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Keywords

blueschist, blocks, within, serpentinite, m, lange, port, macquarie, eastern, eclogite, australia, middle, implications, evolution, gondwana, 039, margin, triassic, early, carboniferous, GeoQuest

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**Middle Carboniferous - Early Triassic eclogite-blueschist blocks within a
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the evolution of Gondwana's eastern margin**

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Abstract

The New England Orogen of easternmost Australia is dominated by suites of Palaeozoic to earliest Mesozoic rocks that formed in supra-subduction zone settings at Gondwana's eastern margin. On the northern New South Wales coast at Rocky Beach, Port Macquarie, a serpentinite mélangé carries rare tectonic blocks of low-grade, high-pressure, metamorphic rocks derived from sedimentary and igneous protoliths. Dominant assemblages are glaucophane + phengite ± garnet ± lawsonite ± calcite ± albite blueschists and lawsonite-bearing retrogressed garnet + omphacite eclogites. In some blocks with sedimentary protoliths, eclogite forms folded layers within the blueschists, which is interpreted as Mn/(Mn+Fe) compositional control on the development of blueschist versus eclogite assemblages. Review of previous studies indicates pressure-temperature conditions of 0.7-0.5 GPa and $\leq 450^{\circ}\text{C}$. Three samples of high-pressure metasedimentary rocks contain Archaean to 251 ± 6 Ma (Permo-Triassic) zircons, with the majority of the grains being Middle Devonian to Middle Carboniferous in age (380-340 Ma). Regardless of age, all grains show pitting and variable rounding of their exteriors. This morphology is attributed to abrasion in sedimentary systems, suggesting that they are all detrital grains. New *in situ* metamorphic zircon growth did not develop because of the low temperature ($\leq 450^{\circ}\text{C}$) of metamorphism. The Permo-Triassic, Devonian and Carboniferous zircons show strong heavy rare earth element enrichment and negative europium anomalies, indicating that they grew in low pressure igneous systems, not in a garnet-rich plagioclase-absent high pressure metamorphic environment. Therefore the youngest of these detrital zircons provide the *maximum* age of the metamorphism. A titanite + rutile porphyroblast within an eclogite has a U-Pb age of 332 ± 140 Ma (poor precision due to very low U abundances of mostly < 1 ppm.) and provides an imprecise direct age for metamorphism. In the south of the Port Macquarie area, the Lorne Basin ≥ 220 Ma Triassic sedimentary and volcanic rocks unconformably overlie serpentinite mélangé, and provide the *minimum* age of the high-pressure metamorphism. Our preferred interpretation is that the 251

43 Ma zircons are detrital and thus the Port Macquarie high-pressure metamorphism is
44 constrained to the end of the Permian – Early Triassic. Emplacement of the serpentinite
45 mélange carrying the Rocky Beach high-pressure rocks might have been due to docking of a
46 Permian oceanic island arc (represented by the Gympie terrane in southern Queensland?) and
47 an Andean-style arc at the eastern Australian margin (expressed in the New England Orogen by
48 260-230 Ma north-south orientated magmatic belts). Alternatively, if the 251 Ma grains are
49 regarded as having grown in thin pegmatites, then the dominant Devonian-Carboniferous
50 detrital population still indicate a *maximum* age for the high pressure metamorphism of ca. 340
51 Ma. A ≤ 340 Ma age of metamorphism would still be much younger than the previously
52 suggested ca. 470 Ma (Ordovician) age, which was based on Ar-Ar dating of phengites.

53

54 *Keywords: New England Orogen; Blueschist-eclogite; Serpentinites; Gondwana; Port*
55 *Macquarie*

56

57 **1. Introduction**

58 Throughout the Palaeozoic, eastern Australia was at the margin of Gondwana,
59 and was growing eastwards via the addition of granitoids and their volcanic and
60 sedimentary carapaces, largely formed in supra-subduction zone settings (e.g.,
61 Aitchison et al., 1994, Cawood, 2005; Glen, 2005; Cawood et al., 2011; Rosenbaum et
62 al., 2012). Lineaments carrying slivers of tectonised, serpentinitised, mantle are found
63 intertwined between the granitoids and their carapaces (e.g., Spaggiari et al., 2004;
64 Glen, 2005). The serpentinites carry sedimentary and igneous rocks as mélanges of
65 exotic blocks, including rare ones carrying eclogite and blueschist facies assemblages.
66 They are interpreted as vestiges of subduction zone assemblages modified by younger
67 tectonic events (e.g., Glen, 2005).

68 In the New England Orogen (NEO) of northeastern New South Wales and
69 south-eastern Queensland (Fig. 1), two notable occurrences of serpentinite mélange
70 are the Great Serpentine Belt in the Peel-Manning fault system in the southwest
71 (Benson, 1913, 1914a, b, 1915a,b; Offler and Williams, 1987; Sano et al., 2004;
72 Phillips and Offler, 2011) and at Port Macquarie in the southeast (Benson, 1918;
73 Barron et al., 1976; Leitch, 1980; Och et al., 2003, 2007; Lennox and Offler, 2009).
74 Exotic blocks within the Great Serpentine Belt have so far all yielded latest
75 Neoproterozoic to early Palaeozoic U-Pb zircon protolith ages (Aitchison and Ireland,
76 1995; Watanabe et al., 1997). The NEO serpentinites have been interpreted as
77 exhumed vestiges of early Palaeozoic subduction zone complexes, caught-up in latest
78 Palaeozoic to earliest Mesozoic crust-forming events (e.g., Och et al., 2003). However,
79 the protolith ages of the included blocks in the serpentinites can give only maximum,
80 rather than direct, ages for the high-pressure metamorphic events and the incorporation
81 of the blocks within the serpentinite belts. Age determinations on minerals grown or
82 recrystallised during high-pressure metamorphism will give the sought-after direct

metamorphic ages. Particularly at medium to high metamorphic grade, this can be achieved by employing U-Pb dating of metamorphic zircon growths or Sm-Nd determinations on coexisting garnet and omphacite (e.g., Hermann et al., 2001; Gilotti et al., 2004; Nutman et al., 2008). At low grade, direct determination of metamorphic ages of high pressure assemblages becomes difficult, because under these low temperature conditions the growth of metamorphic zircon is uncommon and because of the issue of excess Ar in metamorphic phengites derived from older detrital grains resulting in incorrect, older ages in K-Ar and Ar-Ar geochronology (e.g., Arnauld and Kelley, 1995; Li et al., 1999; Sherlock and Kelley, 2002).

In this paper we present field relationships, zircon U-Pb geochronology and rare earth element (REE) chemistry and metamorphic rutile and titanite U-Pb dating from metasedimentary blueschist and eclogite facies blocks in the NEO's easternmost serpentinite mélange at Port Macquarie (Fig. 1). Our results show that these rocks formed at the end of the Palaeozoic and that high-pressure metamorphism was most likely at ≤ 251 Ma, i.e., ca. 200 million years later than the previously proposed Ordovician timing for this event at Port Macquarie (Fukui et al., 1995; Och et al., 2003, 2007). We discuss the implications of this Permo-Triassic event for the evolution of Gondwana's eastern margin.

