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Permian fragmentation, accretion and subsequent translation of a low-latitude Tethyan seamount to the high-latitude east Gondwana margin: evidence from detrital zircon age data

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Abstract – Ion microprobe analyses of detrital zircons in the Te Akatarawa Terrane, New Zealand, reveal that the age of unfossiliferous turbidites overlying a fusuline- and coral-bearing limestone block olistostromal mélange is no older than 255 ± 4 Ma (Late Permian). This is approximately 15 m.y. younger than the Kungurian age of the fusulinid limestone. We interpret this to indicate collapse of a Permian oceanic seamount as it entered a subduction zone along the Pacific margin of Gondwana. These turbidites differ markedly in composition from adjoining Permian to Middle Triassic sandstones of the Torlesse Terrane. Detrital zircon age data indicate predominantly Permian and Carboniferous ages for source rocks supplying the Te Akatarawa turbidites, but also reveal significant earlier Palaeozoic and Proterozoic components, ranging back to 1.9 Ga. The warm-water setting of limestone blocks and the short 15 m.y. time period between sedimentation and accretion onto a continental margin require the limestone to have formed in a low-latitude position probably off the northeast Australian (New Guinea) margin of Gondwana. Zircons within the sample underwent recrystallization at around 230 ± 11 Ma which may be related to alteration during accretion in a subduction zone environment. Over a period of 100 to 150 m.y. from 255 Ma the terrane underwent more than 5000 km translation along the continental margin southward to its current location as an exotic mini-terrane enclosed within the New Zealand Torlesse Terrane.

1. Introduction

Permian fusulinid-bearing limestones are minor but important components of the siliciclastic-dominated sedimentary sequences accreted to the Pacific margin of Gondwana (Aita & Spörli, 1992; Carter *et al.* 1992; Hada & Landis, 1995; Helwig, 1972; Rapalini *et al.* 2001; Spörli & Gregory, 1981). The limestones are associated with mafic volcanic rock and sometimes chert which, combined with Tethyan faunal affinities, are taken as evidence for accumulation in an open ocean, low-latitude setting. These oceanic assemblages are enclosed within siliciclastic accretionary complexes of Permian to Cretaceous age and contain high-latitude cold water faunas. The contrasting affinities and settings of these oceanic and continental margin assemblages have led to the view that the former are exotic terranes accreted to the Gondwanan margin (Aita & Spörli, 1992; Bishop, Bradshaw & Landis, 1985; Helwig, 1972; Spörli & Gregory, 1981). We present U/Pb detrital zircon age data for sandstone directly overlying, and in stratigraphic continuity with, a fusulinid limestone olistostrome sequence from Te Akatarawa, South Island, New Zealand, to constrain further the age of the formation and its history of accretion onto Gondwana. These data show that the youngest detrital grains are only some 15 m.y. younger than the limestone, and suggest that the zircon-bearing detritus was derived from Gondwana. This implies accretion of the limestone to the continental margin soon after its formation. Regional relations constrain the history of subsequent translation along some 5000 km of the Gondwana margin to a period of 100–150 m.y.

Mesozoic and older basement rocks of New Zealand developed in oceanic areas along the Pacific margin of Gondwana, and are divided into Western and Eastern provinces separated by the Median Tectonic Zone (Fig. 1; Bradshaw, 1993; Kimbrough *et al.* 1993; Landis & Coombs, 1967). The Western Province consists of early Palaeozoic rock units intruded by Devonian–Carboniferous and Cretaceous plutons and it is correlated with rock sequences in southeast Australia and Antarctica (Cooper & Tulloch, 1992; Muir *et al.* 1996a). The Median Tectonic Zone is a strongly deformed and fragmented zone comprising subduction-related igneous sequences and minor volcanogenic sedimentary rocks ranging from

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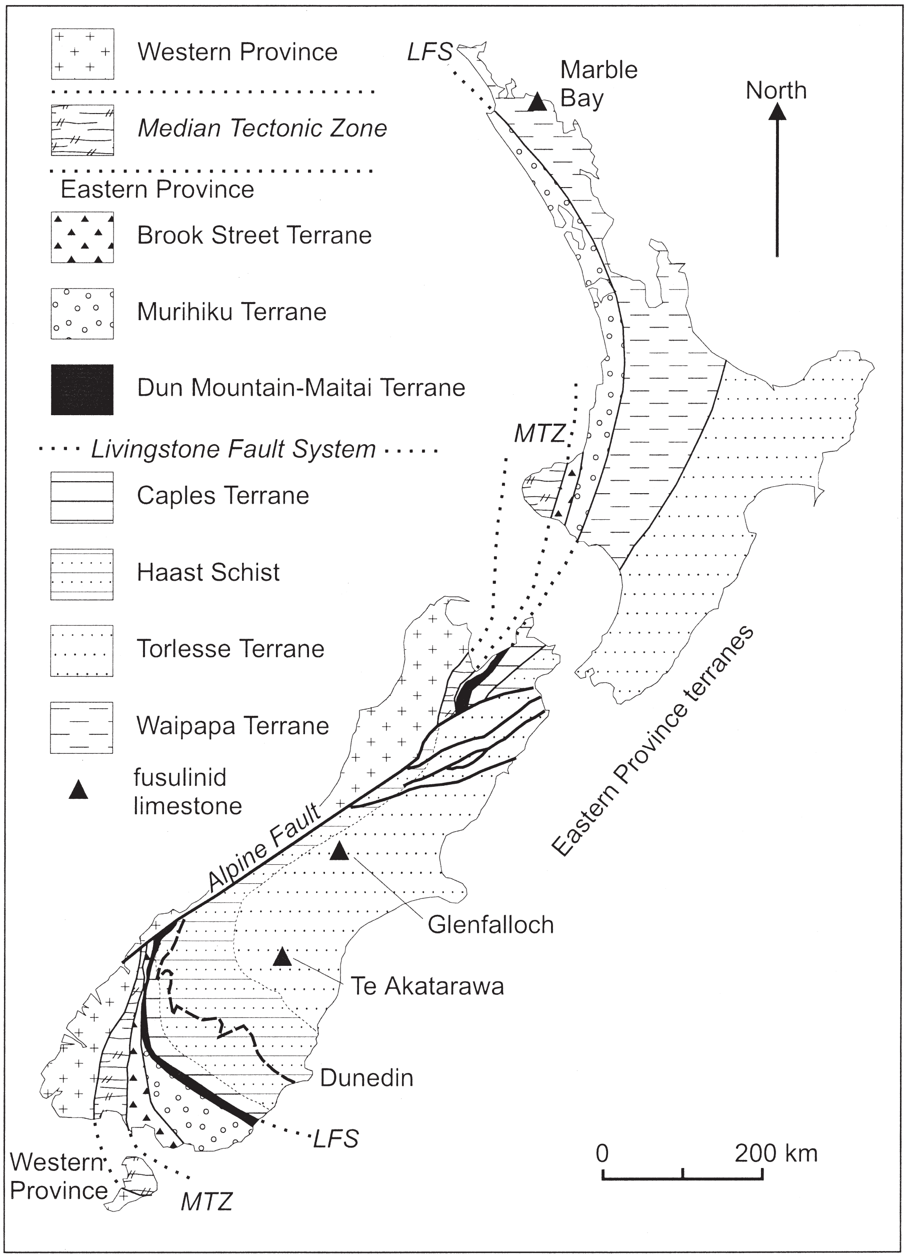

Figure 1. Basement terranes of New Zealand adapted from Coombs *et al.* (1976), Landis *et al.* (1999), Mortimer (1995) and Sutherland (1999). Heavy dashed line in Haast Schist approximates boundary between schist derived from the Caples Terrane with that derived from the Torlesse Terrane. Abbreviations: MTZ – Median Tectonic Zone; LFS – Livingstone Fault system. Triangles show locations of fusulinid limestone.

