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Apatite recrystallisation during prograde metamorphism, Cooma, southeast Australia: implications for using an apatite–graphite association as a biotracer in ancient metasedimentary rocks

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Early Silurian low-pressure (<500 MPa) greenschist to granulite facies metamorphism in Ordovician sedimentary rocks of the Cooma Complex culminating in the production of the Cooma Granodiorite, Lachlan Fold Belt (southeast Australia) provides an opportunity to determine the physical and chemical response of apatite (Ca phosphate) to prograde metamorphism. Electron probe elemental mapping (P, Ca, Ce, Si) of metapelite polished sections shows that apatite grains become less abundant but larger with increasing metamorphic grade (<20 μm at chlorite grade to >200 μm in enclaves in migmatites). Many apatite grains are composite, with clear overgrowths and cloudy cores, which in rare cases contain microscopic inclusions interpreted to delineate microfolds. Therefore, during progressive metamorphism there was dissolution and regrowth of apatite. Recrystallisation and growth of apatite crystals with increasing metamorphic grade was accompanied by the progressive dissolution then regrowth of monazite (Ce–Th phosphate), as previously reported from the Cooma metasedimentary sequence. The Cooma apatites mostly have similar REE patterns at all grades. But upgrade, there is a confluence in REE abundances of apatite grains, indicating an increasing volume of chemical equilibration. Infrared absorbance spectrometry indicates that carbon is present as carbonate substituting for phosphate and hydroxyl ions in the lattice of apatites at all metamorphic grades. Carbonaceous material (graphite?) is only a rare inclusion phase found in the younger clear apatite in the higher-grade rocks. The Cooma apatite study shows that, contrary to previous assertions for earliest (>3700 Ma, amphibolite–granulite facies) metasediments from Greenland, apatite is unlikely to be a stable ‘capsule’ which will reliably protect any biogenic carbon (graphite at high metamorphic grade) from reactions and isotopic exchange during prograde metamorphism.

KEY WORDS: apatite, biotracers, Cooma Complex, crystal growth, metamorphism.

INTRODUCTION

At Cooma, in southeast Australia, Early Paleozoic flysch was progressively metamorphosed from greenschist to granulite facies in the Early Silurian, culminating in pervasive partial melting and the production of the Cooma Granodiorite (Joplin 1942; Johnson 1992, 1999; Richards *et al.* 2000). The metamorphic sequence around Cooma provides an excellent opportunity to study the stability of minerals across a continuous broad temperature range. Williams (2001) reported a detailed petrographic and U–Pb dating study of zircon and monazite from the Cooma Complex, documenting the corrosion of early (detrital) monazite [(Ce,La,Th)PO₄] below the K-feldspar isograd and then its regrowth at higher grades. This present study complements that work through a study of apatite in the same metamorphic sequence.

Apatite [Ca₅(PO₄)₃(OH,F,Cl)] is a common if not ubiquitous accessory mineral in metasedimentary rocks. It has been proposed that apatite growth during deposition/diagenesis can trap reduced organic matter (Filippelli & Delaney 1996). Consequently, apatite with carbon (graphite) inclusions has been sought in the world’s oldest (>3700 Ma) amphibolite or granulite facies metasediments as a possible ‘chemofossil’ that might retain evidence for early life, and it has been reported that such evidence has been found (Mojzsis *et al.* 1996). Such an approach is valid only assuming that apatite did not recrystallise subsequently during metamorphism, so that any carbon inclusions within it could then be regarded as early (pre-metamorphic) objects, protected from reaction and isotopic exchange during metamorphism. The present study of the behaviour of apatite during progressive metamorphism tests that general assumption.

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COOMA COMPLEX

The Lachlan Fold Belt (southeast Australia) is a multiply deformed, imbricated Early Paleozoic flysch sequence intruded by voluminous Silurian to Carboniferous granites. Regionally the metamorphic grade is low, apart from the linear medium to high-grade Wagga–Omeo and Cooma Metamorphic Belts (Vallance 1967). The Cooma Metamorphic Belt comprises several small metamorphic complexes, including the Cooma Complex studied for this paper. Throughout the higher grade belts, parageneses are marked by cordierite ± sillimanite, rather than garnet or kyanite, reflecting generally low-pressure (<500 MPa), high-temperature metamorphic conditions (Vernon 1988; Johnson 1992).

