table 5** – LA-ICPMS zircon trace element compositions and Ti in zircon  
13 thermometry.

14 **Table 6** – LA-ICPMS monazite trace element compositions

15

16

Figure 1

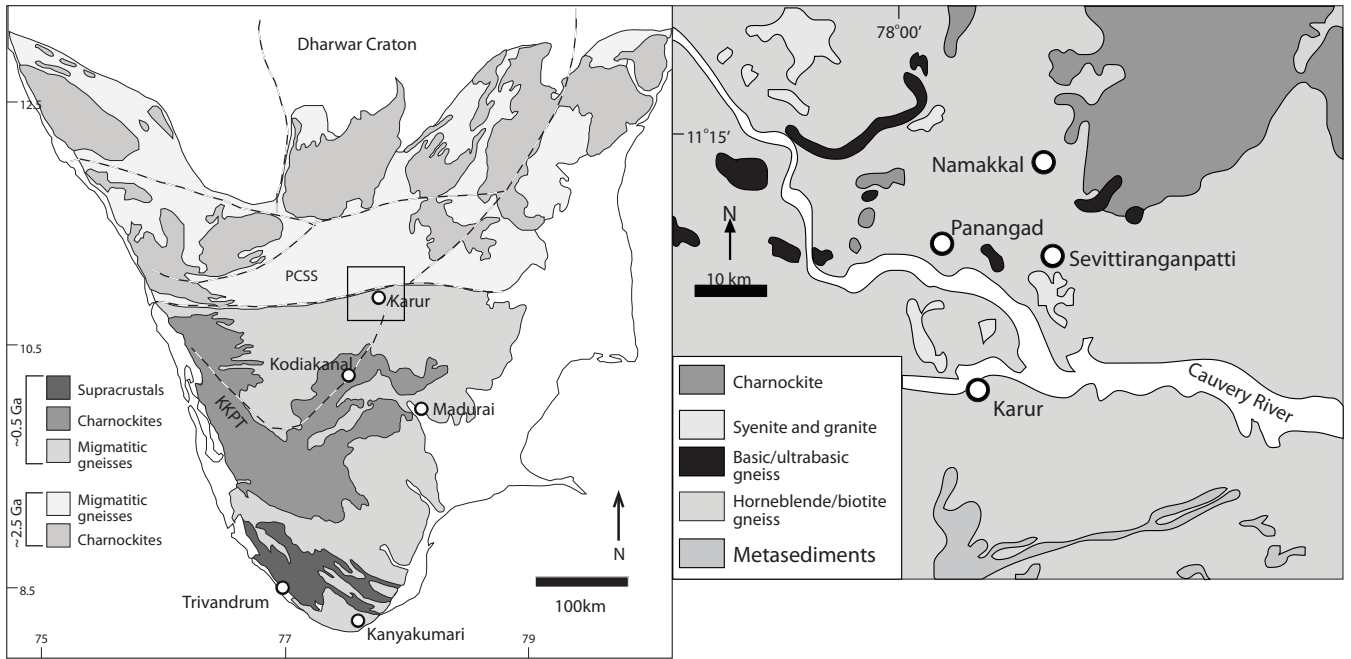
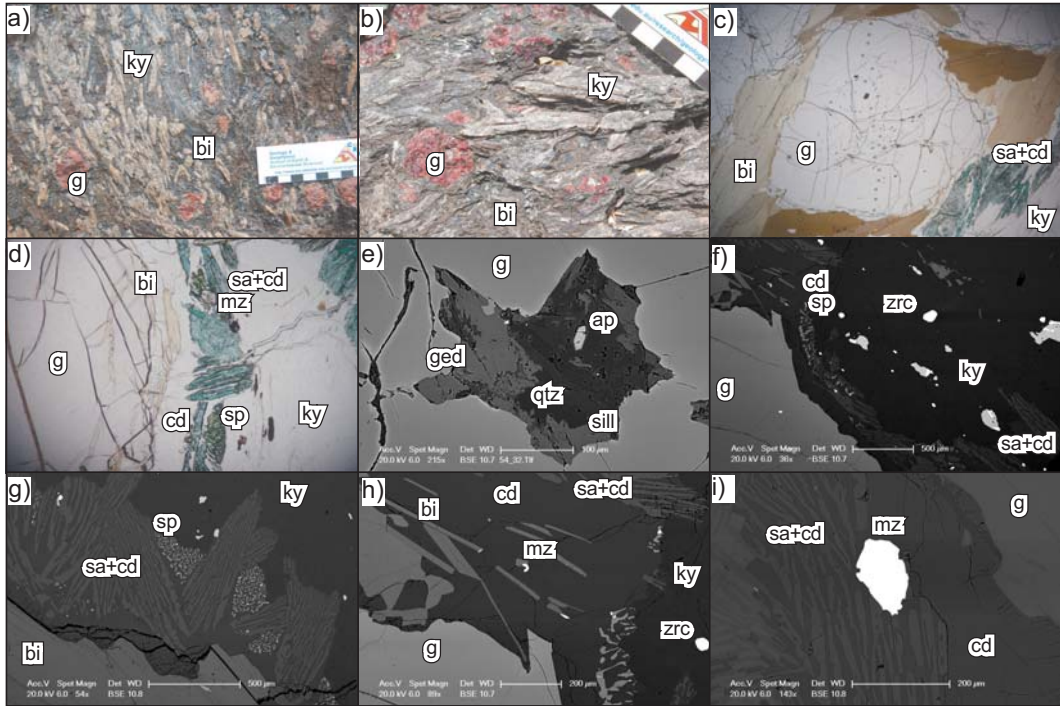
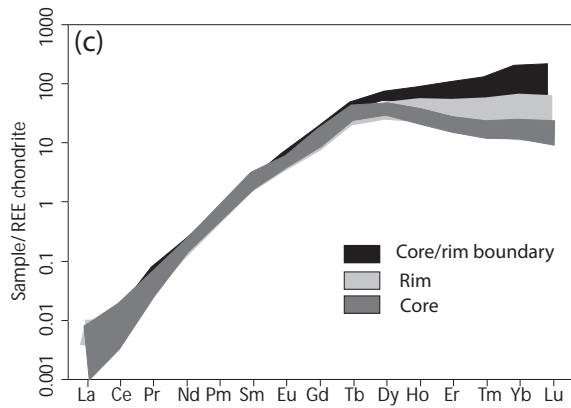
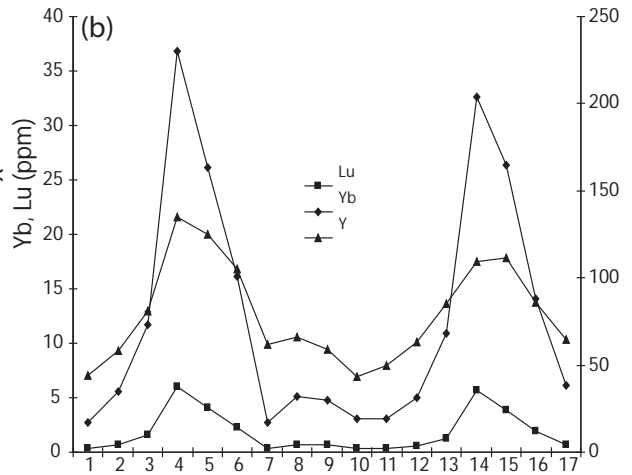
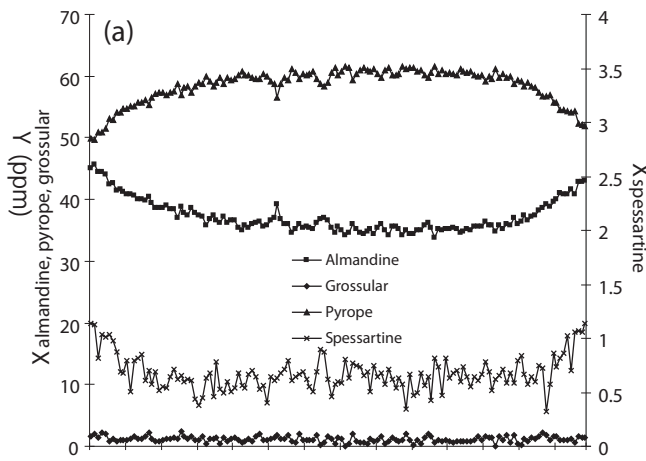