Carboniferous to mid-Cretaceous in age (Bradshaw, 1993; Kimbrough *et al.* 1994; Mortimer *et al.* 1999; Muir *et al.* 1998). The Eastern Province consists of late Palaeozoic to Cretaceous, predominantly igneous-derived, terrigenous clastic sedimentary successions, that have undergone low-grade metamorphism. It is interpreted as a series of fragmented arc-accretionary prism complexes accreted onto the Gondwana margin (Bishop, Bradshaw & Landis, 1985). The Eastern Province is transected by the Livingstone Fault system (Fig. 1) into a western succession of magmatic arc and arc-flanking basin terranes (Brook Street, Murihiku and Dun Mountain-Maitai terranes) and eastern accretionary prism assemblages (Caples, Torlesse, Waipapa terranes). Fusulinid-bearing limestones, including those of the Te Akatarawa Formation, are restricted to the east of the Livingstone Fault system and occur as fault-bounded blocks (mini-terranes) within the predominantly siliciclastic Torlesse and Waipapa terranes of the Eastern Province (Fig. 1).

2. Te Akatarawa Terrane

The Te Akatarawa Terrane comprises a distinctive, approximately 700 m thick suite of limestone, basalt, fine- to coarse-grained siliciclastic rock and sheared mudstone, all belonging to the fault-bounded Te Akatarawa Formation (Hada & Landis, 1995). It includes the Trig E Conglomerate Member and the Akatarawa Melange Member (Fig. 2). Limestone, basalt and minor siliceous rocks occur as blocks within the mélange, which represents a deformed olistostromal deposit enclosed by deep-water siliciclastic rocks. The contact between the mélange and overlying clastic rocks is stratigraphic, but a localized obliquity between the mélange fabric and the overlying bedded sequence suggests a minor angular unconformity developed during sedimentation (Hada & Landis, 1995). The limestones are pure calcarenites lacking siliciclastic detritus and containing a distinctive fossil assemblage of crinoid plates, algal grains, corals, ammonoids, brachiopods and fusulinids. The fusulinids are *Parafusulina cf. japonica* (Gumbel) suggesting an Early Permian, Kungurian age, corresponding to an absolute date of around 270 to 272 Ma according to the recent time scale compilation of Yugan *et al.* (1997). The possibility of a slightly younger, Roadian, age (~268 Ma) has been suggested by Leven & Campbell (1998). A Carboniferous coral within fusulinid limestone olistolith indicates some reworking of older limestone (Hada & Landis, 1995). Sandstones within the formation contain more than 50% quartz (measured on the basis of the quartz–feldspar–lithic components of the rock), which contrasts with nearby Permo-Triassic Torlesse Terrane sandstones which contain only 20–40% quartz (T. C. MacKinnon, unpub. Ph.D. thesis, Univ. Otago, 1980; MacKinnon, 1983; Smale, 1980, 1984).

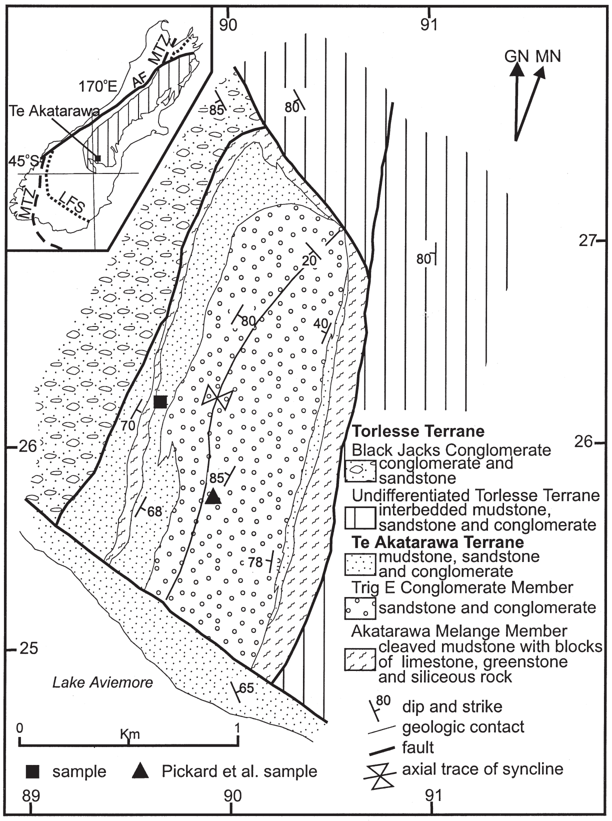

Figure 2. Geological map of the Te Akatarawa area, Southern Canterbury, New Zealand (adapted from Hada & Landis, 1995). Inset shows location of study area with respect to Torlesse Terrane (vertical lines) in South Island, New Zealand. Abbreviation: AF – Alpine Fault; LFS – Livingstone Fault system; MTZ – Median Tectonic Zone. Grid references refer to NZMS 1 topographic map sheet S116.

All contacts between the Te Akatarawa Terrane and the enclosing Torlesse Terrane are marked by high-angle faults (Fig. 2). The main fault block of the formation comprises a SSW-plunging syncline, whereas a further block of the unit on the shores of Lake Aviemore forms a homoclinal NE-dipping succession. The formation is metamorphosed to pumpellyite–actinolite facies in contrast to adjoining Middle Triassic Torlesse strata which contain low-grade zeolite and prehnite–pumpellyite facies assemblages (Coombs & Cox, 1991; Hada & Landis, 1995; Suggate, 1990). These Middle Triassic rocks include weakly metamorphosed conglomerate and sandstone of the Black Jacks Conglomerate (Retallack, 1983). Sandstone clasts within this conglomerate resemble rocks of the Permian Torlesse Terrane and are distinct from the Te Akatarawa Terrane.