2. Regional geological setting – the New England Orogen

The New England Orogen (NEO; Fig. 1) is the easternmost, youngest, component of the Tasmanides orogenic belt of eastern Australia (Flood and Aitchison, 1988; Harrington and Korsch, 1985; Leitch, 1974, 1975; Murray et al., 1987; Aitchison et al., 1994; Cawood, 2005; Glen, 2005; Cawood et al., 2011; Rosenbaum, 2012). The NEO contains latest Neoproterozoic to Permo-Triassic arc-related

108 magmatic rocks (Leitch, 1974; Murray et al., 1987; Aitchison et al., 1994; Cawood et
109 al., 2011; Rosenbaum et al., 2012). Devonian-Carboniferous supra-subduction zone
110 components are the Tamworth Belt forearc basin and Tablelands Complex
111 accretionary wedge rocks (Fig. 1) which developed on top of previously-accreted early
112 Palaeozoic oceanic terranes (Flood and Aitchison, 1988). The core of a
113 Devonian-Carboniferous volcanic arc lies farther to the west, but it is now largely
114 obscured by post-Devonian sedimentary rocks (Leitch, 1974, 1975; McPhie and
115 Fergusson, 1987; Roberts and Engel, 1987; Roberts and James, 2010; Roberts et al.,
116 1995, 2004, 2006). It is only evident from intermediate to felsic volcanic rocks of the
117 Currabubula Arc on the western edge of the Tamworth Belt. Southwards,
118 tectonically-displaced forearc basin rocks in the Hastings Block (Figure 1 inset) are
119 correlated with the Tamworth Belt. The Tablelands Complex rocks are mostly
120 Carboniferous to early Permian deep marine volcanoclastic turbidites and cherts, mafic
121 volcanic rocks and olistostromal deposits (Leitch & Cawood, 1980; Cawood, 1982;
122 Fergusson, 1984; Aitchison et al., 1994). These rocks show penetrative steeply dipping
123 fabrics and display prehnite-pumpellyite/lower greenschist to amphibolite-facies
124 metamorphic assemblages (Binns et al., 1966; Korsch and Harrington, 1981; Dirks et
125 al., 1992). The Peel-Manning fault system (Fig. 1a) forms the tectonic boundary
126 between the Tamworth Belt and the Tablelands Complex. It is marked by serpentinite
127 belts that contain exotic tectonic blocks of early Phanerozoic to Neoproterozoic
128 arc-related rocks and rare blocks of eclogite and blueschist facies rocks (e.g., Shaw and
129 Flood, 1974; Fukui et al., 1995; Aitchison and Ireland, 1995). Generally, an early
130 Palaeozoic age has been ascribed for the Peel-Manning fault system assemblage and
131 the age of high-pressure metamorphic blocks within it (e.g., Fukui et al., 1995; Phillips
132 and Offler, 2011), albeit it is recognised that the Peel-Manning serpentinites were

133 deformed and metamorphosed at the end of the Permian (Aitchison and Flood, 1992;
134 Aitchison et al., 1997).

135 The Early Permian history of the NEO is marked by development of
136 sedimentary basins dominated by proximal seep marine mass flow deposits (Aitchison
137 and Flood, 1992; Aitchison et al., 1997; Korsch et al., 2009). The Early Permian
138 granitoids are the S-type Bundarra granite and the Hillgrove suite, and several other
139 small S- and I-type plutons; Figure 1a). U-Pb zircon ages (Cawood et al., 2011;
140 Rosenbaum et al., 2012) show that these were all emplaced between 296 and 267 Ma.
141 Thereafter, from 250 to 225 Ma, subduction resumed, and there was the emplacement
142 of eastward-stepping north-south trending arc-related plutons. The 250–225 Ma
143 magmatism produced I-type granitoids and calc-alkaline volcanic rocks, which are
144 interpreted to have been emplaced in an Andean arc setting (Cawood, 1984; Flood &
145 Shaw, 1975; Bryant et al., 1997).

146 One proposed geodynamic setting for 296-230 Ma crustal evolution is an
147 eastwards, asymmetric, subduction rollback, that between ca. 300 and 267 Ma lead to
148 the evolution of an orocline in the southern end of the NEO (Jenkins et al., 2002;
149 Collins and Richards, 2008; Cawood et al., 2011; Rosenbaum et al., 2012). After 267
150 Ma the proposed orocline in the southern NEO continued to tighten (Murray et al.,
151 1987; Cawood et al., 2011; Rosenbaum et al., 2012) and hence there was a hiatus in arc
152 magmatism between 267-250 Ma. Subduction with arc magmatism resumed from 250
153 Ma. Thereafter, there was the onset of the Hunter-Bowen orogeny – a phase of E-W
154 contractional deformation (Collins, 1991; Holcombe et al., 1997; Korsch et al., 2009).
155 This orogeny involved westward-propagating thrusting of the early Permian basins,
156 with their transformation into foreland systems (Fergusson, 1991; Korsch et al., 2009).
157 The east-west compression of the Hunter-Bowen orogeny has been attributed to

158 coupling in the subducted and over-riding plates, following further eastward migration
159 of subduction systems located at the edge of Gondwana (Rosenbaum et al., 2012).
160 However, another alternative is the docking of a Permian intra-oceanic island arc
161 terrane against the eastern edge of Gondwana (Harrington, 1983). Following the
162 Hunter-Bowen orogeny, Triassic to Jurassic depositional basins developed over the
163 NEO.

164

165 3. The Port Macquarie serpentinite mélange

166 3.1. *Geological background*

167 The Port Macquarie area is mostly underlain by a ‘broken formation’ of
168 Palaeozoic units intercalated with the Port Macquarie serpentinite mélange (Leitch,
169 1974; Barron et al., 1976; Och et al., 2007). Common lithologies are metabasalts, with
170 preservation of pillow structures quite widespread, cherts bearing radiolarians and
171 conodonts, and clastic sedimentary rocks that are mostly volcanic lithic arenites (e.g.,
172 Barron et al., 1976; Leitch, 1980). The easternmost of these along the coast are well
173 exposed, and have been named the Watonga Formation (Leitch, 1980). Based on
174 radiolarian and conodont assemblages, Watonga Formation metacherts have been
175 ascribed Ordovician and Devonian ages (Ishiga et al., 1988; Och et al., 2007a). The
176 Tacking Point Gabbro (31°28’24”S 152°56’14”E; Och et al., 2007b) was intruded into
177 Watonga Formation metabasalts and cherts, and based on U-Pb zircon dating, is
178 Devonian in age, (Buckman et al., in preparation). Zircon U-Pb dating on
179 detrital/volcanic zircons from a Watonga Formation volcanic lithic arenite from Green
180 Point (31°25’49”S 152°55’26”E; Parker, 2010) indicates a maximum
181 mid-Carboniferous depositional age (Buckman et al., in preparation). Thus the
182 Watonga Formation contains rocks of different age and origin. Similar

183 metasedimentary units inland are poorly exposed. They are either intruded or
184 intercalated with metadolerite, and were assigned to the ‘middle’ Palaeozoic
185 Touchwood Formation and the Lower Permian Thrumster slate by Leitch (1980).
186 Cropping out sporadically along the shoreline from Town Beach (31°25’47”S
187 152°55’20”E) to just north of Tacking point (around 31°28’13”S 152°56’05”E) is the
188 Port Macquarie serpentinite mélange (Barron et al., 1976; Och et al., 2007b). Recent
189 mapping suggests that the mélange structurally overlies the parts of the Watonga
190 Formation that consist of lithic arenites with Carboniferous detrital zircons (Buckman
191 et al., in preparation). However, inland, because of poor exposure, the relationship of
192 the mélange to the Touchwood Formation and the Thrumster slate has not been
193 elucidated. These Ordovician to Lower Permian tectonic assemblages, including the
194 serpentinites, are overlain unconformably by Early Triassic alluvial deposits and
195 volcanic rocks of the Lorne Basin (Leitch, 1980; Och et al., 2007b; Pratt, 2010). Thus
196 the last major tectonic event involved the intercalation of Devonian to Lower Permian
197 rocks, and must have occurred after deposition of the Early Permian Thrumster slate
198 and before the deposition of the unconformable Lorne Basin Early Triassic rocks
199 (timescale of Gradstein et al., 2012). Some deformation continued after deposition of
200 the Lorne basin, as shown by folding in its eastern parts (Pratt, 2010).

201

202 3.3. Rocky Beach blueschist and eclogite blocks

203 At the northern end of Rocky Beach (31°26’12”S 152°55’33”E) several blocks
204 of high-pressure metamorphic rocks up to 10 m diameter occur within the Port
205 Macquarie serpentinite mélange (Barron et al., 1976; Och et al., 2003, 2007b). One ca.
206 10 m block of massive blueschist preserves relict pillow structures in its centre, which
207 towards its margin becomes obliterated by higher strain with the development of a
208 glaucophane schistosity. Such rocks are clearly derived from basaltic protoliths. Given

209 the protolith nature and the low temperature of metamorphism, such rocks are unlikely
210 to carry zircon and were not investigated in this study. Other blocks consist of
211 blueschist with thin, folded layers of eclogite (Fig. 2a; also illustrated by Och et al.
212 2003 as their Fig. 2). This block was the source of our samples eclogite 21-06 and
213 blueschist RB-2. There are also blocks of widely retrogressed, high-pressure
214 metamorphic rocks that also have compositional layering (Fig. 2b; our sample RB-3 is
215 from this block). These retrogressed rocks still contain some relict garnet, but the
216 omphacite and/or glaucophane have been entirely replaced by chlorite. Consequently,
217 it is uncertain whether they originally carried blueschist or eclogite facies assemblages.
218 The blocks with compositional layering are likely to have been derived from
219 sedimentary or volcano-sedimentary protoliths. Thus we targeted them for zircon U-Pb
220 dating, because even if it transpired that the metamorphic grade was too low to grow
221 zircon *in situ* during high-pressure metamorphism, their youngest detrital zircons
222 would define a *maximum* possible age for that metamorphism.