The Cooma Complex, centred on the town of Cooma, is exposed over an area of ~300 km² (Figure 1). Much of the complex is hidden under a cover of soil or Tertiary basalt, but examples of most of the metamorphic sequence are exposed in creeks and road cuttings. The complex is elongated north–south, parallel to regional structural trends. At the centre of the Complex lies the Cooma Granodiorite, which has yielded a SHRIMP U–Pb zircon age of 432.8 ± 3.5 Ma (95% c.l.). This matches closely the mean age of monazite in the granodiorite and high-grade rocks of 435.2 ± 6.3 Ma (Williams 2001). By combining the zircon and the monazite dating, Williams (2001) proposed 433.4 ± 3.1 Ma as the best estimate for the age of both the granodiorite and the metamorphism.

Figure 1 General geological map of the Cooma Complex (adapted from Williams 2001 figure 1).

Metamorphic assemblages at Cooma are Abukuma type, with the progressive appearance upgrade of chlorite, biotite, andalusite, K-feldspar, sillimanite and partial melt. A consensus has yet to be reached concerning the P–T path of the metamorphic rocks. Some authors suggested that the prograde segment was almost isobaric (Vernon 1988), whereas others cited evidence for higher pressures in the higher-grade rocks (Johnson 1992).

The rocks of the Cooma Complex and their environs show multiple fabrics (Johnson 1992; Johnson *et al.* 1994), with perhaps three generations of fabrics in common to the metamorphic rocks of the complex and the surrounding low-grade flysch. The Cooma Granodiorite contains one fabric, demonstrating that deformation continued after it was emplaced. It remains unresolved whether the Cooma Complex represents a local high-temperature anomaly within the regional low-grade slate belt or was produced by a later, discrete tectonothermal event. The main point relevant to the present study is that, within a relatively monotonous sedimentary succession, there is a largely uninterrupted progression in metamorphic grade from greenschist to upper amphibolite or granulite facies, culminating in widespread partial melting and granite genesis.

SAMPLES

Field setting

Samples (Figure 1) were collected along the Cooma–Berridale road, in most cases from localities sampled for Williams' (2001) zircon and monazite study. Sample C-1 of chlorite zone metapelite comes from a low cut on the Cooma–Berridale road (UTM 068005, 598452), ~10 km west-southwest of Cooma. The sample selected is fine grained, in order to avoid a possible volcanogenic component in the sediments at this outcrop. Sample C-4 of biotite zone metapelite comes from a low cut on the east side of the Berridale road (UTM 068241 598558), from a mostly pelitic sequence with a few psammitic layers that describe small fold closures. Sample C-5 is a spotted schist from the freshest exposures on the west side of the road (UTM 068304 598594). The schists are spotted with white mica, but it is uncertain whether these replaced cordierite or andalusite. Sample C-7 is sedimentary-rich material from migmatites on the west side of the Berridale road, at the southern outskirts of Cooma (UTM 068665 598717). The migmatite contains granitic leucosome patches, and the metasedimentary melanosome contains feldspar + cordierite. Garnet is absent because of the low pressure of metamorphism (~400 MPa; Ellis & Obata 1992). Sample C-8 is a metasedimentary relict in the margin of the Cooma Granodiorite, from a fresh cut on the east side of the Berridale road (UTM 068955, 598724). The sedimentary relicts form jumbled blocks in the granodiorite and are dominated by siliceous layers that were too refractory to melt.

Apatite petrography

Electron microprobe maps of P, Ca, Ce and Si in polished thin-sections of samples C-1 (chlorite zone),

C-4 (biotite zone) and C-7 (migmatite melanosome) revealed the distribution of phosphate phases with increasing temperature from medium to high metamorphic grade. By combining Ca and P images (Figure 2), apatite grains (Ca phosphate), which show as bright spots, could be distinguished from grains of monazite. The images show that with increasing metamorphic grade, the apatite grains become less numerous and larger. Preferred orientation of the enlarged apatite grains along the schistosity (horizontally in the image of sample C-4, Figure 2) is consistent with growth and recrystallisation during metamorphism under directed stress. Coincident with these observed changes in apatite, Williams (2001) reported that monazite first decreases in both grain size and abundance up to upper amphibolite grade, before regrowing at a higher grade.

Apatite grains (~20 to >200 μm) were separated from the rocks by standard gravimetric and isodynamic magnetic techniques. Loose grains were used for Infra-red Absorbance Spectrometry. Apatite grains for the petrography and LA-ICPMS trace-element analysis were cast in epoxy resin and polished so that they were exposed in cross-section.