3. Data and results

A sample for detrital zircon dating was collected from a graded sandstone bed immediately overlying the limestone-bearing mélange at grid reference 896262 (New Zealand Map Sheet S116). A total of 84 U/Pb ages were determined from 67 zircon grains on the Sensitive High Resolution Ion MicroProbe (SHRIMP II) at Curtin University. Analytical procedures are similar to those described by Compston, Williams & Meyer (1984), Nelson (1997) and Williams (1998*b*), and general operating conditions are outlined in Cawood & Nemchin (2000) and Cawood *et al.* (1999). In order to maximize the number of analyses and minimize the probability of missing a significant age component in the time available, most of the analyses are based on four scans through the mass stations (Table 1) in contrast to the normal operating mode of seven scans. Zircon data are corrected for common lead using ^{204}Pb and reported ages are based on their ^{206}Pb/^{238}U ratios. Concordia plots and cell-less summed probability histograms of the data are presented in Figure 3. Age uncertainties reported in Table 1 and on Figure 3 are given at $\pm 1\sigma$.

Analysed zircon grains range in age from around 250 Ma to 2000 Ma. Most of the analyses (72%) yielded ages younger than 390 Ma (Table 1) which show considerable overlap but with peaks in the data at around 250 Ma, 280 Ma, 320 Ma, 330 Ma, 350 Ma and 375 Ma. A minor age peak occurs at 440 Ma with