223 The whole rock geochemical analyses for eclogite 21-06, blueschist RB-2 and
224 retrogressed high-pressure rock RB-3 are presented in Table 1. Their high MgO +
225 Fe₂O₃, Cr (400-206 ppm) and Ni (68-64 ppm) contents show dominance of mafic
226 material. However, high K₂O (3.63-1.02 wt%), Ba (1102-401 ppm) and overall low
227 SiO₂ contents (down to 43.88 wt%) suggest that the protoliths were not fresh mafic
228 rocks. Furthermore Zr content is high (275-103 ppm). Retrogressed sample RB-3 has
229 an anomalously high TiO₂ content (3.37 wt%). The block from where RB-3 was
230 sampled contains ilmenite + rutile segregations (sample RB-4, see below).
231 Over-representation of such segregation material in the bulk sample is a likely reason
232 for the high TiO₂ content. Combining the interlayered nature of eclogite and blueschist
233 (21-06 and RB-2), with the whole rock chemistry, we propose that the protoliths of the

234 dated samples are dominated by altered mafic volcanic material, with an additional
235 detrital component.

236 In the Rocky Beach blueschist facies rocks, the main assemblage is
237 glaucophane + garnet + phengite $\pm$ lawsonite $\pm$ albite + titanite + pyrite. In the eclogites
238 lawsonite is present, but there has been extensive retrogression of the garnet and
239 omphacite, with the development of chlorite. Both Barron et al. (1976) and Och et al.
240 (2003) recorded complex metamorphic textures, with several generations of
241 high-pressure mineral growth, during the development syn-kinematic fabrics. The
242 blueschists are traversed by thin albite-bearing veins. For the Rocky Beach
243 lawsonite-bearing blueschist rocks Price (1991) estimated pressure-temperature
244 conditions of ca. 0.75-0.6 GPa and 270-200°C, whereas Och et al. (2003) suggested
245 somewhat higher temperatures of 450-350°C, in a similar pressure regime. Och et al.
246 (2003) suggested appreciably high temperatures and pressures for the Rocky Beach
247 eclogites (see Discussion).

248

249 **4. Zircon petrography, U-Pb dating and rare earth element chemistry**

250 *4.1. Analytical methods*

251 Zircon concentrates were prepared by standard heavy liquid and isodynamic
252 separation techniques at the mineral separation laboratory of the Research School of
253 Earth Sciences, the Australian National University (ANU). The location of the three
254 samples investigated are shown in Figs. 2a,b). The concentrates were hand picked
255 under a binocular microscope, and the selected grains were cast in epoxy resin discs
256 together with the zircon Temora 1 reference material (Black et al., 2003). The discs
257 were ground to reveal mid-sections through the grains and then polished. The grains
258 were documented with reflected and transmitted light photomicrographs (Fig. 3), and

259 also by cathodoluminescence (CL) imaging. CL images of representative zircons are
260 shown in Fig. 4.

261 Zircons were U-Pb dated on the SHRIMP II instruments at the University of
262 Hiroshima and Geoscience Australia (Canberra). Analytical protocols followed
263 Williams (1998), and reduction of the raw data used the ANU software 'PRAWN' and
264 'Llead'. $^{206}\text{Pb}/^{238}\text{U}$ of the unknowns was calibrated using measurements of the Temora
265 2 reference material (U-Pb ages concordant at 417 Ma; Black et al., 2003) interleaved
266 with analyses of the unknowns. U and Th abundance was calibrated using
267 measurement of the reference zircon SL13 (U=238 p.p.m.) located in a set-up mount.
268 The zircon U-Th-Pb data are summarised in Table 2. The reduced and calibrated data
269 were assessed and plotted using the ISOPLOT program of Ludwig (2003).

270 Rare earth element (REE) analyses of some zircons were undertaken using the
271 Hiroshima University SHRIMP II instrument, and for others the REE and other trace
272 element abundances were acquired by LA-ICP-MS at ANU. The SHRIMP analyses
273 were undertaken in the normal mass-resolution mode (~6000), and according to the
274 method outlined by Maas et al. (1992) and Hidaka et al. (2002). Abundances were
275 calibrated using count rates obtained from analyses of the zircon standard 91500
276 (Wiedenbeck et al., 2004). The zircon LA-ICP-MS data was acquired according to the
277 methodology given by Eggins et al. (1998). It was calibrated using interspersed
278 analyses of NIST610 glass. As a check on the accuracy of elemental abundance, SL13
279 zircons were analysed twice as unknowns, and yielded an average U abundance of 230
280 p.p.m., compared to the accepted isotope dilution value of 238 ppm. REE analyses are
281 summarised in Table 3.

282

283 *3.2. Zircon morphology and U-Pb dating*

284 Three blueschist-eclogite samples from Rocky Beach (samples 21-06, RB-2
285 and RB-3; Fig. 2a,b) all gave low yields of zircons (<50 grains per kilogram), and
286 display the same range of morphologies. The exteriors of all grains are rounded, and
287 regardless of their age show pitting of their surface, which is attributed to abrasion
288 within sedimentary systems (Fig. 3a-c). Their rounded and pitted form contrasts
289 strongly with igneous zircons in Port Macquarie rocks, such as from the Tacking Point
290 gabbro (31°28'24"S 152°56'14"E; Och et al., 2007b), at the southern end of the Port
291 Macquarie coastal tract. In such rocks, the zircons are not pitted and sharp clear
292 boundaries are preserved between the grain facets (Fig. 3d). Furthermore, the exterior
293 form of the zircons in Rocky Beach samples differs from definite syn-
294 high-temperature eclogite facies metamorphic zircon, for example from the Franklin
295 metamorphics of Tasmania (Fig. 3e). In such eclogites, metamorphic zircons have
296 clean, exterior surfaces, with common development of multifaceted habits. Therefore,
297 combined with evidence from CL images for the lack of overgrowths developed *in*
298 *situ*, we conclude that the zircons from both Rocky Beach blueschist and eclogite
299 facies metamorphic rocks are best interpreted as detrital grains, largely devoid of
300 coatings of new, syn-metamorphic growth.

301 CL images of selected zircons are shown in Fig. 4. A few rare grains (2 in
302 sample 21-06, 1 in sample RB-3; Figs. 4a,b) are structurally simple, slightly rounded
303 euhedral prisms with well-preserved oscillatory zoning. Multiple analyses on these
304 three grains yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 251 ± 6 Ma (MSWD=0.16; Fig.
305 5a; Induan = earliest Triassic, according to the timescale of Gradstein et al., 2012).
306 These grains are interpreted to be detrital in origin and derived from an Induan igneous
307 source. Their age falls at the start of the youngest arc magmatism in the New England
308 Orogen. Seven 380-340 Ma grains (Middle Devonian to Middle Carboniferous) are
309 somewhat more rounded, devoid of inherited cores and with well developed oscillatory

310 zoning (Figs. 4c and 5a). Older grains form more complex populations, with many
311 grains being composite, with magmatic cores and younger magmatic overgrowths, or
312 more commonly rounded cores of oscillatory-zoned zircon with overgrowths that
313 appear homogeneous or sector-zoned in CL images. In all such cases our interpretation
314 is that the metamorphic overgrowths have been abraded and partly removed during
315 sedimentary transport, showing that they carry a record of distal metamorphism in their
316 source region, and not *in situ* metamorphism in the Rocky Beach blueschist-eclogite
317 facies blocks. This is illustrated by RB-2 grains 2 and 4 and RB-3 grain 3 (Figs. 4d,e,f).
318 In Neoproterozoic RB-2 grain 2, a 735 Ma core has a 594 Ma overgrowth, partly
319 removed by abrasion such that the core occurs at half of the grain's surface. For RB-3
320 grain 3, a rounded oscillatory core (not dated) has a sector-zoned ca. 405 Ma (early
321 Devonian) rim, which is partly abraded. At the right hand grain margin (Fig. 4f), the
322 inclusion of another mineral previously entirely enclosed, is now at the grain surface.
323 Thus the eclogite and blueschist samples all yielded essentially the same zircon
324 populations, both in terms of habit, structure and age distribution.