Figure 2



# Figure 3



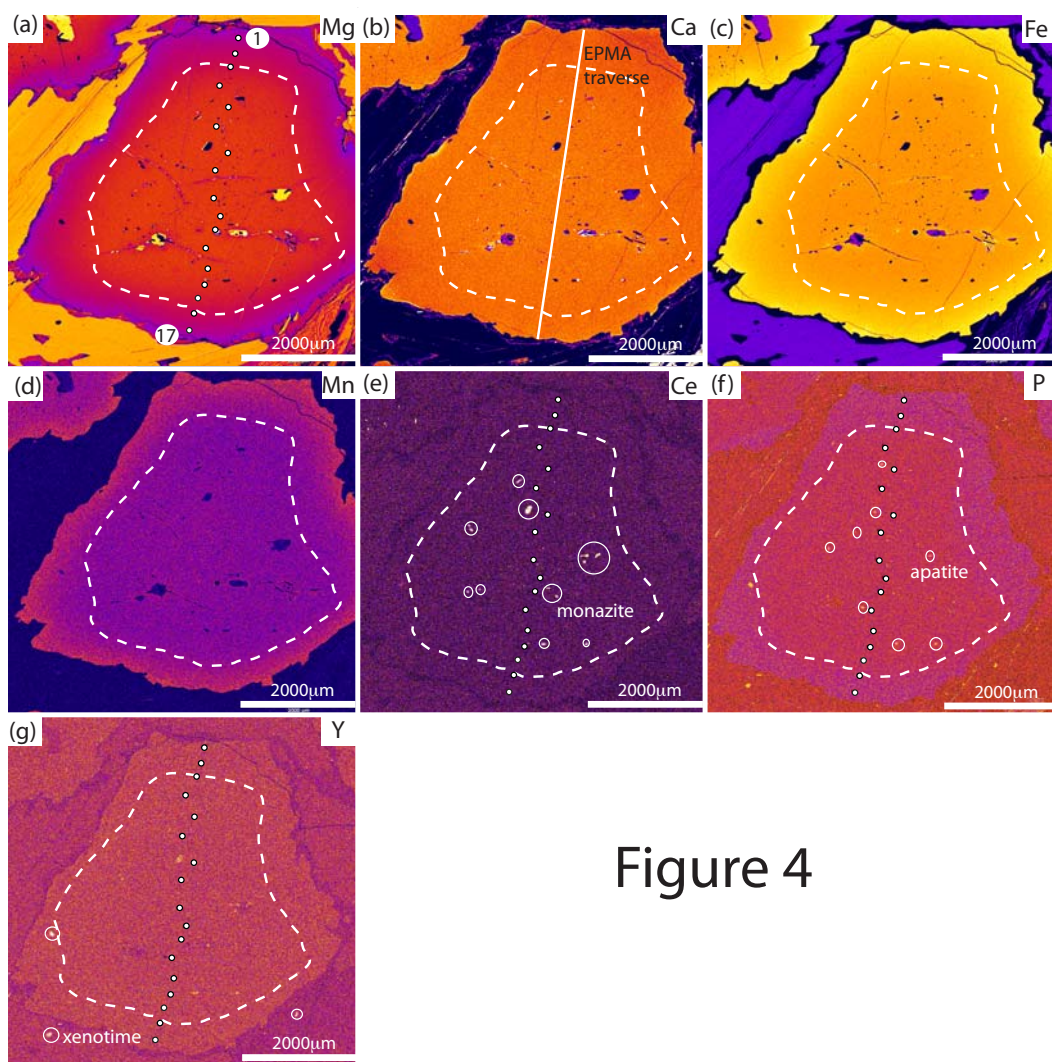


Figure 4

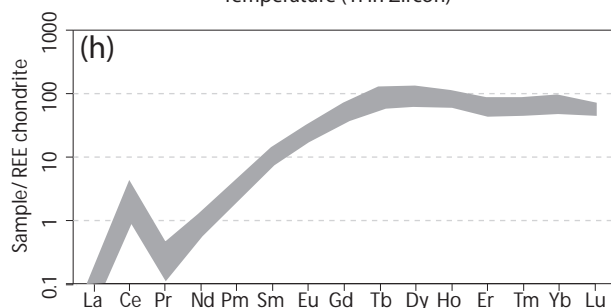
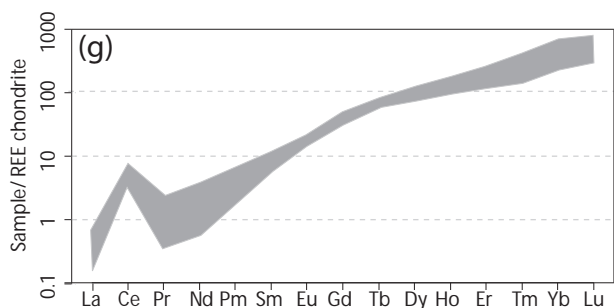
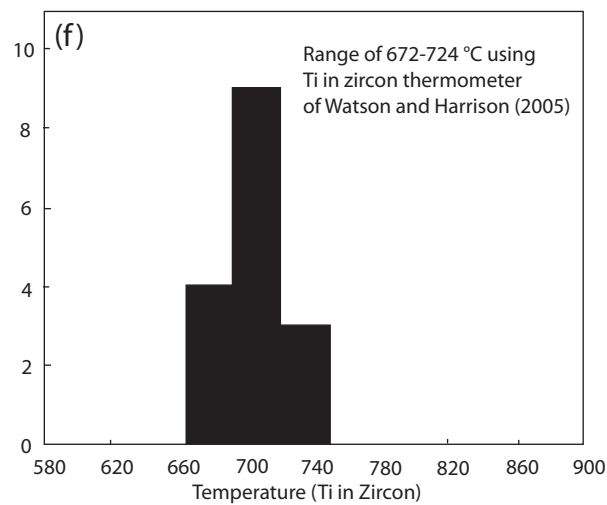
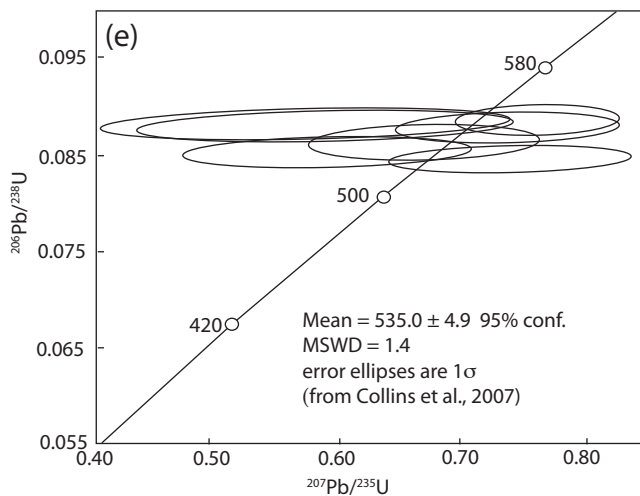
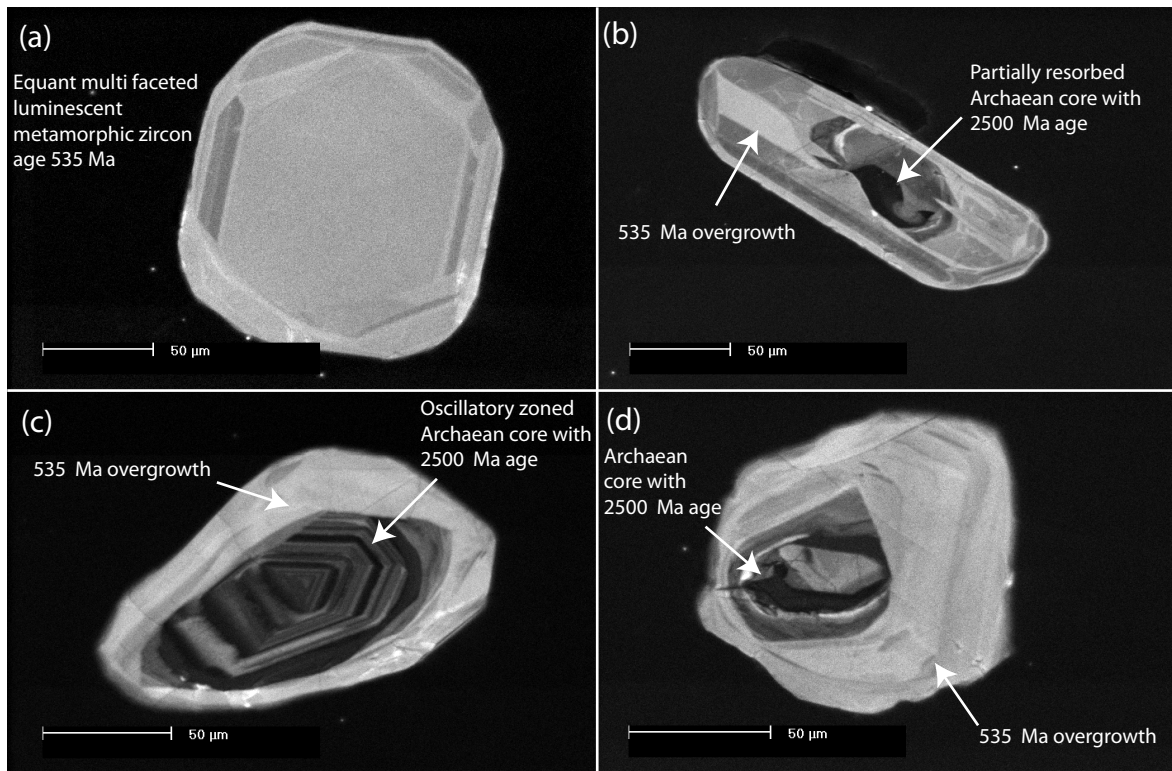