Table 1. U/Pb analyses of detrital zircons from the Te Akatarawa Formation

Grain	U(ppm)	Th(ppm)	Th/U	Pb(ppm)	4f206	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{208}Pb}{^{232}Th}$	Age $\frac{^{206}Pb}{^{238}U}$
94te-18	162	82	0.51	7	0.0351 ± 119	0.0465 ± 108	0.130 ± 27	0.0368 ± 8	0.236 ± 56	0.009 ± 2	233 ± 5
94te-20	326	180	0.55	14	0.0179 ± 64	0.0491 ± 58	0.171 ± 15	0.0386 ± 6	0.261 ± 32	0.012 ± 1	244 ± 4
94te-46	156	136	0.87	7	0.0284 ± 111	0.0356 ± 100	0.244 ± 26	0.0393 ± 9	0.193 ± 55	0.011 ± 1	248 ± 5
94te-40	226	107	0.47	11	0.0376 ± 107	0.0399 ± 97	0.124 ± 24	0.0411 ± 8	0.226 ± 56	0.011 ± 2	259 ± 5
94te-66	199	160	0.80	9	0.0000 ± 0	0.0583 ± 18	0.264 ± 8	0.0412 ± 7	0.331 ± 13	0.014 ± 0	260 ± 4
94te-25	260	264	1.02	13	0.0035 ± 29	0.0526 ± 30	0.326 ± 11	0.0414 ± 7	0.300 ± 18	0.013 ± 0	262 ± 4
94te-15	301	183	0.61	14	0.0000 ± 0	0.0556 ± 17	0.212 ± 7	0.0421 ± 7	0.323 ± 12	0.015 ± 1	266 ± 5
94te-67	98	58	0.59	5	0.0437 ± 182	0.0408 ± 165	0.156 ± 41	0.0413 ± 12	0.232 ± 95	0.014 ± 3	261 ± 7
94te-57	442	221	0.50	19	0.0008 ± 28	0.0535 ± 27	0.159 ± 7	0.0418 ± 6	0.308 ± 16	0.013 ± 1	264 ± 4
94te-32	626	525	0.84	30	0.0020 ± 19	0.0510 ± 19	0.263 ± 6	0.0421 ± 6	0.297 ± 12	0.013 ± 0	266 ± 3
94te-43	204	120	0.59	10	0.0222 ± 89	0.0520 ± 80	0.180 ± 20	0.0429 ± 8	0.307 ± 48	0.013 ± 1	271 ± 5
94te-47	336	199	0.59	16	0.0081 ± 42	0.0497 ± 39	0.184 ± 10	0.0440 ± 7	0.301 ± 24	0.014 ± 1	277 ± 4
94te-42	129	67	0.52	6	0.0082 ± 76	0.0517 ± 69	0.181 ± 18	0.0442 ± 9	0.315 ± 43	0.015 ± 2	279 ± 6
94te-34	1013	520	0.51	48	0.0019 ± 12	0.0532 ± 13	0.164 ± 4	0.0445 ± 5	0.327 ± 9	0.014 ± 0	281 ± 3
94te-64	1002	219	0.22	44	0.0017 ± 17	0.0534 ± 16	0.070 ± 4	0.0448 ± 6	0.330 ± 11	0.014 ± 1	282 ± 3
94te-1	562	605	1.08	31	0.0056 ± 25	0.0538 ± 24	0.354 ± 8	0.0452 ± 6	0.335 ± 16	0.015 ± 0	285 ± 4
94te-28	240	234	0.97	13	0.0000 ± 0	0.0561 ± 24	0.308 ± 11	0.0452 ± 10	0.349 ± 17	0.014 ± 1	285 ± 6
94te-31	693	464	0.67	36	0.0137 ± 31	0.0517 ± 29	0.210 ± 8	0.0455 ± 6	0.325 ± 19	0.014 ± 1	287 ± 4
94te-14	495	280	0.57	24	0.0024 ± 24	0.0567 ± 23	0.184 ± 6	0.0458 ± 6	0.358 ± 16	0.015 ± 1	289 ± 4
94te-35	317	197	0.62	16	0.0037 ± 32	0.0507 ± 31	0.204 ± 9	0.0460 ± 7	0.322 ± 21	0.015 ± 1	290 ± 4
94te-7	152	128	0.84	9	0.0220 ± 118	0.0569 ± 106	0.285 ± 27	0.0469 ± 10	0.367 ± 70	0.016 ± 2	295 ± 6
94te-2	368	117	0.32	18	0.0067 ± 30	0.0562 ± 29	0.117 ± 7	0.0474 ± 7	0.367 ± 20	0.017 ± 1	299 ± 4
94te-12	175	105	0.60	9	0.0092 ± 58	0.0506 ± 54	0.184 ± 15	0.0487 ± 10	0.340 ± 38	0.015 ± 1	307 ± 6
94te-50	344	324	0.94	19	0.0021 ± 16	0.0519 ± 18	0.270 ± 7	0.0490 ± 7	0.351 ± 14	0.014 ± 0	308 ± 4
94te-53	152	113	0.74	9	0.0252 ± 82	0.0482 ± 75	0.216 ± 20	0.0501 ± 10	0.333 ± 53	0.015 ± 1	315 ± 6
94te-30	122	86	0.70	7	0.0012 ± 74	0.0628 ± 67	0.248 ± 18	0.0502 ± 10	0.435 ± 49	0.018 ± 1	316 ± 6
94te-27	1721	1389	0.81	98	0.0011 ± 10	0.0516 ± 11	0.250 ± 4	0.0505 ± 6	0.359 ± 9	0.016 ± 0	318 ± 4
94te-45	125	89	0.72	7	0.0142 ± 69	0.0472 ± 63	0.201 ± 17	0.0512 ± 11	0.333 ± 46	0.014 ± 1	322 ± 6
94te-49	169	75	0.45	9	0.0074 ± 42	0.0512 ± 40	0.127 ± 10	0.0519 ± 9	0.366 ± 30	0.015 ± 1	326 ± 6
94te-22	588	610	1.04	37	0.0038 ± 16	0.0507 ± 16	0.323 ± 6	0.0527 ± 7	0.368 ± 13	0.016 ± 0	331 ± 4
94te-65	306	174	0.57	18	0.0233 ± 54	0.0463 ± 49	0.157 ± 13	0.0526 ± 8	0.336 ± 37	0.014 ± 1	331 ± 5
94te-19	96	60	0.63	6	0.0082 ± 83	0.0621 ± 76	0.212 ± 20	0.0540 ± 12	0.462 ± 59	0.018 ± 2	339 ± 7
94te-51	607	339	0.56	35	0.0000 ± 0	0.0551 ± 9	0.178 ± 3	0.0538 ± 7	0.409 ± 9	0.017 ± 0	338 ± 4
94te-52	128	75	0.59	8	0.0060 ± 61	0.0516 ± 56	0.179 ± 15	0.0542 ± 11	0.385 ± 44	0.017 ± 1	340 ± 7
94te-56	480	301	0.63	29	0.0037 ± 24	0.0540 ± 23	0.194 ± 6	0.0552 ± 7	0.411 ± 19	0.017 ± 1	347 ± 5
94te-55	138	92	0.66	9	0.0147 ± 86	0.0554 ± 77	0.203 ± 20	0.0554 ± 11	0.424 ± 61	0.017 ± 2	348 ± 7
94te-63	79	44	0.56	5	0.0199 ± 164	0.0510 ± 147	0.170 ± 36	0.0559 ± 16	0.393 ± 115	0.017 ± 4	351 ± 10
94te-58	192	120	0.63	12	0.0154 ± 73	0.0461 ± 65	0.175 ± 17	0.0561 ± 10	0.357 ± 52	0.016 ± 2	352 ± 6
94te-24	86	68	0.79	6	0.0141 ± 84	0.0519 ± 78	0.251 ± 21	0.0562 ± 14	0.402 ± 62	0.018 ± 2	352 ± 8
94te-5	339	231	0.68	21	0.0043 ± 47	0.0590 ± 43	0.227 ± 11	0.0563 ± 9	0.458 ± 35	0.019 ± 1	353 ± 5
94te-39	112	71	0.64	7	0.0011 ± 104	0.0609 ± 93	0.211 ± 24	0.0569 ± 13	0.478 ± 75	0.019 ± 2	357 ± 8
94te-13	127	88	0.69	8	0.0054 ± 50	0.0537 ± 50	0.218 ± 14	0.0572 ± 13	0.424 ± 41	0.018 ± 1	359 ± 8
94te-11	218	133	0.61	14	0.0184 ± 65	0.0435 ± 60	0.162 ± 15	0.0577 ± 11	0.346 ± 49	0.015 ± 1	362 ± 7
94te-23	841	535	0.64	56	0.0130 ± 24	0.0527 ± 23	0.192 ± 6	0.0596 ± 7	0.433 ± 20	0.018 ± 1	373 ± 4
94te-4	790	456	0.58	51	0.0040 ± 17	0.0522 ± 17	0.180 ± 5	0.0602 ± 8	0.433 ± 15	0.019 ± 1	377 ± 5
94te-21	420	15	0.04	23	0.0023 ± 23	0.0567 ± 23	0.011 ± 5	0.0601 ± 8	0.471 ± 21	0.018 ± 8	377 ± 5
94te-16	263	233	0.88	19	0.0000 ± 0	0.0582 ± 14	0.285 ± 6	0.0613 ± 9	0.492 ± 15	0.020 ± 1	384 ± 6
94te-33	433	189	0.44	27	0.0018 ± 15	0.0540 ± 17	0.129 ± 4	0.0615 ± 8	0.458 ± 16	0.018 ± 1	385 ± 5
94te-6	282	113	0.40	20	0.0047 ± 29	0.0562 ± 28	0.131 ± 7	0.0690 ± 10	0.534 ± 29	0.023 ± 1	430 ± 6
94te-17	670	611	0.91	54	0.0016 ± 11	0.0548 ± 12	0.283 ± 4	0.0702 ± 9	0.530 ± 14	0.022 ± 0	437 ± 5
94te-8	838	281	0.33	60	0.0057 ± 16	0.0534 ± 16	0.100 ± 4	0.0708 ± 9	0.522 ± 17	0.021 ± 1	441 ± 5
94te-26	85	51	0.60	8	0.0156 ± 140	0.0549 ± 128	0.140 ± 32	0.0870 ± 25	0.659 ± 157	0.020 ± 5	538 ± 15
94te-44	273	89	0.33	25	0.0017 ± 22	0.0581 ± 22	0.104 ± 5	0.0914 ± 13	0.731 ± 31	0.029 ± 2	564 ± 8
94te-37	864	358	0.41	86	0.0000 ± 0	0.0611 ± 6	0.128 ± 2	0.0971 ± 12	0.818 ± 14	0.030 ± 1	598 ± 7
94te-8a	407	170	0.42	46	0.0050 ± 16	0.0638 ± 17	0.150 ± 4	0.1074 ± 14	0.944 ± 30	0.039 ± 1	658 ± 8
94te-59	537	412	0.77	67	0.0053 ± 14	0.0634 ± 15	0.241 ± 4	0.1094 ± 14	0.955 ± 27	0.034 ± 1	669 ± 8
94te-38	117	78	0.67	15	0.0034 ± 35	0.0645 ± 35	0.210 ± 10	0.1182 ± 21	1.051 ± 63	0.037 ± 2	720 ± 12
94te-36	95	94	0.99	14	0.0073 ± 43	0.0608 ± 42	0.280 ± 12	0.1218 ± 22	1.022 ± 75	0.035 ± 2	741 ± 13
94te-10	170	90	0.53	25	0.0032 ± 23	0.0702 ± 24	0.174 ± 6	0.1332 ± 21	1.288 ± 51	0.044 ± 2	806 ± 12
94te-29	730	155	0.21	118	0.0008 ± 5	0.0723 ± 7	0.064 ± 1	0.1650 ± 19	1.644 ± 26	0.049 ± 1	985 ± 11
94te-60	162	43	0.26	28	0.0069 ± 25	0.0732 ± 26	0.083 ± 6	0.1680 ± 25	1.694 ± 69	0.053 ± 4	1001 ± 14
94te-48	55	24	0.44	10	0.0089 ± 57	0.0696 ± 56	0.132 ± 14	0.1688 ± 35	1.621 ± 139	0.051 ± 5	1005 ± 19
94te-54	164	97	0.59	32	0.0013 ± 16	0.0780 ± 19	0.179 ± 5	0.1779 ± 26	1.913 ± 57	0.054 ± 2	1055 ± 14
94te-41	315	359	1.14	71	0.0112 ± 21	0.0758 ± 21	0.341 ± 6	0.1793 ± 23	1.875 ± 60	0.054 ± 1	1063 ± 13
94te-61	274	102	0.37	65	0.0045 ± 15	0.0850 ± 17	0.113 ± 4	0.2272 ± 30	2.662 ± 66	0.069 ± 3	1320 ± 16
94te-3	270	110	0.41	69	0.0040 ± 13	0.1090 ± 17	0.119 ± 4	0.2381 ± 31	3.579 ± 76	0.069 ± 2	1377 ± 16
94te-62	96	83	0.87	40	0.0017 ± 21	0.1236 ± 26	0.251 ± 6	0.3505 ± 57	5.973 ± 170	0.101 ± 3	1937 ± 27

Number system refers to sample 94te grain 18.

scattered analyses between 540 to 800 Ma, at about 1000 Ma, and at about 1300 Ma.