325

326 4.3. Zircon REE chemistry

327 REE analyses of zircons from the blueschist and eclogite facies rocks were
328 undertaken to ascertain which phases they equilibrated with (chondrite-normalised
329 data are plotted in Fig. 5b). 251 Ma oscillatory zoned prism grains 4 and 7 from sample
330 21-06 display strong enrichment of the heavy over the light REE, with a negative Eu
331 anomaly. This indicates the youngest grains grew in the presence of plagioclase and
332 absence of garnet, showing that they did not grow during high-pressure
333 metamorphism. A similar REE pattern is found for sample 21-06 Carboniferous grains
334 10, 11 and 14 (Fig. 5b). Other REE analyses focussed on metamorphic (albeit abraded)

335 overgrowths, to ascertain if they provide evidence of blueschist-eclogite facies
336 metamorphism at an earlier time, i.e. in accord with suggestion that it occurred in the
337 early Palaeozoic (Och et al., 2003, 2007b, 2010 and references therein). Most of these
338 rims, ranging in age from ca. 405 Ma on RB-3 grain 3 to ca. 595 Ma Neoproterozoic
339 ones such as on RB-2 grains 2 and 4 (Figs. 4d and e) show similar heavy REE enriched
340 patterns with negative Eu anomalies, demonstrating that during metamorphism they
341 grew in a low pressure plagioclase-present, garnet-absent environment (Rubatto,
342 2002). The only exceptions are the ca. 560 Ma rim on RB-2 grain 6 and the entire 1100
343 Ma 21-06 grain 15, which both show depressed heavy REE abundances but still carry
344 negative Eu anomalies (Fig. 5b). These indicate source region metamorphisms at
345 medium pressures with both garnet and plagioclase present (Rubatto, 2002). Thus
346 none of the dated zircons from the blueschist-eclogite blocks carry a depressed heavy
347 REE without a Eu anomaly signature, which would be indicative of high-pressure
348 metamorphism (example from an eclogite facies metamorphic zircon from the
349 Franklin metamorphics is shown in Fig. 5b for comparison).

350

351 **5. Titanite-rutile U-Pb dating**

352 *5.1. Sampling and analytical method*

353 Rocky beach eclogites locally contain porphyroblasts of titanium rich phases
354 which were identified by use of a Niton hand-held portable XRF analyser. One >1 cm
355 diameter porphyroblast (sample RB-4; Fig. 2b,c) was sawn from a retrogressed high
356 pressure metamorphic block, cast in an epoxy resin disc along with the ANU Khan
357 titanite standard and polished for phase identification via EDS spectral analysis with a
358 scanning electron microscope. The phases were then dated by the LA-ICP-MS method.

LA-ICP-MS analysis was undertaken at GEMOC at Macquarie University, Sydney using a New Wave UP213 Nd:YAG 213 nm laser ablation system coupled to an Agilent 7700 quadrupole ICP-MS. The setup for LA-ICP-MS analysis and analytical procedure were described by Jackson et al. (2004) and R19 rutile (489.5 ± 0.9 Ma; Zack et al., 2011) was used as a calibration standard.

5.2. Titanite-rutile segregation petrography and U-Pb dating

A backscattered electron image of part of the segregation is shown in Fig. 6. The main phases present are titanite and rutile, seemingly in equilibrium with each other. Sulphides, chlorite, glaucophane and ilmenite also occur.

The U-Pb data are summarised in Table 4. The high $^{207}\text{Pb}/^{206}\text{Pb}$ combined with low $^{238}\text{U}/^{206}\text{Pb}$ in all the analyses shows that Pb in the rutiles and titanites are dominated by ‘common’ non-radiogenic Pb. In order to obtain a radiogenic age avoiding the problem of isobaric mercury (^{204}Hg) interference at the ^{204}Pb mass when undertaking a correction for common Pb, the data was regressed in $^{207}\text{Pb}/^{206}\text{Pb}$ versus $^{238}\text{U}/^{206}\text{Pb}$ space, as shown in Fig. 7. In this approach, where the regression line intercepts the $^{207}\text{Pb}/^{206}\text{Pb}$ axis ($^{238}\text{U}/^{206}\text{Pb}=0$), it gives the $^{207}\text{Pb}/^{206}\text{Pb}$ composition of the common Pb. Where the regression line gives a lower intercept with concordia, it signifies the U-Pb radiogenic component in the rutiles and titanites, which in this case is interpreted as the timing of metamorphic growth. All the data fall along a single regression line, with an MSWD=0.71. Given that most of the coexisting rutiles and titanites have <1 ppm, each determination has a large analytical error and is dominated by the non-radiogenic ‘common’ Pb. Hence, there is a long extrapolation of a regression line with a broad error envelope to a lower concordia intercept. The ‘closure’ temperature of both titanite and rutile are ca. 600°C (Scott and St-Onge,

1995; Cherniak, 2000), which is above the peak metamorphic temperature of these rocks. Therefore the lower concordia intercept of 332 ± 140 Ma (95% confidence) is interpreted as giving the age of metamorphic rutile + titanite growth, but with poor precision.

388

6.1. Garnet rare earth element chemistry

6.1. Sampling and analytical method

Fragments of garnet grains were cast in an epoxy resin disc and polished to reveal cross sections for analysis. They were analysed by the LA-ICP-MS method at GEMOC at Macquarie University, Sydney using a New Wave UP213 Nd:YAG 213 nm laser ablation system coupled to an Agilent 7700 quadrupole ICP-MS. The setup for LA-ICP-MS analysis and analytical procedure were described by Jackson et al. (2004) and NIST610 glass was used as a calibration standard. REE analyses of 21-06 and RB-2 garnets are summarised in Table 3.

398

6.2. Results

Overall the garnet REE abundances are low, but relative to chondrite, the heavy REE are enriched and the light REE are depleted (Fig. 5b). There are no Eu anomalies, indicating that the garnet grew in a plagioclase-free environment, during high pressure metamorphism.

404

7. Discussion

7.1. Interpretation of the garnet and zircon rare earth element signatures and the zircon ages

408 With two exceptions (see below) all zircons in samples 21-06, RB-2 and RB-3
409 are strongly enriched in the heavy REE and depleted in the light REE relative to
410 chondrite, and show negative Eu anomalies (Fig. 5b). These patterns and abundances
411 are coincident with magmatic zircons grown from common granitic melts, in the
412 presence of plagioclase (Belousova et al., 2002). The only zircons that equilibrated
413 with garnet (based on lesser enrichment of the heavy REE) are 21-06 grain 15 (a 1100
414 Ma low Th/U oval grain), and RB-2 analysis 6.1 (a 560 Ma abraded overgrowth; Fig.
415 5b). However, both these show negative Eu anomalies, indicating equilibration with
416 plagioclase. Therefore they did not grow *in situ* in a plagioclase-free high-pressure
417 metamorphic environment, but instead are detrital grains reflecting lower pressure
418 metamorphism in the sediment source regions. In contrast, the 21-06 and RB-2 garnets
419 do not show Eu anomalies and thus did not equilibrate with plagioclase. Consequently,
420 none of zircons grew in equilibrium with the high pressure metamorphic garnet.
421 Instead, they are interpreted as detrital grains, thereby they only give a *maximum* age
422 for the high-pressure metamorphism.

423

424 7.2. Timing of high-pressure metamorphism

425 At Green Point (31°25'49"S 152°55'26"E) the Port Macquarie serpentinite
426 mélange carrying the high-pressure rocks is in tectonic contact with low metamorphic
427 grade Carboniferous volcanic lithic arenites previously ascribed to the upper portion of
428 the Watonga Formation (Buckman et al., in preparation). In the south at Tacking Point
429 the serpentinites are in tectonic contact with an Ordovician-Devonian metachert and
430 Devonian igneous complex (Buckman et al., in preparation). On the basis that these
431 tectonic contacts are not entirely late faults much younger than upper crustal
432 emplacement of the serpentinite with its high-pressure inclusions, these field

relationships would argue that the Port Macquarie serpentinite mélange is Late Carboniferous or younger. In the southern part of the Port Macquarie area, Early Triassic, >220 Ma alluvial sedimentary rocks of the Lorne Basin unconformably overlie serpentinites, giving the minimum age for the high pressure metamorphism (Leitch, 1980; Och et al., 2007b; Pratt, 2010).