No apatite was recovered from chlorite zone sample C-1, despite the thin-section mapping showing it to be present, but as very small grains (Figure 2). It was probably lost with the dust fraction in the early stages of mineral separation because of its typically fine grain size (<20 μm). Ample apatite was recovered from all samples from higher metamorphic grades. The apatite grain size was typically 50–150 μm in the biotite zone sample C-4, 100–200 μm in migmatite sample C-7 and 200–250 μm in the enclave sample C-8 (Figures 2, 3).

Apatite recovered from the biotite zone and higher metamorphic grades consists of both clear apatite and apatite that is cloudy, olive-green and commonly containing micrometre-scale inclusions of other minerals. The cloudy apatite forms the cores of grains, and with increasing metamorphic grade the amount of clear apatite increases, occurring as both overgrowths and whole grains (Figure 3a). The micrometre-scale mineral inclusions in the cloudy apatite are commonly oriented into a planar fabric (Figure 3a), and in rare cases they seem to delineate an axial (S_1) fabric to warps in layering (S_0 bedding?) overgrown by the cloudy apatite (Figure 3b). This additional evidence of the growth of apatite crystals during progressive metamorphism cautions that the oldest observed inclusion-bearing apatite may not be detrital or authigenic, but instead grew after first fabric development and maybe even after the first folding. At a higher metamorphic grade, there are larger (>5 μm) mineral inclusions in the clear apatite that have been identified by electron microprobe analysis to be zircon, biotite and more rarely carbonaceous matter, which forms globular clusters of grains up to 20 μm across (Figure 3c). Thus, carbonaceous matter (graphite?) has been positively identified in only the (younger) clear apatite overgrowths and whole grains, making it unlikely that it represents reduced carbon encapsulated in the apatite immediately following diagenesis of the sedimentary protolith.

Figure 2 P + Ca electron probe maps of polished thin-sections of chlorite zone C-1, biotite zone C-4 and migmatite zone C-7. All are shown at the same scale. Apatite grains appear as bright spots, whereas phases containing only P or Ca appear dull grey. Domains that do not contain Ca or P appear black in the images.

Infrared absorbance spectroscopy

Infrared absorbance spectra of Cooma apatites were obtained using a Bruker A590 infrared microscope and Bruker IFS28 infrared spectrometer. For presentation for the absorbance spectroscopy, a random selection of apatites was loaded as loose grains sprinkled over a fine metal mesh. In the sprinkled apatites, transmitted-light microscopy was used to select dominantly cloudy or clear domains for absorbance spectroscopy. The high absorbance at wavenumbers below 1300 cm^{-1} (Figure 4) is due to phosphate (Elliot 1964; Dahm & Risnes 1999). The complex absorbancies between 1400 and 1600 cm^{-1} (Figure 4) show the presence of carbonate in the apatite structure at all metamorphic grades. The spectra from biotite grade sample C-4, where the apatite grains are smaller and cloudy grain centres predominate (e.g. spectra C4-8 to C4-10), show strong absorbancies at ~ 1455 and 1425 cm^{-1}

which correspond to (B-type) substitution of carbonate for the phosphate ion (Elliot 1964). In contrast, the spectra from the clear apatite overgrowths (most prominent in the coarser-grained apatites at a higher metamorphic grade) show absorbancies at ~ 1576 , 1544 , 1493 and 1415 cm^{-1} (e.g. spectra C8-7 to C8-9) corresponding to the (A-type) substitution of carbonate for the hydroxyl ion (Elliot 1964). Spectra from low-grade grains in which both types of apatite are present in approximately equal abundance show weak A-type absorbancies (e.g. C4-12), and from the cloudy cores in large apatites from enclave sample C-8, show both A- and B-type absorbancies (e.g. C8-5 and C8-6), in both cases because of mixed sampling. These spectra indicate that carbonate substitution in the lattice is an important repository for carbon in apatites in these meta-sedimentary rocks. Such substitution is common geologically: from apatite formed during diagenesis of

Figure 3 (a) Photomicrographs of representative apatites from biotite zone sample C-1 and migmatite zone sample C-7, and enclave sample C-8. (b) Sample C-4 apatite with what are interpreted as folded inclusion trains. (c) Uncommon graphite inclusion in clear apatite. All grains are shown at the same scale.

sediments to apatite in some igneous rocks (McConnell 1973; Pan & Fleet 2002).