Cathodoluminescence imaging showed that most of the analysed grains, including the bulk of those younger than 400 Ma, show simple concentric oscillatory zoning (Fig. 4a) indicative of crystallization from a melt and hence derivation of this material from an igneous source terrain (Hanchar & Miller, 1993). In addition, a number of the youngest grains reveal small structureless areas of high luminosity that truncate an older oscillatory zoning (Fig. 4b–d). These are interpreted to represent a phase of intragranular recrystallization (Pidgeon, 1992) related to a hydrothermal or tectonothermal alteration. Older grains often contain a complex internal morphology with core structure, unrelated to external grain shapes, overgrown by either an oscillatory-zoned or thin, structureless rim. The presence of multiple growth phases within the older grains indicates a complex history prior to incorporation in the sedimentary sequence (cf. Cawood *et al.* 1999).

In an attempt to constrain better the maximum depositional age of the unit as well as to ascertain the significance of high luminosity zones in the youngest grains, multiple reanalyses of the five youngest grains were undertaken in two separate analytical sessions using seven scans through the mass stations (Table 2). The age data are divisible into two groups that correspond with the two cathodoluminescence types (Fig. 4). An older set of ages which corresponds with areas of oscillatory zoning yielded a combined weighted mean age with 95% confidence limits errors for 15 analyses from all five grains of 255 ±4 Ma. A younger set of ages which occurs in three of the five grains and corresponds with areas of high luminosity yielded a combined weighted mean age with 95% confidence limits errors for 6 analyses of 230 ± 11 Ma. We consider the older ages to represent the youngest detrital ages for the unit and the younger ages to represent low-grade alteration of the unit. Individual analyses reflecting this latter event range from 239 ± 5 Ma to 212 ± 5 Ma. This wide range and corresponding large error on the combined age likely reflects the fact that the diameter of the ion-probe analysis spot was larger than the area of alteration resulting in the probable inclusion of components from the older normally oscillatory zoned zircon.

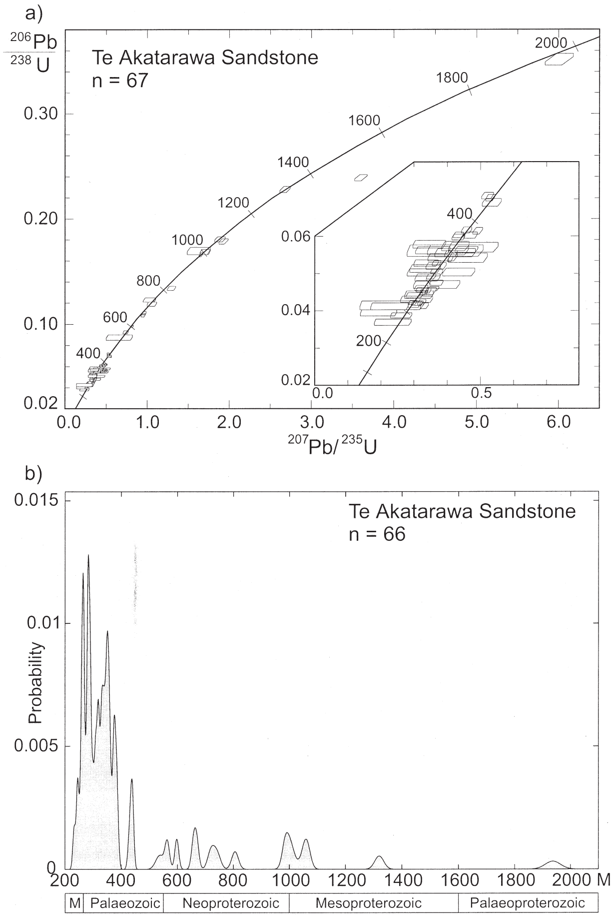

Figure 3. (a) Concordia diagram for analysed sample constructed from ^{204}Pb corrected data (Table 1). Error boxes are plotted at the 1σ level of confidence. (b) Probability plots (Dodson *et al.* 1988; Pell, Williams & Chivas, 1997) for entire detrital zircon data set except point 94te-3 (Table 1) which is highly discordant (Fig. 3a). Curves represent summed probability densities for individual age measurements, assuming that all error distributions are Gaussian. Each analysis contributes equally to the area under the curve (analyses with large uncertainties form low, broad peaks and analyses with small uncertainties form high, sharp peaks). Probability on the vertical axis is normalized to the total area under the curve. M – Mesozoic.

4. Discussion

A maximum depositional age for the Te Akatarawa Formation sandstone is provided by the youngest detrital zircon grains which yield a weighted mean age of 255 ± 4 Ma (Table 2). U/Pb studies of detrital zircons from Permo-Mesozoic sequences in New Zealand show that the youngest detrital grains consistently approximate the depositional age of siliciclastic units independently constrained by the presence of an *in situ* fauna (Cawood *et al.* 1999; Miller, 1999; Pickard, Adams & Barley, 2000). This is consistent with sediment accumulation along an active convergent plate margin, with detritus derived from contemporaneous igneous activity. We thus interpret the Te Akatarawa siliciclastics to have accumulated at around 255 Ma during the Late Permian Wuchiapingian Stage. This is at least some 15 m.y. younger than the Kungurian age of the fusulinid limestone blocks in the immediately underlying Te Akatarawa Mélange. This age discrepancy is consistent with the presence of a discontinuity at the contact between the mélange and the overlying turbidites interpreted by Hada & Landis (1995) as a syn-sedimentary intrabasinal unconformity.