Zircons from sample 21-06 were concentrated in 2010, whereas zircon concentrates for the other two samples RB-2 and RB-3 were prepared in 2011. All samples gave a small yield of zircons (<50 grains per kilogram), with similar morphology and age distribution, including young, ca. 250 Ma zircons. Given that the zircon concentrates were prepared at two different times, and the zircons hand-picked and cast into epoxy mounts at different times, we consider it unlikely that the ca. 250 Ma zircons are laboratory contaminants, but are the youngest detrital grains from these samples. Even if these ca. 250 Ma grains are discounted (such as being sourced from the thin albite pegmatite veins), it should be noted that the majority of the grains are Middle Carboniferous or Devonian in age, and are thus still appreciably younger than the Ordovician age for the high-pressure metamorphism proposed by Och et al. (2003, 2007b, 2010). Thus from geological relationships and from our zircon studies we conclude that the high-pressure metamorphism occurred before deposition of the Early Triassic Lorne basin rocks and probably after 251 Ma, but certainly after ca. 340 Ma.

452

7.2. *Contradiction between zircon U-Pb and mica K-Ar and Ar-Ar ages?*

The interpretation of the zircon data as indicating late Palaeozoic to earliest Triassic high-pressure metamorphism contradicts the interpretation of older, >400 Ma, Ar-Ar and K-Ar mica ages as indicating growth during Ordovician high-pressure metamorphism (Fukui et al., 1995; Hyodo, 2008; Och et al., 2003, 2007a, 2010).

458 However, high pressure metamorphic terranes commonly give anomalously old Ar-Ar
459 mica ages, relative to ages of high pressure metamorphism established by U-Pb zircon
460 and Sm-Nd mineral isochrons (Kelley et al., 1994). The apparently too-old ages are
461 most likely the result of excess argon. This is despite the fact that the mica samples
462 might yield apparently acceptable stepped-heating plateau. Three examples of this
463 follow: (a) In the ultra high-pressure terrane of Dabie Shan, China, Ar-Ar mica ages
464 are Neoproterozoic, whereas U-Pb and Sm/Nd ages are ca. 220 Ma (Li et al., 1999).
465 The macroscopic reason for this was investigated by Li et al. (1999). They noted that
466 high-pressure rocks from the same outcrop failed to equilibrate Ar-isotopes between
467 each other, on a centimetre to metre scale. They proposed that excess ^{40}Ar was derived
468 internally from the high-pressure rocks, through the degassing of early-generation
469 (detrital) minerals, but was not completely expelled from the rock body prior to its
470 closure for the isotopic system. This is accord with the ultra-high-pressure
471 metasedimentary rocks containing early Palaeozoic and Precambrian detrital zircons
472 (Maruyama et al., 1998), demonstrating the presence of old crustal material in these
473 rocks. (b) The high pressure rocks of the Dora Maira Massif in the western Alps give
474 ca. 100 Ma Ar-Ar ages, conflicting with ca. 40 Ma zircon U-Pb ages (Arnaud and
475 Kelley, 1995). (c) In a study of blueschist and low-temperature eclogite facies rocks
476 from the Tavsanli Zone of NW Turkey (Sherlock and Kelley, 2002), samples were
477 analysed by the UV Laser Ablation method and yielded apparent ages ranging from 72
478 to 155 Ma. Detailed *in situ* intra-grain profiling of phengites, and analyses of
479 sodic-amphibole, lawsonite, quartz and garnet, provided the detailed spatial
480 distribution of excess argon within different minerals in the same samples. This
481 revealed that they acted as near closed systems where excess argon was preferentially
482 partitioned into phengite. They concluded that excess argon was derived *in situ*, rather
483 than having been introduced by fluids. Therefore, Sherlock and Kelley (2002)

484 proposed that a combination of stepped-heating and *in situ* laser spot analyses is
485 required to provide the most reliable understanding of Ar-Ar ages from high pressure
486 metamorphic rocks. They also advised that any Ar-Ar mica ages that are older than the
487 Rb-Sr ages on the same micas should be regarded as suspect, and likely to contain
488 excess argon. In the case of the Port Macquarie Rocky Beach eclogites and blueschists,
489 to our knowledge, Rb/Sr mica ages have not been published. Such Rb/Sr mica ages
490 would help to clarify the meaning of the Ar-Ar ages. Given the general problems of
491 excess argon in low-temperature, high-pressure, Ar-Ar mica geochronology (e.g., Li et
492 al., 1999; Arnauld and Kelley, 1995; Sherlock and Kelley, 2002) and the present lack
493 of Rb/Sr dating of the Rocky Beach phengites, we contend that our zircon ages give a
494 more robust constraint on the timing of metamorphism than the available mica ages.

495

496 7.3. Appraisal of conditions of the high-pressure metamorphism at Port Macquarie

497 Appraisal of the glaucophane schists suggests pressures of ca. 0.7-0.6 GPa,
498 with temperatures of 450-350°C (Och et al., 2003). These conditions coincide with the
499 stability field of glaucophane-bearing assemblages of Maresch (1977) and are in
500 accord with albite being present with the glaucophane (Och et al., 2003). The low
501 temperature for the blueschists is in accord with the widespread coexistence of
502 lawsonite + glaucophane (Barron et al., 1976; Och et al., 2003), because lawsonite is
503 generally regarded as breaking-down above ca. 400°C at these pressures (Newton and
504 Kennedy, 1963; Carson et al., 2000). Thus overall, the Port Macquarie glaucophane
505 schist assemblages record low grade, only moderate high-pressure regimes. This
506 regime is typical for blueschists from the upper parts of subduction zones, such as in
507 the Central Franciscan of California (Oh et al., 1991).

508 Associated with the Rocky Beach blueschists are eclogites, which can occur
509 together as thin interfolded layers (Fig. 2a). This has been recorded in other low-grade
510 high-pressure rocks, such as in the Franciscan of California (Oh et al., 1991; their Fig.
511 2). They demonstrated that at low grade, the development of glaucophane-dominated
512 blueschists versus omphacite-bearing eclogites is controlled by variations in
513 Mn/(Mn+Fe) in bulk compositions.

514 Presently, the only constraint on the pressure-temperature conditions for the
515 Rocky Beach eclogite assemblages are the coexistence of lawsonite with garnet +
516 omphacite, together with a single estimate of ca. 560°C from garnet-omphacite Fe-Mg
517 cation exchange thermometry (Och et al., 2003). Och et al. (2003) based this
518 temperature on a single pair of garnet-omphacite analyses (Tables 1 and 2 of Och et al.,
519 2003). These Tables indicate that there is considerable variation in Fe/Mg between
520 different garnet and omphacite analyses. By using different permutations of the
521 published analyses this would lead to possible calculated temperatures between
522 900-300°C at 0.7-0.6 GPa (calculated by the Excel™ spreadsheet PX-NORM of
523 Sturm, 2003). Och et al. (2003) did not explain why one particular mineral pair giving
524 560°C was chosen. Furthermore, we note the rather modest Al₂O₃ content (mostly
525 10-7 wt%) of the Port Macquarie omphacites, which is similar to those from other low
526 grade (<1 GPa, <450°C) eclogites (e.g., from the Franciscan - Oh et al., 1991), rather
527 than those encountered >1.0 GPa medium to high temperature eclogites. Therefore, the
528 suggestion of a much higher temperature (560°C) and pressure (>1.5 GPa) for the
529 Rocky Beach eclogites compared with the blueschists needs to be substantiated.
530 Instead, we consider it most likely that the eclogites formed within the same low
531 temperature, moderately high-pressure conditions as the blueschists, with the
532 eclogite-blueschist transition governed by bulk composition. Supporting this
533 interpretation are; the intimate interlayering of eclogites with blueschists (samples

534 21-06 and RB-2; Fig. 2a), the three times higher Mn/(Mn+Fe) of the eclogite (Table 1),
535 and as presented in Och et al. (2003) the stability of lawsonite with omphacite and
536 garnet.