Figure 5



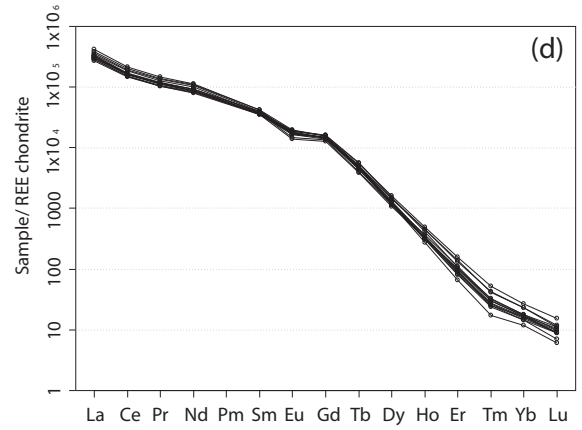
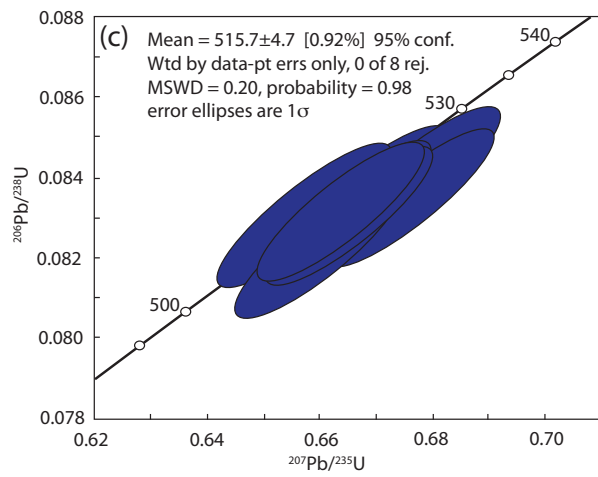
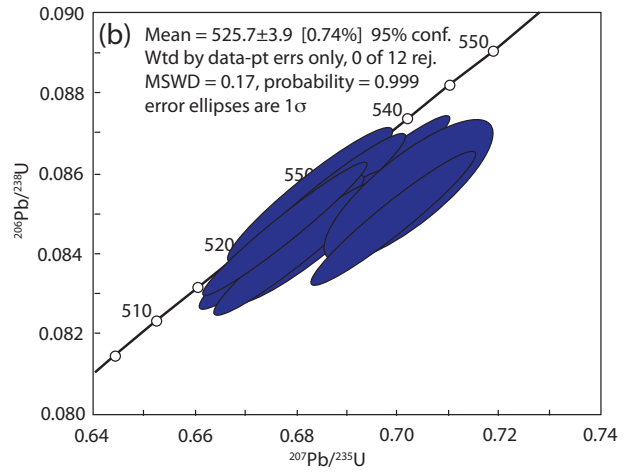
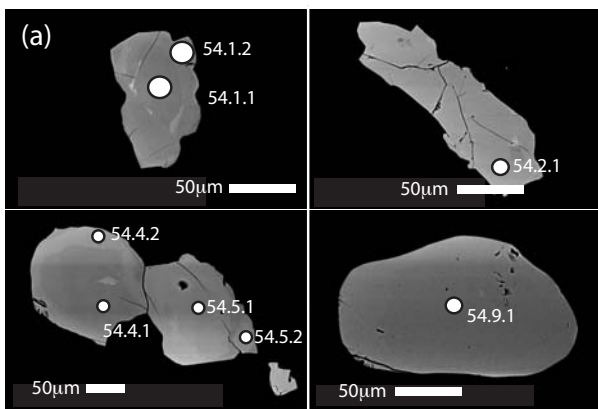