Apatite chemistry

A selection of apatite grains from the Cooma Complex was analysed for REE and other trace elements by LA-ICPMS using methods described by Eggins *et al.* (1998). Data were reduced offline using an Excel spreadsheet (written by S. Eggins and C. Allen, Australian National University, Canberra). Data were referenced to NIST glass 610 analyses, and assumed CaO 54 wt% in the

apatites. Trace-element analyses of both cloudy and clear apatite from biotite grade sample C-4, migmatite sample C-7 and sedimentary enclave sample C-8 are listed in Table 1 and illustrated in Figure 5a–c. Regardless of metamorphic grade, all apatites show negative chondrite-normalised Eu anomalies and are depleted in heavy rare-earth elements relative to the middle rare-earth elements (Figure 5). Except for three analyses (C-4-1a, C-4-7, C-4-11) of cloudy apatite from biotite zone sample C-4, all apatite is light rare earth (LREE) depleted. This possibly reflects the presence of monazite in Cooma metasedimentary rocks (Williams

Figure 4 Representative infrared absorption spectra for apatites. Only wavelengths 1300–1600 cm^{-1} , where there are absorbancies related to carbonate substitution in the apatite lattice, are shown.

Table 1 Laser-ablation ICPMS *in situ* analyses of apatites.

Analysis	Site	Si	Sr	Y	Th	U	Th/U	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
A-4 biotite grade																					
1a	Cloudy	0.60	169.1	2263.1	296.5	134.4	2.206	1131.2	2764.2	316.8	1299.2	325.4	53.5	439.7	84.4	562.1	100.6	264.4	34.9	208.0	23.5
1b	Clear	0.20	151.8	666.8	7.3	24.8	0.296	40.8	174.5	33.1	196.2	95.0	16.8	155.8	29.1	184.6	31.0	74.8	9.5	54.1	6.1
2	Cloudy	0.04	199.1	1015.5	12.0	19.7	0.611	73.6	274.0	48.7	273.7	126.6	17.4	205.5	37.4	240.8	43.0	109.6	14.1	84.4	10.1
3	Clear	0.10	161.2	1081.4	7.3	82.0	0.089	140.0	545.1	103.2	634.8	253.0	26.0	291.4	45.3	266.6	44.1	108.0	14.3	83.5	9.5
4	Cloudy	0.10	266.4	695.4	12.9	11.2	1.158	98.9	331.2	51.1	253.0	92.2	16.5	117.0	23.4	152.3	26.3	70.1	10.0	64.3	7.4
5	Cloudy	0.05	248.8	684.7	1.4	5.5	0.250	51.0	197.2	35.6	194.2	92.9	15.0	137.4	26.1	163.9	27.4	67.6	8.9	52.6	6.1
6	Cloudy	0.04	187.9	655.5	0.5	13.9	0.039	39.0	168.8	32.8	195.5	98.0	15.6	157.4	28.5	173.2	28.5	68.2	8.2	45.7	5.1
7	Cloudy	0.70	148.9	1425.8	142.3	154.7	0.920	1381.9	3262.7	388.6	1582.1	346.4	51.0	404.2	66.8	395.8	62.8	147.2	18.2	103.8	11.3
8	Clear	0.04	170.6	751.3	10.0	57.9	0.173	115.2	380.9	63.2	341.7	142.4	19.6	217.2	34.9	202.9	32.3	79.0	10.4	62.0	7.1
9	Clear	0.09	400.8	701.8	1.0	13.9	0.074	50.6	203.6	37.1	208.4	95.6	17.0	154.1	29.4	188.2	32.1	78.6	10.2	59.2	6.6
10	Cloudy	0.10	243.7	586.3	1.2	13.6	0.088	42.4	168.6	31.1	181.2	85.7	15.9	140.8	25.6	161.8	26.8	64.3	8.1	46.3	5.3