537 If all the blueschist and eclogite facies rocks formed at low grade conditions at
538 only <450°C, it is unlikely that new *in situ* metamorphic zircon overgrowths would
539 have developed during the high-pressure metamorphism. Thus the grains from
540 eclogites show the same pitted surfaces as those from the blueschists, *without* the
541 development of euhedral, faceted metamorphic overgrowths, as is seen on zircons
542 definitely grown during higher temperature eclogite facies metamorphism (Fig. 3).

543

544 *7.3. Late Palaeozoic blueschist-eclogite facies metamorphism at Port Macquarie and*
545 *the evolution of the New England Orogen and eastern Gondwana*

546 The Port Macquarie serpentinite mélange is an isolated occurrence on the
547 coast, and there is no proven connection with the Great Serpentine Belt of the
548 Peel-Manning fault system inland (Fig. 1a). Thus given the geological complexity of
549 the New England Orogen, with several Devonian-Permian arc-accretionary
550 assemblages present, we do not presume here a Late Palaeozoic to earliest Triassic age
551 for the crustal emplacement of the Great Serpentine Belt, and our following discussion
552 on tectonic significance will be based solely on our data from the Port Macquarie
553 serpentinite.

554 In the Permo-Triassic, eastwards migration of arc activity meant that the
555 Carboniferous Tablelands-Wandilla subduction complex was the basement of the
556 250-225 Ma north-south components of the New England batholith and related
557 volcanic rocks (Fig 1a; Cawood et al., 2011; Rosenbaum et al., 2012). We note that the
558 youngest detrital zircons in our eclogite and blueschist facies samples coincide with

the inception of this arc activity, which is likely to be their ultimate source. At the extreme eastern fringe of Australia in south-eastern Queensland is the enigmatic Gympie terrane, which seems to be a Permian island arc assemblage (Sivell and McCulloch, 2001). Prior to opening of the Tasman Sea, perhaps this was contiguous with the Brook Street Terrane in New Zealand and the Teremba Terrane of New Caledonia (Harrington, 1983; Spandler et al., 2005). We propose that the emplacement of Port Macquarie serpentinite mélange carrying the eclogites and blueschists was related to subduction at the margin of Gondwana and/or to the juxtaposition a Palaeopacific Ocean Permian island arc (now represented by the dispersed Gympie, Brook Street and Teremba Terranes) against an Andean eastern Australian margin (represented by the 260-230 Ma New England Batholith and volcanic components, Fig. 1a; Cawood et al., 2011; Rosenbaum et al., 2012). This event might be the driving force behind the Permo-Triassic Hunter Bowen orogeny (Carey and Browne, 1938), during which basement Carboniferous Tamworth Belt forearc rocks were thrust westwards over Permian back-arc basin rocks of the eastern fringes of the Sydney-Gunnedah-Bowen basins (Fig. 1a).

575

576 **8. Conclusions**

577 (1) Three samples of metasedimentary eclogite and blueschist facies rocks from the Port
578 Macquarie serpentinite mélange at Rocky beach yielded detrital zircons with ages from >3000
579 to 251 Ma.

580 (2) Metamorphic overgrowths developed *in situ* during high-pressure metamorphism were not
581 detected. This is in accord with reappraisal of the conditions of the blueschist and eclogite
582 facies metamorphism, for which all the available information indicate low-grade for both, with

583 temperatures of $<450^{\circ}\text{C}$ at 0.7-0.6 GPa. If so, this would be in accord with the lack of
584 syn-eclogite facies metamorphic zircon growth.

585 (3) Hence, from the U-Pb zircon studies, the youngest detrital grains (251 Ma) give the
586 *maximum* age for the high-pressure metamorphism. Lorne Basin alluvial sedimentary rocks
587 (≥ 220 Ma) deposited unconformably on Port Macquarie serpentinite mélange give the
588 *minimum* age for the high-pressure metamorphism.

589 (4) The zircon U-Pb age constraint for the high-pressure metamorphism and the previously
590 reported Ordovician Ar-Ar mica ages for this event are contradictory. Our explanation for this
591 is that the micas contain excess ^{40}Ar , as is commonly found in micas from low-grade
592 high-pressure metamorphic terranes. This can be tested by Rb/Sr dating of the micas with
593 apparent Ordovician Ar-Ar ages.

594 (5) The new age constraints suggest that the high-pressure metamorphic event at Port
595 Macquarie occurred during late Palaeozoic to earliest Triassic subduction at the Gondwanan
596 margin. Cessation of the high pressure metamorphism and emplacement into the crust of the
597 serpentinite mélange carrying blocks of the high pressure rocks might have been related to
598 juxtaposition of an exotic arc terrane (now represented by the Gympie terrane of southern
599 Queensland) rafted into a 260-230 Ma Andean arc at the margin of Gondwana. This coincides
600 with the timing of the 260-230 Ma Hunter-Bowen orogeny.

601

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884

885 **Figure captions**

886 Figure 1. (a) Geological sketch map of the southern end of northeastern New South Wales.
 887 (b) Synthesis of New England Orogen terranes in northeastern New South Wales and
 888 south-eastern Queensland.

889 Figure 2. Field photographs of eclogite and blueschist blocks at the northern end of Rocky
 890 Beach, Port Macquarie. Location of analysed samples is indicated.

891 Figure 3. Transmitted light photomicrographs of zircons. (a-c) Grains from Rocky Beach
 892 eclogite and blueschist facies rocks. (d) Example of an igneous zircon from the
 893 Devonian Tacking Point Gabbro, Port Macquarie. (e) Examples of syn-metamorphic
 894 (low HREE, no Eu negative anomaly) eclogite facies zircons from the Franklin
 895 metamorphics, Tasmania.

896 Figure 4. Cathodoluminescence images of representative zircons from Rock Beach eclogite
 897 and blueschist facies rocks.

898 Figure 5. Analytical data for minerals from Rocky Beach eclogite and blueschist facies rocks.
 899 (a) Summary Tera-Wasserburg $^{238}\text{U}/^{206}\text{Pb}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ plot for zircons.
 900 Analytical errors are depicted at the 2σ level. (b) Chondrite-normalised plot of REE
 901 analyses for zircons and garnets. Noted analyses are as follows: (i) 21-06 oval low
 902 Th/U ca. 1100 Ma zircon 15.1 and (ii) RB-2 abraded ca. 560 Ma metamorphic rim have
 903 negative Eu anomalies and low HREE abundance, showing they equilibrated with
 904 plagioclase *and* garnet; (iii) example of a 500 Ma syn-eclogite facies zircon from the
 905 Franklin metamorphics of Tasmania, equilibrated with garnet but not plagioclase and
 906 thus shows no Eu anomaly but low HREE abundance (from Fergusson et al.,
 907 submitted).

908 Figure 6. Back Scatter Electron image of part of the titanite + rutile porphyroblast RB-4.
 909 LA-ICP-MS U-Pb dating sites are indicated.

910 Figure 7. Tera-Wasserburg $^{238}\text{U}/^{206}\text{Pb}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ plot of rutile and titanite analyses.
 911 Analytical errors are depicted at the 2σ level.

912

913 **Table Captions**

914 Table 1. Whole rock XRF geochemical analyses.

915 Table 2. Summary SHRIMP zircon U-Th-Pb data

916 Table 3. SHRIMP and LA-ICP-MS zircon and garnet rare earth element analyses.

917 Table 4. Summary LA-ICP-MS rutile and titanite U-Pb data

918

RB-3
grain 1
250 Ma

RB-3
grain 2
350 Ma

RB-2
grain 2
595 Ma
rim

Tacking Point
Gabbro
magmatic
zircon

syn-eclogite
facies (500 Ma)
metamorphic
zircons,
Tasmania

50 μ m

21-06 grain 7

RB3 grain 1

RB3 grain 2

RB2 grain 2

RB2 grain 4

RB3 grain 3

100 μ m

2 σ errors on ages (Ma)