Figure 6



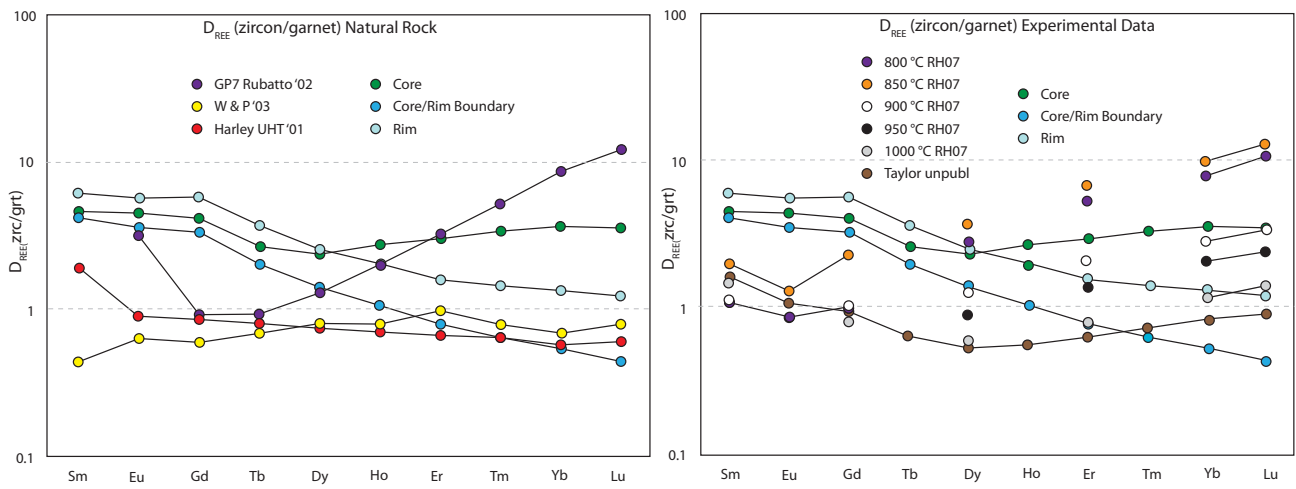


Figure 7

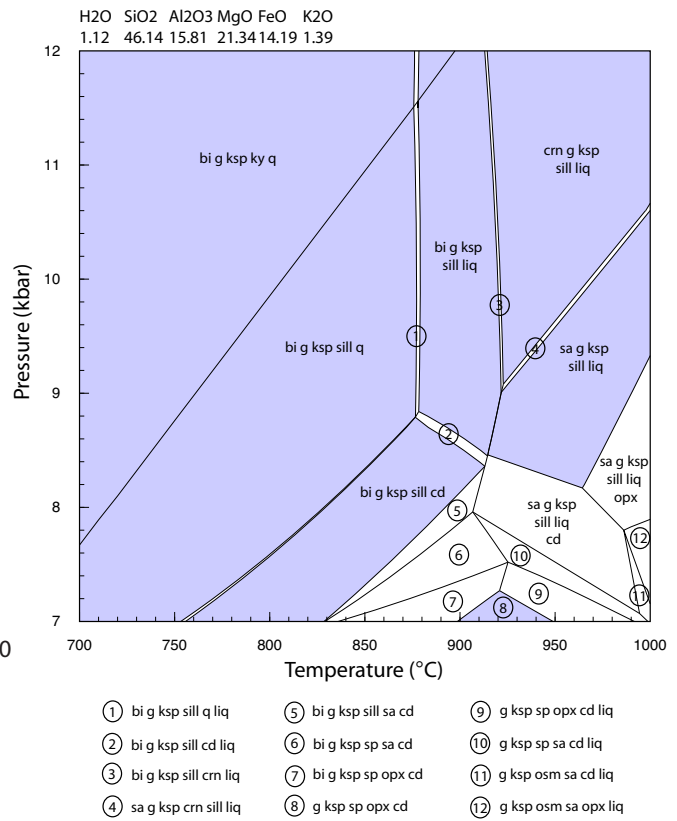
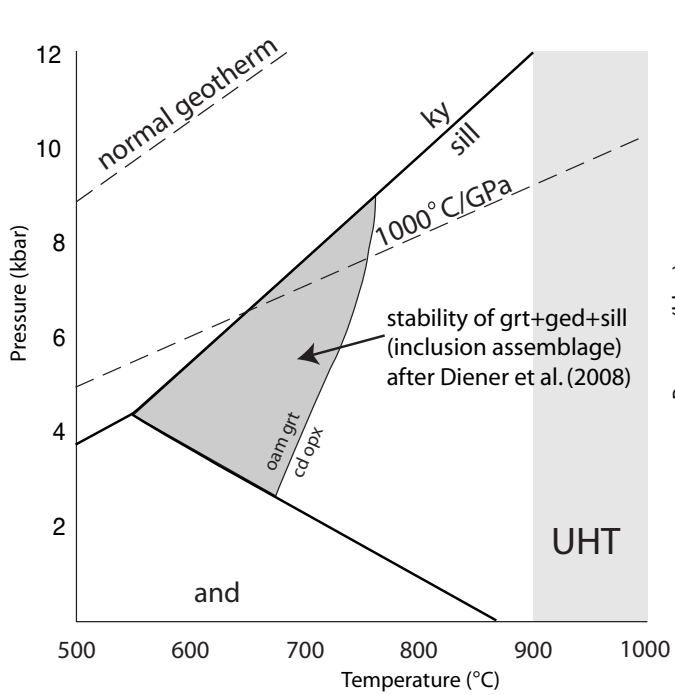
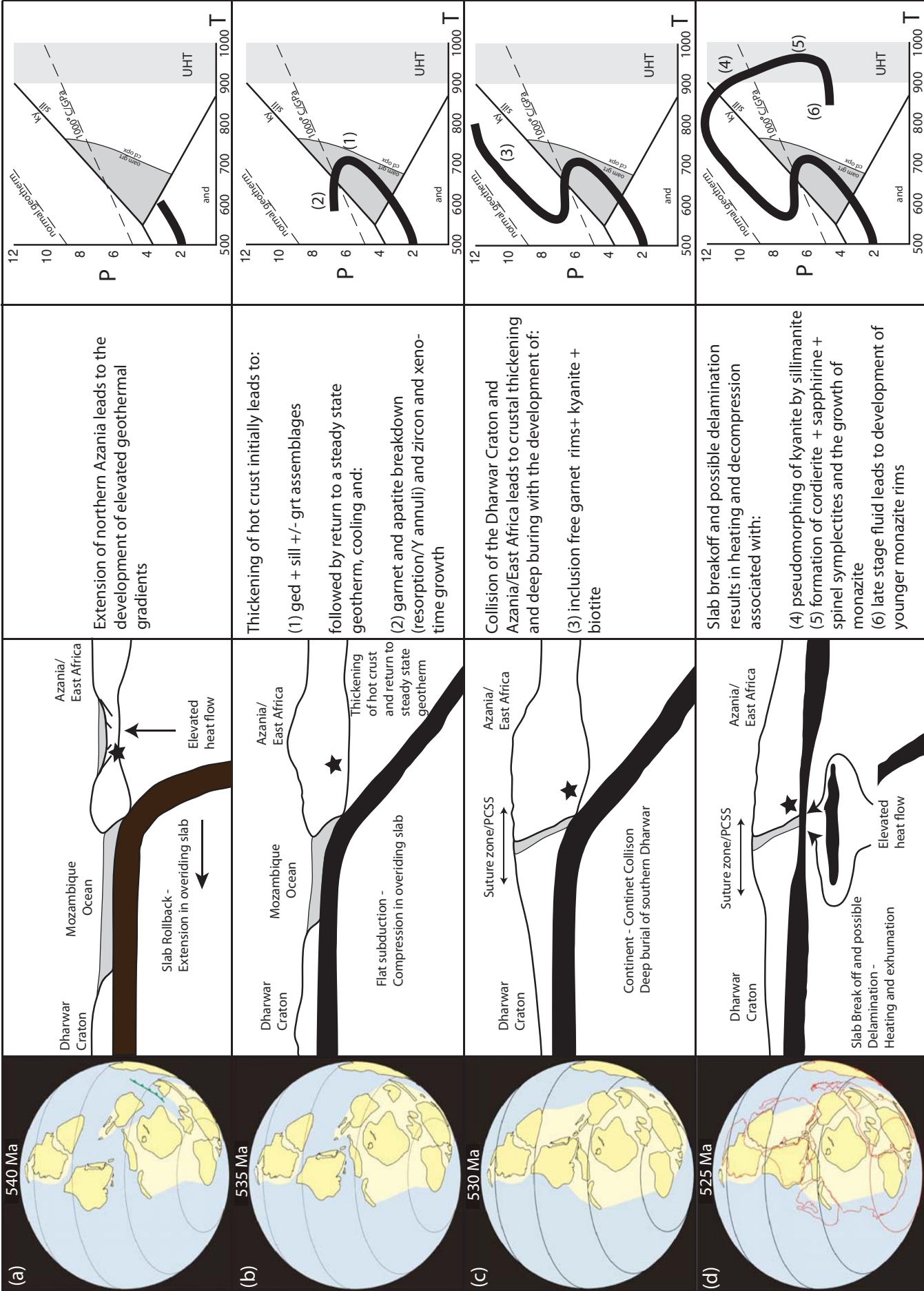
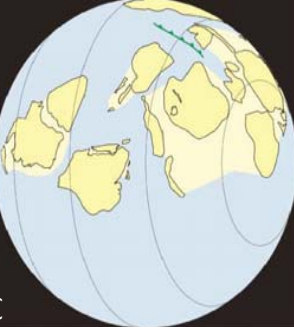


Figure 8

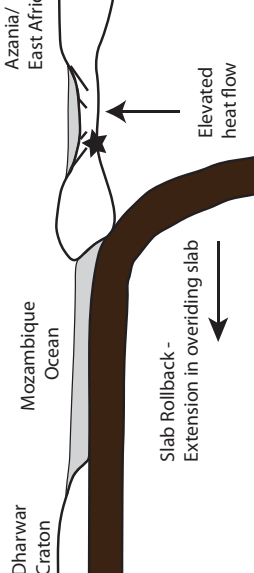


(a)

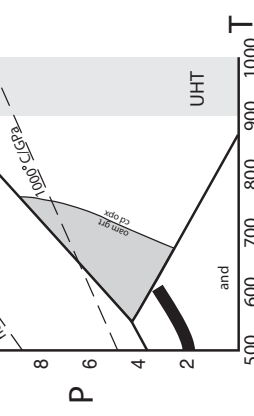
540 Ma



Dharwar Craton, Mozambique Ocean, Azania/East Africa



Extension of northern Azania leads to the development of elevated geothermal gradients

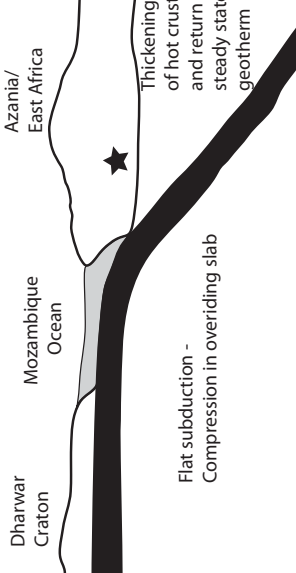


(b)

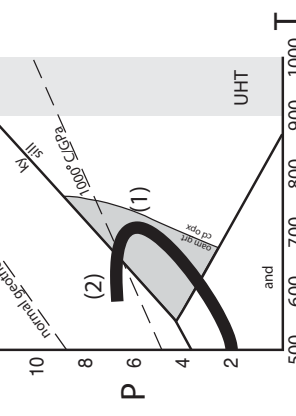
535 Ma



Dharwar Craton, Mozambique Ocean, Azania/East Africa



Thickening of hot crust initially leads to:  
 (1) ged + sill +/- grt assemblages followed by return to a steady state geotherm, cooling and:  
 (2) garnet and apatite breakdown (resorption/Y annuli) and zircon and xenotime growth

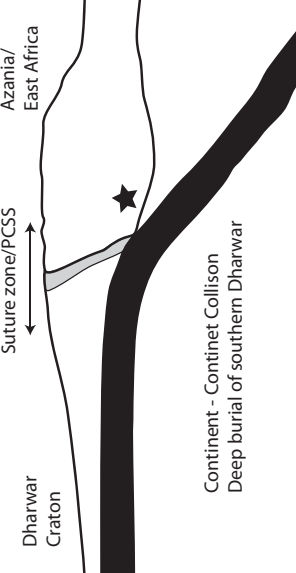


(c)

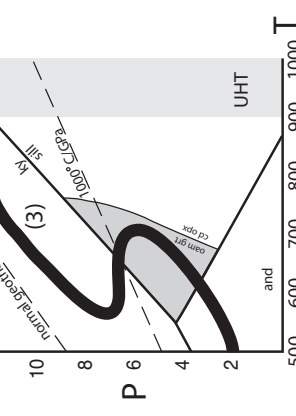
530 Ma



Dharwar Craton, Suture zone/PCSS, Azania/East Africa

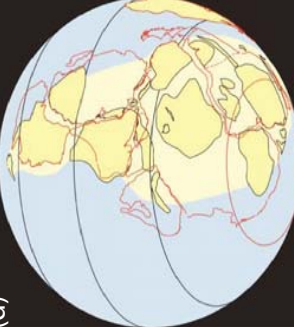


Collision of the Dharwar Craton and Azania/East Africa leads to crustal thickening and deep burying with the development of:  
 (3) inclusion free garnet rims + kyanite + biotite