The youngest grains within the sample constitute only a small proportion of the entire analysed age spectrum. This indicates that although syn-sedimentary igneous activity supplied zircon-bearing detritus to

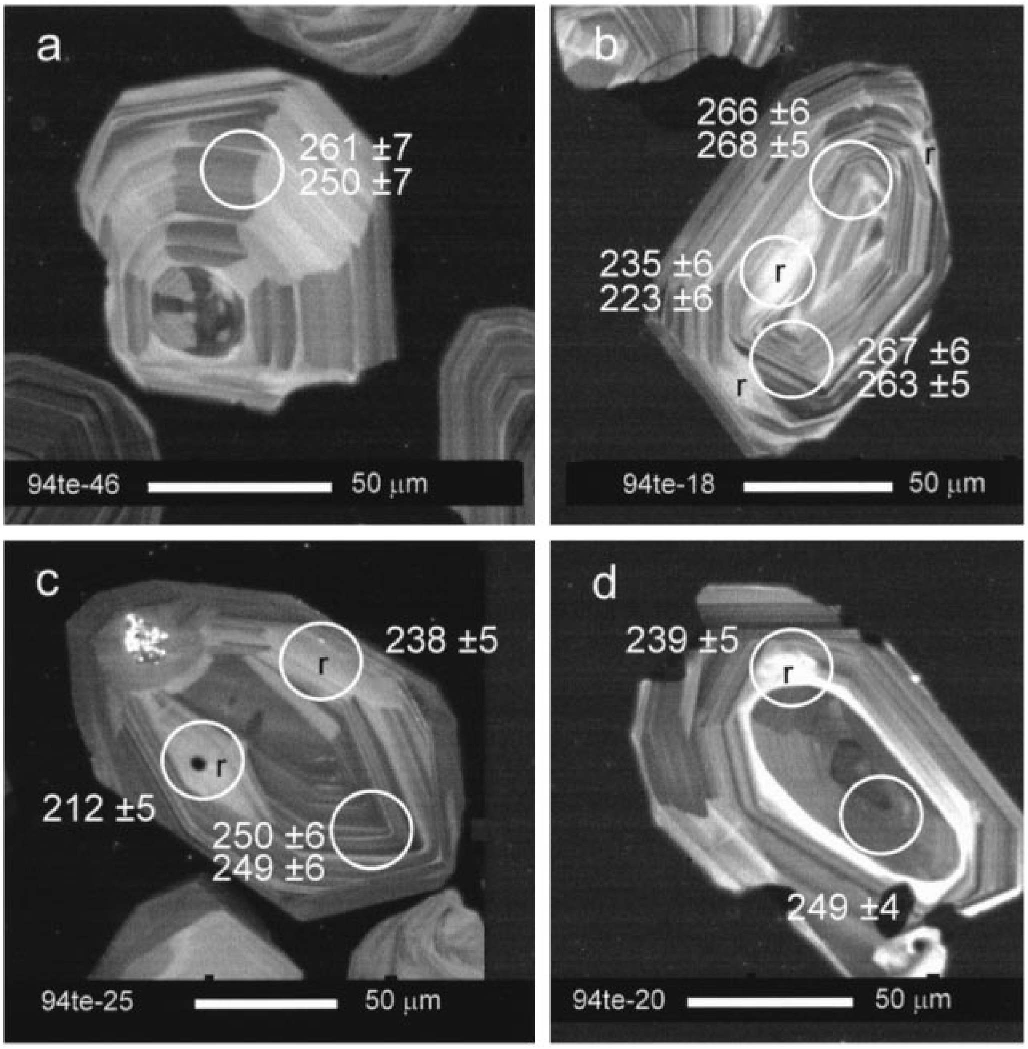

Figure 4. Cathodoluminescence images of detrital zircon grains. Area of grain analysed by ion-probe highlighted with white circles. Ages (Ma) are based on seven scans through the mass stations and are detailed in Table 2. (a) Grain te-46 showing concentric oscillatory-zoned zircon interpreted as magmatic in origin. (b) Grain te-18 showing truncation of oscillatory zoning by structureless high luminosity domains (r) that represent zones of recrystallization. (c) Grain te-25 showing overprinting of older oscillatory zoned zircon by younger high luminosity zones of recrystallization. (d) Grain te-20 showing prominent high luminosity zone developed at interface within oscillatory zoned zircon grain.

the depositional basin, most of the detritus was derived from older, pre-existing rock units. Four main age groups are recognized for zircon detritus within the sample (Fig. 3): Permian zircons (< 290 Ma) constituting 30 % of analysed detrital grains; Devonian–Carboniferous zircons (290–390 Ma) containing some 42 % of analysed grains; Neoproterozoic grains ranging from 535–810 Ma which constitute approximately 12 % of the age spectrum; and late Mesoproterozoic analyses (some 9 % of the spectrum) predominantly in the range 1000 to 1100 Ma but including a single analysis at 1300 Ma.

The range of zircon ages, extending from the Permian to the Proterozoic, and the quartzose nature of the sediments, indicate that the host sandstone was deposited proximal to a continental margin, rather than an intra-oceanic arc system. Neoproterozoic and Mesoproterozoic detritus is a characteristic component of Palaeozoic and Mesozoic sedimentary rocks in orogenic systems in east Australia, New Zealand and east Antarctica (Adams *et al.* 1998; Adams & Kelley, 1998; Cawood *et al.* 1999; Frost & Coombs, 1989; Ireland, 1992; Ireland & Gibson, 1998; Pickard, Adams & Barley, 2000; Turner *et al.* 1996; Veevers, 2000; Williams, 1998*a*; Wysoczanski, Gibson & Ireland, 1997). The Neoproterozoic detritus is related to Pan African-age source rocks associated with Gondwana assembly between 800 and 530 Ma (Stern, 1994; Trompette, 1994, 1997). Mesoproterozoic age material is related to Rodinia assembly, and belts of this age within Gondwana occur in Antarctica, India, South America, Africa and Western Australia but also extend into central and northeastern Australia (Blewett *et al.* 1998; Clarke, Sun & White, 1995; Fitzsimons, 2000; Hutton & Fanning, 2000; Myers, Shaw & Tyler, 1996).