	21-06	RB-2	RB-3
	eclogite	blueschist	retrogressed
SiO2	43.88	52.14	44.74
TiO2	1.65	1.62	3.37
Al2O3	14.16	9.91	14.30
Fe2O3	14.39	14.90	12.76
MnO	0.39	0.15	0.13
MgO	5.75	7.29	5.59
CaO	9.15	4.54	9.58
Na2O	2.09	4.74	3.36
K2O	3.63	1.02	2.59
P2O5	0.52	0.16	0.40
SO3	3.44	1.43	0.12
LOI	4.51	3.34	2.75
Total	103.55	101.22	99.70
Mn/(Mn+Fe)	0.030	0.011	0.011
V	416	400	329
Cr	260	161	138
Ni	64	68	67
Cu	111	27	23
Zn	120	165	73
Rb	61	18	48
Sr	182	96	185
Ba	1102	401	1072
Y	44	28	33
Zr	106	103	275
Nb	16	11	36
La	<2	<2	24
Ce	20	2	93
Hf	4	3	5

Labels	site	U/ppm	Th/ppm	Th/U	f206%	$^{238}\text{U}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	age $^{206}\text{Pb}/^{238}\text{U}$	age $^{207}\text{Pb}/^{206}\text{Pb}$	%conc
RB-2 blueschist										
1.1	e,osc,p,fr	146	69	0.48	<0.001	15.10 ± 0.32	0.0574 ± 0.0018	414 ± 9		
1.2	e,osc,p,fr	196	117	0.60	<0.001	14.18 ± 0.31	0.0564 ± 0.0011	441 ± 9		
2.1	r,h,ov	185	33	0.18	2.277	10.13 ± 0.23	0.0772 ± 0.0024	594 ± 13		
2.2	c,osc,ov	145	61	0.42	1.147	8.19 ± 0.20	0.0682 ± 0.0018	735 ± 17		
3.1	e,osc,p	630	306	0.48	0.905	16.41 ± 0.34	0.0663 ± 0.0012	378 ± 8		
3.2	e,osc,p	660	343	0.52	0.246	17.23 ± 0.39	0.0611 ± 0.0010	363 ± 8		
4.1	r,h,ov	353	219	0.62	<0.001	10.32 ± 0.27	0.0591 ± 0.0023	596 ± 15		
5.1	r,sz,ov	135	136	1.01	0.404	11.35 ± 0.25	0.0623 ± 0.0012	542 ± 11		
6.1	r,sz,ov	381	176	0.46	0.192	11.02 ± 0.21	0.0607 ± 0.0007	559 ± 10		
7.1	e,osc,p,fr	103	64	0.62	<0.001	18.36 ± 0.49	0.0550 ± 0.0022	344 ± 9		
7.2	e,osc,p,fr	114	80	0.70	<0.001	18.22 ± 0.42	0.0581 ± 0.0024	345 ± 8		
RB-3 eclogite										
1.1	e,osc,p	265	180	0.68	<0.001	25.40 ± 0.60	0.0534 ± 0.0013	251 ± 6		
1.2	e,osc,p	267	184	0.69	0.146	26.66 ± 0.58	0.0603 ± 0.0019	237 ± 5		
2.1	e,osc,ov	208	125	0.60	<0.001	18.11 ± 0.59	0.0553 ± 0.0014	348 ± 11		
2.2	e,osc,ov	140	104	0.75	0.099	16.97 ± 0.64	0.0599 ± 0.0030	369 ± 14		
3.1	r,sz,ov	157	183	1.17	<0.001	15.53 ± 0.41	0.0557 ± 0.0016	404 ± 10		
3.2	r,sz,ov	76	50	0.65	<0.001	15.41 ± 0.40	0.0579 ± 0.0017	406 ± 10		
4.1	e,rex,ov	90	3	0.03	<0.001	4.81 ± 0.14	0.0847 ± 0.0034	1218 ± 31	1309 ± 79	93
5.1	r,h,ov	139	76	0.55	0.33	11.88 ± 0.26	0.0617 ± 0.0014	519 ± 11		
6.1	e,rex,ov	64	27	0.43	<0.001	2.02 ± 0.05	0.1926 ± 0.0026	2594 ± 56	2765 ± 22	94
7.1	e,h,ov	6	16	2.69	7.956	9.90 ± 0.60	0.1221 ± 0.0144	573 ± 35		
21-06 eclogite										
1.1	h,ov	374	170	0.455	0.041	1.71 ± 0.05	0.2276 ± 0.0016	2965 ± 68	3035 ± 11	98
2.1	m,osc,p	145	62	0.428	0.086	3.55 ± 0.14	0.1723 ± 0.0044	1601 ± 56	2580 ± 44	62
2.2	e,osc,p	365	171	0.468	0.052	1.96 ± 0.06	0.1962 ± 0.0016	2654 ± 62	2795 ± 13	95
3.1	c,osc,p	1029	1217	1.183	4.124	7.86 ± 0.32	0.0964 ± 0.0009	742 ± 29		
3.2	r,osc,p	255	139	0.543	<0.001	15.13 ± 0.40	0.0538 ± 0.0014	415 ± 11		

4.1	e,osc,p	190	86	0.454	<0.001	24.71 ± 0.79	0.0579 ± 0.0029	256 ± 8			
4.2	e,osc,p	139	64	0.462	<0.001	25.91 ± 1.11	0.0533 ± 0.0023	246 ± 10			
5.1	r,hd,ov	2054	732	0.356	1.612	15.87 ± 0.63	0.0737 ± 0.0007	388 ± 15			
5.2	c,osc,ov	573	237	0.413	1.156	7.78 ± 0.25	0.0696 ± 0.0010	771 ± 23			
6.1	c,osc,p	214	89	0.414	<0.001	12.29 ± 0.26	0.0584 ± 0.0016	505 ± 10			
6.2	m,osc,p	114	55	0.481	<0.001	12.40 ± 0.35	0.0581 ± 0.0024	501 ± 14			
7.1	e,osc,p,fr	404	282	0.698	<0.001	25.29 ± 0.76	0.0530 ± 0.0014	252 ± 7			
7.2	m,osc,p	416	287	0.690	<0.001	25.35 ± 0.57	0.0513 ± 0.0018	251 ± 6			
8.1	m,hd,ov	615	150	0.244	0.047	2.55 ± 0.08	0.1370 ± 0.0014	2131 ± 54	2189 ± 18	97	
9.1	e,osc,ov	104	92	0.878	0.002	5.40 ± 0.17	0.0759 ± 0.0065	1096 ± 32	1093 ± 183	100	
10.1	e,osc,p	285	172	0.601	<0.001	17.66 ± 0.33	0.0511 ± 0.0022	358 ± 7			
10.2	e,osc,p	202	114	0.565	<0.001	18.67 ± 0.39	0.0538 ± 0.0016	338 ± 7			
11.1	m,osc,p	255	220	0.863	<0.001	17.91 ± 0.53	0.0555 ± 0.0017	352 ± 10			
11.2	e,osc,p	198	119	0.600	<0.001	17.82 ± 0.60	0.0520 ± 0.0021	355 ± 12			
12.1	r,h,p	802	2	0.002	0.028	10.99 ± 0.34	0.0594 ± 0.0006	561 ± 17			
12.2	r,h,p	719	2	0.003	<0.001	10.83 ± 0.22	0.0580 ± 0.0011	570 ± 11			
13.2	m,sz,ov	329	670	2.035	0.095	10.41 ± 0.29	0.0600 ± 0.0015	591 ± 16			
13.1	m,sz,ov	451	1000	2.215	0.051	10.41 ± 0.29	0.0596 ± 0.0008	591 ± 16			
14.1	e,osc,p,fr	168	102	0.604	<0.001	18.08 ± 0.50	0.0525 ± 0.0016	350 ± 9			
14.2	m,osc,p,fr	303	257	0.845	<0.001	17.84 ± 0.49	0.0526 ± 0.0012	354 ± 9			
15.1	e,hd,ov	1080	213	0.197	0.537	5.42 ± 0.24	0.0780 ± 0.0014	1091 ± 44	1147 ± 35	95	

Site grain type and analysis location: p=prism, ov=oval, fr=fragment, e=end, m=middle, c=core, r=rim/overgrowth

Site CL imagery: osc=oscillatory zoned, h=homogeneous, hd=homogeneous dark, low luminescence, sz=sector zoned, rex=recrystallised