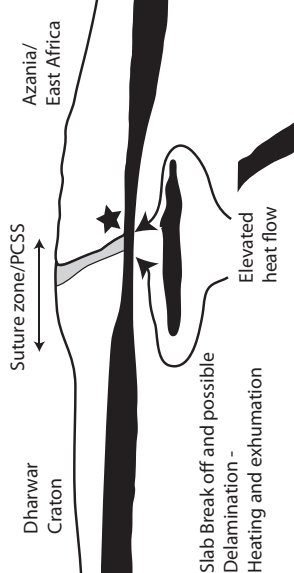


(d)

525 Ma



Dharwar Craton, Suture zone/PCSS, Azania/East Africa



Slab breakoff and possible delamination results in heating and decompression associated with:  
 (4) pseudomorphing of kyanite by sillimanite  
 (5) formation of cordierite + sapphirine + spinel symplectites and the growth of monazite  
 (6) late stage fluid leads to development of younger monazite rims

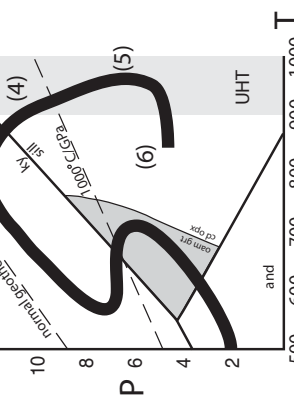


Table 1

TABLE 1: EPMA major element analyses of garnet

|                                | Rim    |        |        |        | Core   |        |        |        | Rim    |        |        |        |
|--------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                                | Gt-6   | Gt-9   | Gt-11  | Gt-13  | Gt-35  | Gt-36  | Gt-37  | Gt-39  | Gt-135 | Gt-136 | Gt-137 | Gt-138 |
| SiO <sub>2</sub>               | 39.54  | 39.42  | 39.48  | 39.81  | 40.17  | 40.04  | 39.80  | 39.94  | 39.70  | 39.31  | 39.86  | 39.77  |
| TiO <sub>2</sub>               | 0.00   | 0.12   | 0.01   | 0.00   | 0.00   | 0.04   | 0.01   | 0.04   | 0.04   | 0.00   | 0.03   | 0.04   |
| Al <sub>2</sub> O <sub>3</sub> | 22.53  | 22.63  | 22.66  | 22.75  | 22.58  | 22.87  | 22.85  | 22.95  | 22.62  | 22.74  | 22.65  | 22.58  |
| Fe <sub>2</sub> O <sub>3</sub> | 0.88   | 0.86   | 0.93   | 0.65   | 0.93   | 0.78   | 1.08   | 0.97   | 0.78   | 1.03   | 0.76   | 0.86   |
| FeO                            | 21.38  | 21.17  | 20.84  | 20.47  | 18.99  | 18.83  | 19.02  | 18.95  | 20.98  | 21.18  | 21.53  | 21.61  |
| MnO                            | 0.48   | 0.32   | 0.37   | 0.37   | 0.22   | 0.37   | 0.25   | 0.28   | 0.33   | 0.49   | 0.50   | 0.50   |
| MgO                            | 14.10  | 14.32  | 14.50  | 14.74  | 15.72  | 15.84  | 15.94  | 15.99  | 14.44  | 14.34  | 14.00  | 13.91  |
| CaO                            | 1.26   | 1.30   | 1.36   | 1.26   | 1.40   | 1.34   | 1.32   | 1.34   | 1.27   | 1.34   | 1.37   | 1.45   |
| Total                          | 100.17 | 100.12 | 100.14 | 100.05 | 100.01 | 100.10 | 100.28 | 100.46 | 100.16 | 100.43 | 100.70 | 100.71 |
| Si                             | 2.96   | 2.94   | 2.94   | 2.96   | 2.97   | 2.96   | 2.94   | 2.94   | 2.96   | 2.93   | 2.96   | 2.96   |
| Al <sup>IV</sup>               | 0.04   | 0.06   | 0.06   | 0.04   | 0.03   | 0.04   | 0.06   | 0.06   | 0.04   | 0.07   | 0.04   | 0.04   |
| Al <sup>VI</sup>               | 1.94   | 1.94   | 1.94   | 1.96   | 1.94   | 1.95   | 1.93   | 1.94   | 1.95   | 1.94   | 1.95   | 1.94   |
| Ti                             | 0.00   | 0.01   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| Fe <sup>3+</sup>               | 0.05   | 0.05   | 0.05   | 0.04   | 0.05   | 0.04   | 0.06   | 0.05   | 0.04   | 0.06   | 0.04   | 0.05   |
| Fe <sup>2+</sup>               | 1.34   | 1.32   | 1.30   | 1.27   | 1.17   | 1.16   | 1.17   | 1.17   | 1.31   | 1.32   | 1.34   | 1.34   |
| Mn                             | 0.03   | 0.02   | 0.02   | 0.02   | 0.01   | 0.02   | 0.02   | 0.02   | 0.02   | 0.03   | 0.03   | 0.03   |
| Mg                             | 1.57   | 1.59   | 1.61   | 1.63   | 1.73   | 1.74   | 1.75   | 1.75   | 1.60   | 1.59   | 1.55   | 1.54   |
| Ca                             | 0.10   | 0.10   | 0.11   | 0.10   | 0.11   | 0.11   | 0.10   | 0.11   | 0.10   | 0.11   | 0.11   | 0.12   |
| Total                          | 8.03   | 8.03   | 8.04   | 8.03   | 8.02   | 8.03   | 8.04   | 8.04   | 8.03   | 8.05   | 8.03   | 8.03   |
| X <sub>Alm</sub>               | 42.41  | 41.64  | 40.78  | 40.63  | 37.47  | 36.68  | 36.21  | 36.14  | 41.67  | 40.92  | 42.88  | 42.90  |
| X <sub>Grs</sub>               | 0.89   | 1.07   | 1.03   | 1.52   | 1.15   | 1.38   | 0.50   | 0.84   | 1.21   | 0.68   | 1.54   | 1.46   |
| X <sub>Pyr</sub>               | 53.15  | 54.15  | 54.74  | 55.20  | 58.32  | 58.97  | 59.70  | 59.67  | 54.21  | 54.39  | 52.36  | 52.14  |
| X <sub>Spss</sub>              | 1.03   | 0.69   | 0.79   | 0.79   | 0.46   | 0.78   | 0.53   | 0.60   | 0.70   | 1.05   | 1.07   | 1.06   |

Table 2

TABLE 2: EPMA major element analyses of spinel, sapphirine, gedrite, cordierite and biotite