Table 2. Multiple U/Pb analyses of the youngest detrital grains

Spot	U(ppm)	Th(ppm)	Th/U	Pb(ppm)	4f206	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{208}Pb}{^{232}Th}$	Age $\frac{^{206}Pb}{^{238}U}$
94-18-1A*	240	181	0.76	13	0.0512 ± 90	0.0461 ± 94	0.227 ± 22	0.0421 ± 10	0.268 ± 55	0.013 ± 1	266 ± 6
94-18-1B	400	224	0.56	19	0.0167 ± 47	0.0525 ± 49	0.179 ± 11	0.0425 ± 9	0.307 ± 30	0.014 ± 1	268 ± 5
94-18-1B	400	224	0.56	19	0.0167 ± 47	0.0525 ± 49	0.179 ± 11	0.0425 ± 9	0.307 ± 30	0.014 ± 1	268 ± 5
94-18-2B	376	201	0.53	17	0.0096 ± 48	0.0516 ± 49	0.171 ± 11	0.0417 ± 9	0.297 ± 30	0.013 ± 1	263 ± 5
94-18-3Az	121	52	0.43	5	0.0370 ± 100	0.0273 ± 101	0.080 ± 23	0.0372 ± 8	0.140 ± 52	0.007 ± 2	235 ± 6
94-18-3Bz	141	77	0.54	5	0.0159 ± 83	0.0460 ± 83	0.158 ± 19	0.0352 ± 7	0.224 ± 41	0.010 ± 1	223 ± 6
94te-18z**	162	82	0.51	7	0.0351 ± 119	0.0465 ± 108	0.130 ± 27	0.0368 ± 8	0.236 ± 56	0.009 ± 2	233 ± 5
94-20-1z	250	174	0.70	11	0.0103 ± 42	0.0492 ± 42	0.220 ± 10	0.0378 ± 7	0.256 ± 23	0.012 ± 1	239 ± 5
94-20-2	478	354	0.74	21	0.0037 ± 18	0.535 ± 18	0.238 ± 5	0.0393 ± 6	0.290 ± 12	0.013 ± 1	249 ± 4
94te-20**	326	180	0.55	14	0.0179 ± 64	0.0491 ± 58	0.171 ± 15	0.0386 ± 6	0.261 ± 32	0.012 ± 1	244 ± 4
94-25-1	251	234	0.93	13	0.0348 ± 82	0.0556 ± 85	0.300 ± 20	0.0395 ± 9	0.303 ± 47	0.013 ± 1	250 ± 6
94-25-2	243	217	0.89	12	0.0255 ± 77	0.0519 ± 79	0.286 ± 019	0.0394 ± 9	0.282 ± 44	0.013 ± 1	249 ± 6
94-25-2z	59	38	0.64	2	0.0658 ± 162	0.0247 ± 169	0.138 ± 39	0.0335 ± 10	0.114 ± 78	0.007 ± 2	212 ± 5
94-25-3z	97	58	0.60	5	0.0716 ± 131	0.0342 ± 138	0.143 ± 32	0.0376 ± 9	0.178 ± 72	0.009 ± 2	238 ± 5
94te-25**	260	264	1.02	13	0.0035 ± 29	0.0526 ± 30	0.326 ± 11	0.0414 ± 7	0.300 ± 18	0.013 ± 1	262 ± 4
94-46-1	118	93	0.78	6	0.0218 ± 129	0.0629 ± 130	0.260 ± 30	0.0413 ± 11	0.359 ± 76	0.014 ± 2	261 ± 7
94-46-2	116	91	0.79	5	0.0186 ± 124	0.0496 ± 124	0.236 ± 29	0.0396 ± 11	0.271 ± 69	0.012 ± 2	250 ± 7
94te-46**	156	136	0.87	7	0.0284 ± 111	0.0356 ± 100	0.244 ± 26	0.0393 ± 9	0.193 ± 55	0.011 ± 1	248 ± 5
94-66-1	196	166	0.85	9	0.0010 ± 78	0.0608 ± 78	0.281 ± 18	0.0397 ± 9	0.333 ± 44	0.013 ± 1	251 ± 6
94-66-2A	222	197	0.89	11	0.0201 ± 63	0.0486 ± 64	0.267 ± 15	0.0407 ± 9	0.273 ± 37	0.012 ± 1	257 ± 6
94-66-2B	184	152	0.82	9	0.0210 ± 78	0.0429 ± 79	0.238 ± 19	0.0393 ± 9	0.233 ± 44	0.011 ± 1	249 ± 6
94te-66**	199	160	0.80	9	0.0000 ± 0	0.0583 ± 18	0.264 ± 8	0.0412 ± 7	0.331 ± 13	0.014 ± 1	260 ± 4

*Number system refers to sample 94te grain 18 spot 1. Letters A and B represent first and second analyses of the same spot, and Z denotes analyses of areas of high luminosity related to recrystallization.
**Analyses from Table 1 and based on four scans through the mass stations. All other analyses based on seven scans.

Sand grains that have been eroded from Permian igneous rocks and deposited in the Te Akatarawa Terrane turbidites are interpreted to have been derived from Gondwana margin plutonic complexes. Although Permian plutonic rocks are found within New Zealand, they are restricted to small bodies of mainly gabbroic–trondhjemitic and tonalitic composition in and adjacent to the Median Tectonic Zone and to plagiogranite within the Dun Mountain Ophiolite Belt (Kimbrough *et al.* 1992, 1994; Mortimer *et al.* 1999), rocks unlikely to have contributed significantly to Te Akatarawa sands. More likely, source rocks should be sought in correlatives of the Median Tectonic Zone, arc-root plutonic suites elsewhere along the Gondwana margin, in eastern Australia, West Antarctica, South America and possibly displaced Gondwana terranes in southeast Asia (e.g. Bahlburg & Hervé, 1997; Bradshaw *et al.* 1996; Cawood, 1984; Metcalfe, 1996).

Potential source rocks for the Devonian–Carboniferous age zircon detritus include plutonic suites west of the Median Tectonic Zone that are exposed in East Australia, New Zealand and Antarctica.

Pickard, Adams & Barley (2000) determined the zircon age spectrum of a sandstone from the Trig E Conglomerate Member of the Te Akatarawa Formation (Fig. 2, grid reference 899257), less than 500 m southeast of our analysed sample. The age spectrum is similar to that reported here with the bulk of the analyses yielding ages between 260 Ma and 390 Ma and with minor clustering of analyses between 500–800 Ma and 900–1100 Ma (Fig. 5a). The youngest detrital grain from the conglomerate yielded an age of 262 ± 7 Ma (1σ).

The age signature of the Te Akatarawa Terrane sandstone is distinct from other Permo-Triassic sedimentary rocks within the Torlesse and Waipapa terranes (Fig. 5b). Ireland (1992) analysed a sample of weakly foliated Torlesse Terrane greywacke of probable Permian age from the southern shore of Lake Aviemore approximately 7 km southeast of the Te Akatarawa sample reported here. The Torlesse yielded ages ranging from around 260 Ma to 1240 Ma. The youngest analyses yielded a mean $^{206}Pb/^{238}U$ age of 260 ± 8 Ma (2σ) for 10 euhedral grains. This is similar to the inferred depositional age of the Te Akatarawa Terrane. The sample also contained a clustering of ages around 500–550 Ma and 1000–1200 Ma. Apart from a single analysis at around 340 Ma, Devonian to Permian detritus older than ~260 Ma is absent, in conspicuous contrast to our data from the nearby Te Akatarawa Terrane sample (Fig. 5b). Analyses of other Permian sandstones from the Rakaia subterrane of the Torlesse by Pickard, Adams & Barley (2000) yielded a similar age signature to that recorded by Ireland (1992) and have a very subdued frequency of Devonian–Carboniferous detritus compared to the Te Akatarawa Terrane sample.