All analytical errors are given a 1 σ

Concordance and $^{207}\text{Pb}/^{206}\text{Pb}$ ages only given for >1000 Ma old sites

f206% is the amount of ^{206}Pb modelled as non-radiogenic, based on measured ^{204}Pb

analysis	site	age	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
zircons from 21-06 eclogite layer within blueschists: LA-ICP-MS in ANU																
1.1	h,eq	3035	1.50	44.1	3.41	28.4	28.8	12.2	100	40.3	477	143	607	131	1200	191
2.2	e,osc,p	2795	0.03	14.3	0.08	1.31	2.81	0.18	17.6	5.72	73.2	26.6	122	26.8	244	42.2
3.2	r,osc,p	415	0.02	11.5	0.08	1.15	3.39	0.64	19.8	6.86	89.1	33.7	163	36.1	346	63.3
4.1	e.osc,p	256	0.03	7.65	0.07	1.12	2.60	0.31	18.3	6.57	88.6	34.4	164	37.1	347	61
5.1	r,hd,ov	388	2.43	20.3	4.41	40.1	45.2	18.1	127	43.9	453	111	394	76.4	668	106
6.1	m,osc,p	505	0.06	4.04	0.07	1.03	2.04	0.35	13.4	4.37	58.3	21.6	101	22.2	209	37.0
7.2	m,osc,p	251	0.06	25.3	0.05	0.92	2.01	0.67	10.7	3.29	41.2	15.6	79.1	19.5	208	41.0
8.1	m,hd,ov	2189	0.02	4.50	0.07	1.49	4.48	0.40	25.4	6.51	66.9	19.3	72.9	13.7	112	17.4
8.B	e,hd,ov	2189	0.01	4.46	0.06	1.39	3.99	0.38	20.9	5.49	54.0	15.1	56.6	10.3	85.1	13.0
9.1	e,osc,ov	1093	0.14	11.7	0.10	1.12	2.25	0.52	12.3	4.18	56.7	21.2	101	21.9	207	36.7
10.1	e,osc,p	358	0.04	14.6	0.07	1.06	1.91	0.68	9.49	3.34	43.1	16.8	88.3	20.8	216	47.2
11.2	e,osc,p	355	bdl	7.76	0.08	1.37	3.10	0.65	17.2	5.35	69.4	25.4	122	27.2	258	47.2
12.2	r,h,p	570	0.62	8.59	0.74	4.78	5.11	3.14	24.0	10.2	135	47.4	246	66.1	760	144
14.1	e,osc,p,fr	350	0.19	15.8	0.19	2.46	5.05	0.99	28.9	8.72	110	38.5	179	40.1	371	63.5
15.1	e,hd,ov	1080	0.78	10.1	0.94	5.77	4.64	1.79	13.9	3.06	23.1	5.13	15.9	2.85	22.4	3.84
15.2	e,hd,ov	1080	2.48	14.9	1.88	10.3	7.19	2.21	16.1	3.30	24.7	4.86	14.4	2.29	16.3	2.27
16	hd,fr	1070*	10.3	127	14.0	101	103	39.4	245	72.1	673	162	587	114	945	146
zircons from RB-2 blueschist interlayered with eclogite: SHRIMP in Hiroshima University																
2.1	r,h,pov	594	0.03	18.9	0.02	1.22	2.73	0.44	13.6	4.57	53.2	19.5	82.4	19	185	36.2
4.1	r,h,ov	596	0.02	5.11	0.03	4.79	12.5	0.15	48.1	11.5	92.2	25.0	85.3	17	145	24.0
5.1	r,h,ov	519	0.01	15.8	0.02	1.13	2.76	0.41	14.9	5.71	70.7	27.6	125	30	296	53.9
6.1	r,sz,ov	559	0.02	5.13	0.02	3.24	9.07	0.17	29.4	5.91	34.6	6.02	14.1	2.12	14.5	1.91
zircons from RB-3 retrogressed high-pressure block: SHIMP in Hiroshima University																
3.2	r,sz,ov	406	0.01	20.4	0.04	4.46	8.23	1.43	35.9	11.7	133.9	48.4	203	46	417	72.9
example of eclogite metamorphic zircon the Franklin metamorphics, Tasmania: SHRIMP in Hiroshima University																
2.2	m,h,ov	513	0.00	0.24	0.01	0.07	0.44	0.40	3.67	0.96	5.79	1.02	2.64	0.43	3.35	0.54
garnet from eclogite 21-06: LA-ICP-MS in Macquarie University																

2106-1A	fr	0.004	0.003	0.004	0.026	0.047	0.043	0.290	0.063	0.370	0.049	0.110	0.012	0.070	0.009
2106-1B	fr	0.004	0.001	0.003	0.023	0.078	0.059	0.410	0.130	1.270	0.250	0.710	0.085	0.500	0.063
2106-2	fr	<0.00	0.004	0.004	0.035	0.083	0.080	0.550	0.130	1.090	0.200	0.600	0.069	0.550	0.078
2106-3	fr	0.012	0.017	0.008	0.043	0.100	0.069	0.510	0.097	0.660	0.130	0.490	0.085	0.770	0.140
2106-4	fr	0.005	0.010	0.006	0.051	0.120	0.083	0.480	0.110	1.060	0.320	1.460	0.240	2.270	0.360
2106-5	fr	0.003	0.002	0.003	0.036	0.063	0.049	0.380	0.120	1.190	0.270	0.950	0.120	0.790	0.090

garnet from blueschist RB-2: LA-ICP-MS in Macquarie University

RB2-1A	fr	0.002	0.003	0.003	0.027	0.059	0.047	0.360	0.110	0.990	0.230	0.740	0.110	0.810	0.120
RB2-1B	fr	0.006	0.017	0.008	0.054	0.079	0.053	0.390	0.110	1.020	0.230	0.780	0.100	0.840	0.140
RB2-2	fr	0.004	0.006	0.004	0.036	0.074	0.059	0.490	0.160	1.540	0.430	1.610	0.230	1.990	0.310
RB2-3	fr	0.004	<0.00	0.002	0.027	0.082	0.053	0.480	0.150	1.570	0.440	1.720	0.260	2.240	0.370
RB2-4	fr	0.005	0.004	0.004	0.030	0.085	0.069	0.450	0.140	1.130	0.220	0.630	0.079	0.530	0.067

grain morphology: eq=equant, p=prismatic, ov=oval, fr=grain fragment, e=grain end, m=grain middle, r=overgrowth, c=core

CL imagery: osc=oscillatory zoned, sz=sector zoned, h=homogeneous, hd=homogeneous dark, rex=recrystallised

age is SHRIMP U-Pb age, apart from *=LA-ICP-MS approximate U-Pb age

analysis	U (ppm)	$^{238}\text{U}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$
R-4	0.20	3.322 ± 0.282	0.7322 ± 0.0717
R-5	0.26	2.368 ± 0.208	0.7532 ± 0.0724
R-6	0.07	1.176 ± 0.053	0.7760 ± 0.0333
R-7	0.02	1.203 ± 0.126	0.7709 ± 0.0792
R-8	0.13	1.491 ± 0.109	0.7878 ± 0.0583
R-9	0.51	1.496 ± 0.047	0.8118 ± 0.0254
R-9	0.02	1.505 ± 0.118	0.8020 ± 0.0666
R-10	1.65	3.260 ± 0.106	0.7566 ± 0.0480
R-11	0.47	1.532 ± 0.066	0.7223 ± 0.0602
R-12	0.09	0.536 ± 0.027	0.8912 ± 0.0647
R-13	0.07	1.173 ± 0.049	0.7166 ± 0.0534
R-14	0.27	0.385 ± 0.034	0.7224 ± 0.1608
T-1	1.59	0.852 ± 0.012	0.7889 ± 0.0100
T-2	2.05	1.029 ± 0.016	0.7893 ± 0.0124
T-3	0.15	0.189 ± 0.005	0.8393 ± 0.0134
T-4	0.43	0.260 ± 0.005	0.8462 ± 0.0124
T-5	0.98	0.683 ± 0.011	0.7947 ± 0.0118
T-6	0.70	0.373 ± 0.006	0.8143 ± 0.0119
T-7	1.25	0.574 ± 0.011	0.8126 ± 0.0149
T-8	0.90	0.545 ± 0.009	0.8151 ± 0.0129
T-09	1.19	0.801 ± 0.024	0.7768 ± 0.0650
T-10	1.54	0.964 ± 0.036	0.7636 ± 0.0811
T-11	0.68	0.435 ± 0.013	0.7994 ± 0.0724
T-12	0.71	0.487 ± 0.021	0.7724 ± 0.0961

R=rutile, T=titanite. Analytical errors given at 1 σ