|                                | Spinel |       |       | Sapphirine |        |        | Gedrite |       |       | Cordierite |       |       | Biotite (coarse) |       |       | Biotite (fine) |       |       |
|--------------------------------|--------|-------|-------|------------|--------|--------|---------|-------|-------|------------|-------|-------|------------------|-------|-------|----------------|-------|-------|
| SiO <sub>2</sub>               | 0.12   | 0.08  | 0.10  | 12.20      | 12.24  | 12.02  | 44.14   | 44.49 | 44.28 | 50.56      | 50.58 | 50.63 | 38.50            | 38.28 | 37.92 | 38.42          | 38.44 | 38.29 |
| TiO <sub>2</sub>               | 0.02   | 0.00  | 0.00  | 0.03       | 0.02   | 0.06   | 0.44    | 0.43  | 0.38  | 0.00       | 0.01  | 0.00  | 1.95             | 2.01  | 2.15  | 2.00           | 1.97  | 1.94  |
| Al <sub>2</sub> O <sub>3</sub> | 61.41  | 61.02 | 60.51 | 62.07      | 62.23  | 62.48  | 19.16   | 19.12 | 19.19 | 33.20      | 32.97 | 32.92 | 17.35            | 17.58 | 17.75 | 17.84          | 17.79 | 17.71 |
| Cr <sub>2</sub> O <sub>3</sub> | 0.41   | 0.33  | 0.42  | 0.19       | 0.21   | 0.24   | 0.07    | 0.08  | 0.06  | 0.00       | 0.00  | 0.00  | 0.13             | 0.06  | 0.06  | 0.09           | 0.09  | 0.02  |
| FeO                            | 24.38  | 24.72 | 24.77 | 8.85       | 9.07   | 8.80   | 10.68   | 10.39 | 10.19 | 2.67       | 2.44  | 2.42  | 8.58             | 8.79  | 8.67  | 8.67           | 8.52  | 8.63  |
| MnO                            | 0.06   | 0.00  | 0.05  | 0.05       | 0.01   | 0.04   | 0.01    | 0.00  | 0.06  | 0.08       | 0.00  | 0.08  | 0.00             | 0.03  | 0.00  | 0.04           | 0.02  | 0.00  |
| MgO                            | 12.48  | 12.11 | 12.24 | 16.56      | 16.72  | 16.36  | 21.51   | 21.89 | 22.16 | 12.80      | 12.79 | 12.91 | 19.56            | 19.70 | 19.73 | 19.74          | 19.68 | 19.50 |
| ZnO                            | 1.18   | 0.87  | 0.99  | 0.04       | 0.00   | 0.00   | 0.00    | 0.06  | 0.08  | 0.05       | 0.00  | 0.00  | 0.02             | 0.04  | 0.09  | 0.08           | 0.00  | 0.00  |
| CaO                            | 0.00   | 0.00  | 0.00  | 0.02       | 0.00   | 0.00   | 0.62    | 0.61  | 0.56  | 0.05       | 0.04  | 0.04  | 0.01             | 0.01  | 0.00  | 0.00           | 0.00  | 0.00  |
| Na <sub>2</sub> O              | 0.01   | 0.03  | 0.00  | 0.00       | 0.00   | 0.04   | 1.48    | 1.46  | 1.62  | 0.27       | 0.30  | 0.20  | 0.75             | 0.71  | 0.79  | 0.68           | 0.71  | 0.73  |
| K <sub>2</sub> O               | 0.00   | 0.00  | 0.01  | 0.00       | 0.00   | 0.00   | 0.01    | 0.00  | 0.01  | 0.00       | 0.00  | 0.01  | 8.51             | 8.37  | 8.47  | 8.45           | 8.41  | 8.62  |
| Total                          | 100.08 | 99.16 | 99.08 | 100.02     | 100.50 | 100.05 | 98.12   | 98.53 | 98.59 | 99.68      | 99.14 | 99.22 | 95.37            | 95.58 | 95.64 | 96.00          | 95.61 | 95.43 |
| Si                             | 0.00   | 0.00  | 0.00  | 1.47       | 1.46   | 1.44   | 6.12    | 6.13  | 6.10  | 5.01       | 5.03  | 5.03  | 2.76             | 2.74  | 2.72  | 2.74           | 2.75  | 2.75  |
| Ti                             | 0.00   | 0.00  | 0.00  | 0.00       | 0.00   | 0.01   | 0.05    | 0.04  | 0.04  | 0.00       | 0.00  | 0.00  | 0.11             | 0.11  | 0.12  | 0.11           | 0.11  | 0.10  |
| Al                             | 1.94   | 1.95  | 1.94  | 8.78       | 8.77   | 8.83   | 3.13    | 3.10  | 3.12  | 3.88       | 3.87  | 3.86  | 1.47             | 1.48  | 1.50  | 1.50           | 1.50  | 1.50  |
| Cr                             | 0.01   | 0.01  | 0.01  | 0.02       | 0.02   | 0.02   | 0.01    | 0.01  | 0.01  | 0.00       | 0.00  | 0.00  | 0.01             | 0.00  | 0.00  | 0.01           | 0.00  | 0.00  |
| Fe <sup>2+</sup>               | 0.55   | 0.56  | 0.56  | 0.89       | 0.91   | 0.88   | 1.24    | 1.20  | 1.17  | 0.22       | 0.20  | 0.20  | 0.51             | 0.53  | 0.52  | 0.52           | 0.51  | 0.52  |
| Mn <sup>2+</sup>               | 0.00   | 0.00  | 0.00  | 0.01       | 0.00   | 0.00   | 0.00    | 0.00  | 0.01  | 0.01       | 0.00  | 0.01  | 0.00             | 0.00  | 0.00  | 0.00           | 0.00  | 0.00  |
| Mg                             | 0.50   | 0.49  | 0.50  | 2.96       | 2.98   | 2.93   | 4.44    | 4.50  | 4.55  | 1.89       | 1.90  | 1.91  | 2.09             | 2.10  | 2.11  | 2.10           | 2.10  | 2.09  |
| Zn                             | 0.02   | 0.02  | 0.02  | 0.00       | 0.00   | 0.00   | 0.00    | 0.01  | 0.01  | 0.00       | 0.00  | 0.00  | 0.00             | 0.00  | 0.00  | 0.00           | 0.00  | 0.00  |
| Ca                             | 0.00   | 0.00  | 0.00  | 0.00       | 0.00   | 0.00   | 0.09    | 0.09  | 0.08  | 0.00       | 0.00  | 0.00  | 0.00             | 0.00  | 0.00  | 0.00           | 0.00  | 0.00  |
| Na                             | 0.00   | 0.00  | 0.00  | 0.00       | 0.00   | 0.01   | 0.40    | 0.39  | 0.43  | 0.05       | 0.06  | 0.04  | 0.10             | 0.10  | 0.11  | 0.09           | 0.10  | 0.10  |
| K                              | 0.00   | 0.00  | 0.00  | 0.00       | 0.00   | 0.00   | 0.00    | 0.00  | 0.00  | 0.00       | 0.00  | 0.00  | 0.78             | 0.77  | 0.78  | 0.77           | 0.77  | 0.79  |

Table 3

TABLE 3: U-Pb LA-ICP MS Monazite Analyses

| Spot No.             | $^{206}\text{Pb}/^{238}\text{U}$ | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$ | $1\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb}$ | $1\sigma$ | $^{206}\text{Pb}/^{238}\text{U}$<br>(Ma) | $1\sigma$ | $^{207}\text{Pb}/^{235}\text{U}$<br>(Ma) | $1\sigma$ | $^{207}\text{Pb}/^{206}\text{Pb}$<br>(Ma) | $1\sigma$ | Conc (%) |
|----------------------|----------------------------------|-----------|----------------------------------|-----------|-----------------------------------|-----------|--|-----------|--|-----------|---|-----------|----------|
| <b>Core Analyses</b> |                                  |           |                                  |           |                                   |           |  |           |  |           |   |           |          |
| 54.1.1               | 0.08425                          | 0.00114   | 0.67858                          | 0.00989   | 0.05831                           | 0.0069    | 521.4                                    | 6.8       | 525.9                                    | 6.0       | 540.8                                     | 26.5      | 96       |
| 54.2.1               | 0.08438                          | 0.00114   | 0.67583                          | 0.00982   | 0.05799                           | 0.0069    | 522.2                                    | 6.8       | 524.3                                    | 6.0       | 528.8                                     | 26.1      | 99       |
| 54.3.1               | 0.08537                          | 0.00116   | 0.69674                          | 0.01048   | 0.05908                           | 0.0074    | 528.1                                    | 6.9       | 536.8                                    | 6.3       | 570.2                                     | 27.0      | 93       |
| 54.4.1               | 0.08493                          | 0.00115   | 0.68472                          | 0.00994   | 0.05836                           | 0.0069    | 525.5                                    | 6.8       | 529.6                                    | 6.0       | 543.5                                     | 25.6      | 97       |
| 54.5.1               | 0.08450                          | 0.00115   | 0.68244                          | 0.01015   | 0.05846                           | 0.0072    | 522.9                                    | 6.8       | 528.2                                    | 6.1       | 547.2                                     | 26.6      | 96       |
| 54.6.1               | 0.08509                          | 0.00116   | 0.68995                          | 0.01034   | 0.0587                            | 0.0073    | 526.4                                    | 6.9       | 532.8                                    | 6.2       | 556.1                                     | 26.9      | 95       |
| 54.7.1               | 0.08570                          | 0.00116   | 0.69540                          | 0.01003   | 0.05874                           | 0.0069    | 530.1                                    | 6.9       | 536.0                                    | 6.0       | 557.5                                     | 25.2      | 95       |
| 54.8.1               | 0.08462                          | 0.00115   | 0.68693                          | 0.0099    | 0.05877                           | 0.0068    | 523.7                                    | 6.8       | 531.0                                    | 6.0       | 558.5                                     | 25.2      | 94       |
| 54.9.1               | 0.08493                          | 0.00115   | 0.68741                          | 0.01      | 0.0586                            | 0.0069    | 525.5                                    | 6.9       | 531.2                                    | 6.0       | 552.2                                     | 25.6      | 95       |
| 54.10.1              | 0.08544                          | 0.00116   | 0.68402                          | 0.00993   | 0.05796                           | 0.0068    | 528.5                                    | 6.9       | 529.2                                    | 6.0       | 527.9                                     | 26.0      | 100      |
| 54.11.1              | 0.08556                          | 0.00119   | 0.70125                          | 0.01201   | 0.05933                           | 0.009     | 529.2                                    | 7.1       | 539.5                                    | 7.2       | 579.2                                     | 32.7      | 91       |
| 54.12.1              | 0.08526                          | 0.00117   | 0.69271                          | 0.01049   | 0.05881                           | 0.0074    | 527.4                                    | 6.9       | 534.4                                    | 6.3       | 560.2                                     | 27.3      | 94       |
| <b>Rim Analyses</b>  |                                  |           |                                  |           |                                   |           |  |           |  |           |   |           |          |
| 54.1.2               | 0.08355                          | 0.00116   | 0.67464                          | 0.01112   | 0.05845                           | 0.0084    | 517.3                                    | 6.9       | 523.5                                    | 6.7       | 546.8                                     | 31.1      | 95       |
| 54.3.2               | 0.08310                          | 0.00114   | 0.65717                          | 0.01036   | 0.05725                           | 0.0077    | 514.6                                    | 6.8       | 512.9                                    | 6.4       | 500.5                                     | 29.4      | 103      |
| 54.4.2               | 0.08311                          | 0.00114   | 0.67038                          | 0.01046   | 0.05839                           | 0.0077    | 514.7                                    | 6.8       | 520.9                                    | 6.4       | 544.4                                     | 28.7      | 95       |
| 54.5.2               | 0.08404                          | 0.00115   | 0.67645                          | 0.01047   | 0.05827                           | 0.0076    | 520.2                                    | 6.8       | 524.6                                    | 6.3       | 539.1                                     | 29.0      | 96       |
| 54.8.2               | 0.08352                          | 0.00115   | 0.66822                          | 0.01075   | 0.05792                           | 0.008     | 517.1                                    | 6.9       | 519.6                                    | 6.5       | 526.4                                     | 30.3      | 98       |
| 54.10.2              | 0.08318                          | 0.00115   | 0.66830                          | 0.0106    | 0.05816                           | 0.0079    | 515.1                                    | 6.8       | 519.7                                    | 6.5       | 535.2                                     | 29.9      | 96       |
| 54.11.2              | 0.08355                          | 0.00116   | 0.66782                          | 0.01079   | 0.05786                           | 0.008     | 517.3                                    | 6.9       | 519.4                                    | 6.6       | 524.4                                     | 30.4      | 99       |
| 54.12.2              | 0.08228                          | 0.00113   | 0.66079                          | 0.01048   | 0.05814                           | 0.0079    | 509.7                                    | 6.7       | 515.1                                    | 6.4       | 534.5                                     | 29.9      | 95       |