11	Cloudy	0.44	166.6	1295.0	150.3	55.1	2.729	1908.9	3760.2	354.0	1196.3	240.5	37.8	298.8	54.9	355.1	60.0	150.3	20.2	120.8	13.8
12	Cloudy	0.03	113.4	970.0	1.2	16.2	0.073	76.1	286.8	51.5	302.6	142.7	9.1	229.5	39.9	238.0	38.6	88.7	10.6	56.8	6.6
C-7 migmatite zone																					
1	Cloudy	0.41	154.6	1946.8	3.7	79.3	0.047	126.5	514.0	94.4	531.7	231.8	33.7	341.1	63.3	416.1	75.6	193.0	24.4	141.8	16.7
2	Cloudy	Bdl	138.2	1187.1	0.5	27.7	0.018	273.7	877.2	130.7	635.2	213.9	24.1	273.1	45.4	276.6	46.6	112.4	13.3	73.6	8.8
4	Clear	0.31	138.9	2077.2	8.6	134.7	0.064	157.7	647.8	119.6	672.8	297.6	38.7	425.0	76.7	487.9	83.9	208.3	26.8	158.0	18.9
5	Cloudy	0.16	156.1	1328.1	3.6	43.5	0.082	107.7	405.6	72.3	410.0	178.9	35.8	274.3	49.4	310.3	54.1	130.0	15.3	84.3	9.8
6	Clear	0.05	175.3	1007.2	0.3	18.0	0.016	77.7	346.1	66.3	380.8	159.0	25.2	222.8	38.2	236.0	39.5	95.4	11.5	64.6	7.7
7	Clear	bdl	192.0	1161.8	0.4	22.8	0.016	104.5	397.2	72.1	405.2	169.9	29.5	242.6	42.5	265.3	45.7	111.5	13.5	77.5	9.3
8	Clear	0.05	167.2	828.5	0.0	10.0	0.004	95.1	360.7	66.4	380.0	153.1	28.1	206.1	34.2	205.1	34.2	79.1	9.1	48.4	5.4
C-8 metasedimentary enclave in Cooma granodiorite																					
1	Clear	0.04	193.4	1011.4	0.2	20.1	0.009	61.9	286.7	58.3	359.5	159.6	18.1	216.8	36.0	228.7	40.0	102.0	12.8	74.5	9.3
2	Cloudy	0.14	251.8	1139.7	0.7	27.0	0.027	93.6	354.7	65.1	383.4	165.0	33.5	242.7	41.6	260.3	45.3	109.7	13.1	71.2	8.3
3a	Cloudy	0.07	230.1	1339.9	1.7	49.1	0.035	118.9	434.5	76.9	440.1	183.6	29.4	271.8	47.3	301.7	53.0	131.5	15.9	87.4	10.3
3b	Clear	0.04	222.1	1147.0	0.7	32.1	0.021	91.8	359.8	67.7	390.9	172.0	29.8	247.7	43.1	266.7	45.4	108.1	12.8	70.0	8.2
4a	Cloudy	0.07	268.9	1113.8	0.2	21.2	0.011	95.2	358.6	65.0	371.0	160.9	36.7	231.9	40.7	257.2	44.9	111.4	13.3	73.5	8.7
4b	Clear	0.19	267.1	1003.6	0.1	13.0	0.007	76.4	304.7	57.6	335.5	148.7	35.9	213.0	37.2	232.1	40.0	97.0	11.5	63.1	7.3
5a	Cloudy	0.05	258.9	1360.7	1.1	48.9	0.022	116.5	451.7	82.6	468.9	192.5	36.9	270.0	47.9	303.4	54.4	135.4	16.5	91.9	10.9
5b	Clear	0.05	262.4	1355.9	0.7	40.5	0.018	109.3	436.2	81.4	466.9	194.1	37.3	273.6	47.4	300.5	53.8	131.3	15.9	88.6	10.6
6	Cloudy	0.04	310.8	1262.2	0.6	31.0	0.018	109.7	388.0	66.1	362.2	148.4	43.3	230.1	41.1	269.4	50.7	127.9	16.3	93.3	11.6
7	Clear	0.05	245.7	1127.9	0.5	27.5	0.017	93.5	347.0	60.4	339.4	147.8	34.4	228.2	40.7	263.3	46.1	110.4	13.7	74.1	9.0
8	Cloudy	0.05	278.9	911.4	2.2	16.2	0.137	121.0	375.3	61.7	342.0	141.5	37.7	202.9	34.6	217.2	37.2	88.6	10.6	58.8	6.9
9	Clear	0.05	220.0	1293.9	0.6	53.7	0.012	80.1	385.9	77.1	460.6	196.8	30.8	274.0	47.4	300.4	52.0	126.4	15.3	84.9	9.8

Abundances are in ppm, and were calculated using interspersed analyses of NIST 610 glass and assuming 54 wt% CaO in the apatite unknowns.