Table 4

TABLE 4: Trace Element LA-ICP MS Garnet Analyses

|    | G-54.1  | G-54.2  | G-54.3  | G-54.4 | G-54.5 | G-54.6 | G-54.7 | G-54.8 | G-54.9 | G-54.10 | G-54.11 | G-54.12 | G-54.13 | G-54.14 | G-54.15 | G-54.16 | G-54.17 |
|----|---------|---------|---------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|---------|---------|
| Sc | 77.37   | 61.02   | 82.61   | 130.94 | 152.12 | 157.92 | 204.57 | 222.91 | 219.1  | 186.43  | 184.32  | 176.12  | 154.66  | 134.5   | 118.39  | 84.06   | 72.92   |
| Ti | 35.41   | 37.95   | 42.51   | 51.88  | 52.32  | 50.38  | 77.2   | 65.26  | 73.36  | 60.05   | 59.94   | 52.35   | 55.21   | 55.6    | 53.25   | 42.33   | 38.85   |
| P  | 159.32  | 169.4   | 167.69  | 43.12  | 46.2   | 64.18  | 64.34  | 58.68  | 67.71  | 6.25    | 4.91    | 6.86    | 37.28   | 55.33   | 77.68   | 204.65  | 266.2   |
| V  | 23.91   | 34.18   | 33.99   | 36.45  | 37.69  | 48.57  | 73.7   | 64.55  | 73.18  | 63.37   | 66.72   | 44.19   | 47.14   | 44.31   | 42.78   | 34.29   | 30.43   |
| Cr | 233.67  | 237.42  | 268.69  | 232.13 | 157.33 | 237.67 | 259.81 | 264.12 | 261.19 | 256.49  | 245.99  | 160.72  | 167.14  | 219.62  | 396.54  | 238.28  | 224.29  |
| Y  | 44.09   | 58.12   | 80.99   | 135.01 | 124.92 | 105.36 | 61.67  | 65.99  | 59.06  | 43.5    | 50.02   | 63.52   | 85.41   | 109.19  | 111.33  | 86.1    | 64.63   |
| Zr | 1.987   | 2.64    | 2.17    | 2.17   | 2.53   | 2.58   | 2.62   | 2.59   | 2.36   | 1.562   | 1.713   | 2       | 2.33    | 2.54    | 2.64    | 2.94    | 4.22    |
| La | bdl     | bdl     | 0.00125 | bdl    | bdl    | bdl    | bdl    | bdl    | bdl    | bdl     | 0.00027 | 0.00238 | 0.0015  | bdl     | bdl     | bdl     | 0.00283 |
| Ce | 0.00335 | 0.003   | 0.0048  | 0.0072 | 0.0112 | 0.0127 | 0.0097 | 0.0061 | 0.0094 | 0.00424 | 0.00273 | 0.0146  | 0.0054  | 0.0095  | 0.007   | 0.0064  | 0.0078  |
| Pr | 0.00327 | 0.00317 | 0.00295 | 0.0047 | 0.0085 | 0.0051 | 0.003  | 0.0085 | 0.0082 | 0.00382 | 0.00394 | 0.00482 | 0.00476 | 0.0051  | 0.00444 | 0.006   | 0.003   |
| Nd | 0.0645  | 0.0865  | 0.0738  | 0.105  | 0.139  | 0.135  | 0.126  | 0.132  | 0.14   | 0.0811  | 0.0901  | 0.107   | 0.104   | 0.099   | 0.091   | 0.09    | 0.093   |
| Sm | 0.278   | 0.283   | 0.315   | 0.379  | 0.374  | 0.441  | 0.502  | 0.431  | 0.59   | 0.317   | 0.324   | 0.344   | 0.398   | 0.37    | 0.37    | 0.313   | 0.33    |
| Eu | 0.237   | 0.251   | 0.29    | 0.387  | 0.409  | 0.456  | 0.401  | 0.433  | 0.398  | 0.286   | 0.306   | 0.322   | 0.354   | 0.328   | 0.335   | 0.301   | 0.299   |
| Gd | 1.752   | 1.896   | 2.48    | 3.44   | 4.06   | 3.99   | 3.76   | 4.32   | 3.91   | 2.39    | 2.66    | 3.06    | 3.23    | 3.42    | 3.36    | 2.72    | 2.38    |
| Tb | 0.858   | 1.016   | 1.301   | 1.99   | 2.18   | 2.01   | 1.98   | 2.07   | 1.95   | 1.173   | 1.327   | 1.558   | 1.743   | 1.829   | 1.738   | 1.327   | 1.136   |
| Dy | 7.83    | 9.79    | 13.28   | 22.12  | 21.03  | 19.86  | 14.9   | 15.91  | 14.32  | 9.85    | 11.15   | 14      | 16.83   | 19.67   | 19.25   | 14.35   | 11.34   |
| Ho | 1.607   | 2.25    | 3.42    | 6.27   | 5.4    | 4.6    | 2.35   | 2.65   | 2.29   | 1.551   | 1.84    | 2.49    | 3.48    | 5.04    | 4.92    | 3.62    | 2.51    |
| Er | 3.59    | 5.4     | 9.4     | 20.02  | 16.06  | 11.97  | 4.19   | 5.29   | 4.69   | 3.26    | 3.74    | 5.52    | 9.08    | 17.04   | 16.03   | 11.03   | 6.62    |
| Tm | 0.456   | 0.807   | 1.56    | 3.9    | 3.11   | 2.09   | 0.517  | 0.744  | 0.666  | 0.405   | 0.447   | 0.698   | 1.386   | 3.3     | 2.92    | 1.741   | 0.872   |
| Yb | 2.71    | 5.55    | 11.74   | 36.84  | 26.13  | 16.19  | 2.75   | 5.07   | 4.77   | 3.1     | 3.12    | 4.98    | 10.88   | 32.67   | 26.36   | 14.07   | 6.09    |
| Lu | 0.306   | 0.667   | 1.61    | 6      | 4.1    | 2.22   | 0.339  | 0.734  | 0.699  | 0.376   | 0.383   | 0.582   | 1.257   | 5.65    | 3.89    | 1.97    | 0.731   |
| Hf | 0.0404  | 0.0799  | 0.0579  | 0.0286 | 0.017  | 0.042  | 0.073  | 0.039  | 0.086  | 0.0281  | 0.0306  | 0.0167  | 0.0388  | 0.04    | 0.0548  | 0.09    | 0.118   |

TABLE54: Trace element LA-ICP MS Zircon Analyses

|                    | Zr-54.1 | Zr-54.2 | Zr-54.3 | Zr-54.4 | Zr-54.5 | Zr-54.6 | Zr-54.7 | Zr-54.8 | Zr-54.9 | Zr-54.10 | Zr-54.11 | Zr-54.12 |
|--------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|----------|----------|----------|
| P                  | 191     | 122     | 130     | 130     | 99      | 138     | 119     | 112     | 91      | 110      | 115      | 105      |
| Sc                 | 389     | 380     | 387     | 350     | 320     | 391     | 356     | 350     | 297     | 337      | 303      | 297      |
| Ti                 | 7.25    | 8.23    | 7.52    | 8.01    | 5.54    | 5.78    | 8.17    | 7.25    | 6.31    | 4.69     | 4.31     | 5.58     |
| Y                  | 175     | 211     | 215     | 191     | 154     | 179     | 230     | 218     | 179     | 138      | 140      | 142      |
| Nb                 | 0.20    | 0.17    | 0.18    | 0.17    | 0.16    | 0.23    | 0.18    | 0.16    | 0.14    | 0.20     | 0.17     | 0.17     |
| La                 | 0.02    | 0.01    | bdl     | 0.03    | 0.01    | 0.01    | 0.03    | bdl     | bdl     | 0.01     | 0.01     | 0.02     |
| Ce                 | 2.28    | 2.09    | 2.19    | 2.21    | 2.02    | 3.14    | 2.26    | 2.21    | 1.99    | 2.82     | 2.34     | 2.09     |
| Pr                 | 0.03    | 0.03    | 0.02    | 0.04    | 0.02    | 0.01    | 0.03    | 0.03    | 0.02    | 0.02     | 0.02     | 0.02     |
| Nd                 | 0.49    | 0.55    | 0.45    | 0.69    | 0.43    | 0.45    | 0.71    | 0.58    | 0.49    | 0.41     | 0.33     | 0.37     |
| Sm                 | 1.77    | 2.28    | 2.23    | 2.17    | 1.60    | 1.91    | 2.45    | 2.31    | 1.96    | 1.47     | 1.46     | 1.55     |
| Eu                 | 1.64    | 1.86    | 1.82    | 1.77    | 1.34    | 1.66    | 2.09    | 1.95    | 1.58    | 1.17     | 1.16     | 1.32     |
| Gd                 | 13.68   | 16.23   | 15.75   | 14.70   | 12.10   | 14.64   | 17.27   | 16.98   | 14.32   | 10.07    | 10.68    | 10.97    |
| Tb                 | 4.36    | 5.42    | 5.27    | 4.77    | 3.88    | 4.65    | 5.73    | 5.46    | 4.52    | 3.12     | 3.41     | 3.50     |
| Dy                 | 30.99   | 38.05   | 37.48   | 33.93   | 27.17   | 31.96   | 41.09   | 38.63   | 32.34   | 23.48    | 24.67    | 25.00    |
| Ho                 | 5.74    | 6.98    | 7.19    | 6.21    | 5.10    | 5.93    | 7.59    | 7.21    | 5.92    | 4.63     | 4.69     | 4.72     |
| Er                 | 12.72   | 15.11   | 15.98   | 13.89   | 11.47   | 13.47   | 16.91   | 16.40   | 13.33   | 11.21    | 10.73    | 10.69    |
| Tm                 | 1.84    | 2.24    | 2.41    | 2.10    | 1.73    | 1.94    | 2.47    | 2.29    | 1.88    | 1.69     | 1.63     | 1.57     |
| Yb                 | 13.21   | 16.62   | 17.55   | 15.76   | 12.72   | 14.00   | 18.24   | 16.94   | 13.57   | 13.42    | 11.62    | 11.54    |
| Lu                 | 1.68    | 2.08    | 2.23    | 1.94    | 1.59    | 1.67    | 2.21    | 2.15    | 1.73    | 1.81     | 1.54     | 1.51     |
| Hf                 | 13937   | 13306   | 13708   | 12920   | 12255   | 15460   | 13041   | 13162   | 11410   | 13889    | 12631    | 12411    |
| Ta                 | 0.04    | 0.03    | 0.03    | 0.04    | 0.03    | 0.05    | 0.02    | 0.03    | 0.03    | 0.04     | 0.04     | 0.03     |
| Pb                 | 1.16    | 0.97    | 0.95    | 1.34    | 1.03    | 1.51    | 1.33    | 1.13    | 0.94    | 1.32     | 1.19     | 1.29     |
| Zr <sub>Ti</sub> T | 713     | 724     | 717     | 722     | 692     | 695     | 724     | 713     | 702     | 679      | 672      | 692      |
| 1 $\sigma$         | 35      | 35      | 35      | 35      | 35      | 35      | 36      | 36      | 36      | 36       | 36       | 36       |



Table 6

TABLE 6: Trace element LA-ICP MS Monazite Analyses

|    | M-54.1 | M-54.2 | M-54.3 | M-54.4 | M-54.5 | M-54.6 | M-54.7 | M-54.8 | M-54.9 | M-54.10 | M-54.11 | M-54.12 | M-54.13 | M-54.14 |
|----|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|
| P  | 71750  | 65621  | 52106  | 62048  | 58773  | 57812  | 56277  | 54493  | 54515  | 61437   | 71810   | 61160   | 63109   | 62134   |
| V  | 13     | 13     | 8      | 16     | 15     | 9      | 9      | 9      | 9      | 10      | 16      | 9       | 11      | 7       |
| Y  | 727    | 707    | 521    | 533    | 516    | 515    | 543    | 577    | 481    | 814     | 571     | 506     | 506     | 660     |
| Zr | 1.60   | 1.14   | 0.80   | 0.94   | 0.97   | 0.95   | 0.81   | 0.83   | 0.78   | 0.87    | 0.97    | 0.91    | 0.86    | 0.94    |
| Nb | 0.05   | 0.05   | 0.05   | 0.05   | 0.05   | 0.04   | 0.05   | 0.04   | 0.04   | 0.04    | 0.07    | 0.05    | 0.05    | 0.04    |
| La | 130242 | 112049 | 85354  | 107435 | 102530 | 95897  | 93651  | 89586  | 89533  | 99458   | 119703  | 101497  | 96844   | 94296   |
| Ce | 176248 | 156294 | 119446 | 148814 | 138210 | 132316 | 129876 | 124544 | 121678 | 135612  | 162234  | 132546  | 132565  | 129052  |
| Pr | 18179  | 16584  | 12564  | 15547  | 14509  | 14142  | 13678  | 13225  | 12830  | 14354   | 17182   | 13684   | 14084   | 13805   |
| Nd | 68609  | 63411  | 48120  | 60368  | 55897  | 55154  | 52506  | 51537  | 49547  | 55271   | 65990   | 51800   | 54712   | 52517   |
| Sm | 8324   | 7854   | 6975   | 7351   | 6864   | 7689   | 7136   | 7098   | 7059   | 7517    | 8137    | 6865    | 7518    | 7396    |
| Eu | 1450   | 1339   | 1276   | 1098   | 1036   | 1417   | 1298   | 1300   | 1317   | 1383    | 1214    | 1225    | 1316    | 1415    |
| Gd | 4033   | 3816   | 3836   | 3468   | 3282   | 4105   | 3850   | 3874   | 3756   | 4136    | 3806    | 3583    | 3852    | 4144    |
| Tb | 236    | 229    | 228    | 190    | 182    | 236    | 228    | 234    | 221    | 261     | 209     | 213     | 227     | 265     |
| Dy | 481    | 469    | 397    | 363    | 347    | 399    | 412    | 429    | 377    | 518     | 392     | 382     | 395     | 493     |
| Ho | 33     | 32     | 23     | 24     | 23     | 22     | 24     | 25     | 19     | 35      | 26      | 22      | 22      | 29      |
| Er | 29     | 28     | 18     | 21     | 21     | 17     | 19     | 20     | 14     | 33      | 23      | 17      | 16      | 23      |
| Tm | 1.35   | 1.39   | 0.86   | 1.05   | 0.96   | 0.81   | 0.81   | 0.89   | 0.56   | 1.70    | 1.02    | 0.76    | 0.69    | 0.97    |
| Yb | 4.79   | 4.77   | 3.23   | 3.68   | 3.57   | 3.37   | 3.05   | 3.36   | 2.48   | 5.64    | 3.71    | 3.05    | 2.93    | 3.54    |
| Lu | 0.38   | 0.36   | 0.30   | 0.31   | 0.28   | 0.31   | 0.28   | 0.29   | 0.20   | 0.49    | 0.36    | 0.23    | 0.27    | 0.33    |
| Hf | 0.46   | 0.48   | 0.53   | 0.49   | 0.44   | 0.59   | 0.48   | 0.52   | 0.60   | 0.51    | 0.53    | 0.47    | 0.49    | 0.54    |
| Pb | 1281   | 1498   | 1424   | 1542   | 1485   | 1508   | 1556   | 1561   | 1385   | 1538    | 1494    | 1408    | 1558    | 1481    |