Figure 5 REE chemistry for apatites in Cooma Complex metasediments. (a) Apatite REE patterns (chondrite normalised) for C-4 biotite grade sample. (b) Apatite REE patterns for C-7 migmatite paleosome sample. (c) Apatite REE patterns for C-8 metasedimentary enclave in the Cooma Granodiorite. (d) Sr vs Y plot for apatites from samples C-4, C-7 and C-8. (e) Th vs U plot for apatites from samples C-4, C-7 and C-8.

2001), which preferentially incorporates the LREE (Spear & Pyle 2002). The anomalous LREE-enriched early cloudy apatite grains from C-4 have Th/U ratios of ≥ 1 and the highest Y (Figure 5d, e), distinguishing them from the LREE-depleted apatite with low Th/U ratios of < 0.2 and lower Y abundances. These features are intrinsic to those grains, not a function of the presence of monazite micro-inclusions, and are most simply explained by growth of those apatites in micro-domains where monazite (LREE- and Th-rich) was absent.

The REE and Sr–Y plots show that the apatite compositions become more uniform with increasing metamorphic grade (temperature), indicating chemical equilibration on an increasing scale (Figure 5). This is consistent with the presence of a few apatite grains at low metamorphic grade that might not have equilibrated with monazite, whereas at a higher grade they all did. A similar convergence in composition with increasing grade has been observed in monazite U–Th (Williams 2001) and the whole-rock Rb–Sr isotopic system (Chappell *et al.* 1990).

DISCUSSION

The results of this integrated study of apatite petrography and chemical composition with increasing metamorphic grade in Cooma metapelites demonstrate that apatite grew and recrystallised during high-grade metamorphism. Processes governing this development of fewer and larger apatite grains with increasing metamorphic grade are beyond the scope of this paper. One process possible is Ostwald ripening (driven by minimisation of surface free energy: Ayers *et al.* 1999). On the other hand, Carlson (1999) suggested that Ostwald ripening is only relevant for very small grains, and instead size distributions observed in coarser grained metamorphic growth are caused by interplay between nucleation rates and temperature-dependent growth rates. Regardless of the mechanism, it is clearly observed that apatite recrystallises and grows during progressive metamorphism. LA-ICPMS analyses show that the composition of apatite is marked by depressed LREE abundances and, with increasing metamorphic grade, decreasing Th abundances and lower Th/U ratios. Also, as metamorphic grade increases, there is a confluence in the apatite REE abundances within each sample. These compositional indications of increasing scale of chemical homogenisation are consistent with the petrological observation that there are fewer, larger apatite grains with increasing metamorphic grade.

The apatite chemical and structural changes in Cooma Complex metapelites indicate that any diagenetic apatite in sediments will be subject to dissolution and regrowth during progressive metamorphism. This can occur even if there is only one stable phosphate phase during metamorphism, as shown by the quartz–monazite experiments of Ayers *et al.* (1999). The second process is reaction between phosphate phases during progressive metamorphism, particularly in compositionally complex rocks (Williams 2001; Wing *et al.* 2002) that will cause the modal abundances of phosphate phases to vary with temperature.

Identifiable (larger than micrometre scale) carbonaceous material (graphite?) is rare in apatites from the Cooma metapelites and, in the present samples, has only been positively identified in overgrowths and new grains of translucent, relatively young apatite. This carbonaceous material could only have become enshrouded by apatite during the later stages of metamorphic growth. In contrast, structural carbon within the apatite lattice as carbonate substituting for both phosphate and hydroxyl ions is ubiquitous. The same has been found in apatite from the ≥ 3850 Ma ‘early life’ rock (G91/26) from Akilia, Greenland. Thus, despite previous claims that that apatite contains abundant graphite inclusions *sensu stricto* (Mojzsis *et al.* 1996), other searches have found none (Lepland *et al.* 2005; Nutman & Friend 2006). However, there is a ubiquitous substitution of carbonate in the crystal lattice of G91/26 apatites (Nutman & Friend 2006). The Ayers *et al.* (1999) quartz–monazite experiments also showed that recrystallisation and regrowth of apatite can be expected to have occurred in the Early Archean siliceous rocks, where apatite is the only phosphate present. This Cooma study places a note of caution on the use of an apatite–graphite association as a biotracer in ancient metasediments, where (micro)fossil evidence is lacking.

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