4.a. Timing of metamorphism

A minimum age for the Te Akatarawa Terrane is limited by the time of deformation and metamorphism. This is dated at 230 ± 11 Ma based on the age of the phases of high luminosity in the detrital grains which we consider to represent intra-grain recrystallization related to fluid alteration during low-grade metamorphism of the unit. This age range corresponds to the

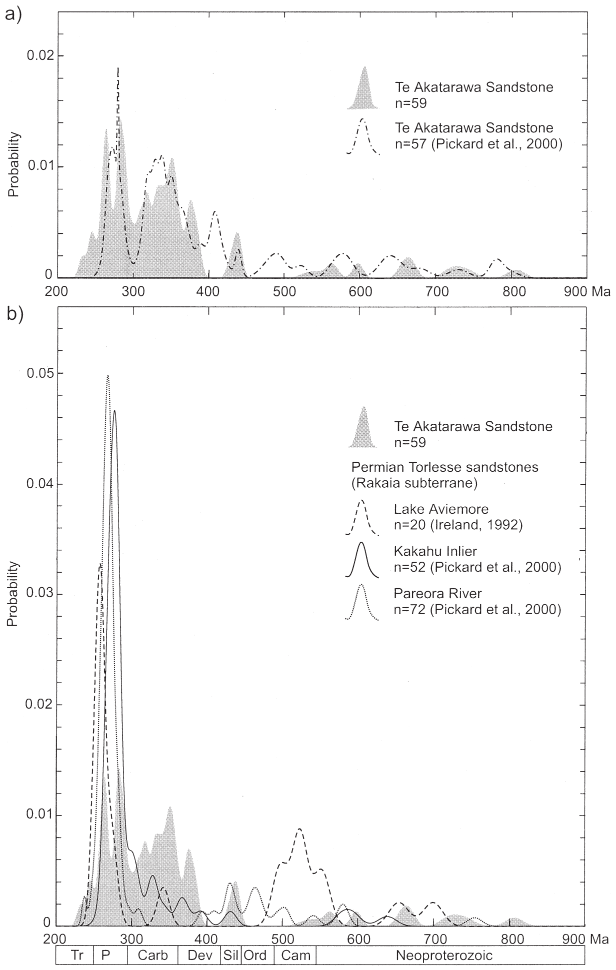

Figure 5. Probability plots comparing Te Akatarawa sample analysed in this study with (a) that of Pickard, Adams & Barley, 2000) and (b) with samples of Permian Torlesse analysed by Ireland (1992) and Pickard, Adams & Barley (2000). Ireland (1992) analysed a total of 79 zircons in a reconnaissance study using only three scans through the mass stations, however, 25 representative zircons were reanalysed using seven scans and it is these published analyses that are plotted here (only 20 have ages less than 900 Ma). Data from Pickard, Adams & Barley (2000) based on four scans (five scans if primary ion beam intensity was = 2 nA). Curves represent summed probability densities for individual age measurements, assuming that all error distributions are Gaussian. Each analysis contributes equally to the area under the curve (that is, analyses with large uncertainties form low, broad peaks and analyses with small uncertainties form high, sharp peaks). Probabilities on the vertical axis are normalized to the total area under the curve. Abbreviations: Tr – Triassic; P – Permian; Carb – Carboniferous; Dev – Devonian; Sil – Silurian; Ord – Ordovician; Cam – Cambrian.

Ladinian age of the Black Jacks Conglomerate (Fig. 2) and indicates that although these units are now structurally juxtaposed they must have been spatially separated, at least vertically and probably laterally along the mid-Triassic Gondwana margin. Pickard, Adams & Barley (2000) noted that a number of their analyses from the Te Akatarawa Terrane yielded U/Pb ages of around 110 Ma and proposed that these grains were also of *in situ* metamorphic origin. The reason for two distinct metamorphic ages from two samples of the Te Akatarawa Terrane is unclear, but we note that the ages of Pickard, Adams & Barley (2000) are not tied to any cathodoluminescence study so it is not known if their sample also contained high luminosity zones.

Constraints on the timing of metamorphism of the Te Akatarawa Terrane are limited but consistent with the regional history of the Eastern Province east of the Livingstone Fault system. The Middle Triassic (~230 Ma) Black Jacks Conglomerate, a component of the Torlesse Terrane which adjoins the Te Akatarawa Terrane (Fig. 2), contains rounded clasts of weakly metamorphosed and veined greywacke derived from the Torlesse Terrane (Hada & Landis, 1995; Retallack, 1983). Ireland (1992) reported an age of 211 ± 5 Ma (1σ) from the rim of one of the younger detrital grains (261 ± 6 Ma) from the Lake Aviemore Torlesse sample. He interprets the rim as a metamorphic overgrowth. As with the Te Akatarawa metamorphic age with which this overlaps at the 95% confidence level, this could represent alteration within a subduction zone setting. MacKinnon (1983) records the widespread presence of recycled clasts of sedimentary and low-grade regional metamorphic rocks in Late Triassic and younger Torlesse Terrane strata. In contrast, a detailed study of geochronology and metamorphism (Nishimura *et al.* 2000) of the transition from Caples greywacke to biotite schist of Torlesse provenance shows no evidence for multiple or pre-Jurassic metamorphism of Caples rocks and any early subduction zone metamorphism there must have been of very low grade and unlikely to be of regional extent. These observations are consistent with accretion of the older Torlesse Terrane sediments in a convergent margin environment prior to Middle Jurassic collision-related regional metamorphism (Little, Mortimer & McWilliams, 1999). The ages of around 110 Ma determined by Pickard, Adams & Barley (2000) on the Te Akatarawa Formation correspond with the mid-Late Cretaceous regional extension and reheating event proposed by Little, Mortimer & McWilliams (1999), and may indicate that the post-metamorphic faults bounding the terrane are Cretaceous structures.

5. Palaeogeographic setting – terrane accretion and translation

The Early Permian Kungurian fusulinid fauna within the limestone blocks of the Te Akatarawa Formation indicates accumulation in a warm-water, low-latitude setting. This, together with the total absence of siliciclastic detritus in the limestones and their association with mafic volcanic rock, indicates they formed in an intra-oceanic environment removed from continental influence, probably a volcanic seamount (Fig. 6; Hada & Landis, 1995). The detrital zircon age signature of

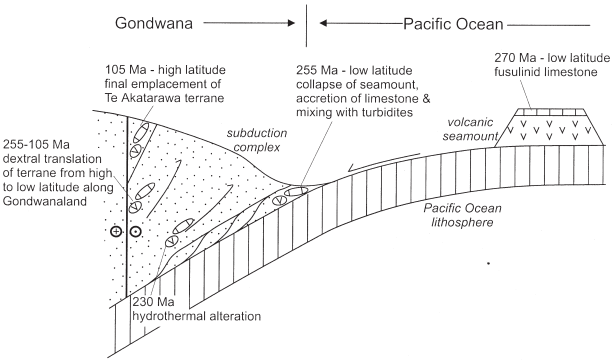

Figure 6. Schematic cross-section of convergent plate margin showing initial setting of fusulinid limestone on a volcanic seamount at 270 Ma, its accretion on the Gondwana margin at 255 Ma, and its cycling through a subduction complex assemblage and final emplacement between 255 and 105 Ma.

the overlying sandstone unit indicates accumulation of the siliciclastic sediment at the Gondwana margin at around 255 Ma. This requires the limestone to have migrated from its intra-oceanic setting to accretion at a continental margin within 15 m.y. of deposition. Sedimentary relations combined with the convergent plate margin setting of the Pacific margin of Gondwana throughout the late Palaeozoic and Mesozoic (Bahlburg & Hervé, 1997; Bishop, Bradshaw & Landis, 1985; Cawood, 1984; López-Gamundi *et al.* 1994) suggest collapse of a limestone-capped seamount on entering a trench. A resulting debris-flow, the olistostromal precursor of the Te Akatarawa mélange, was then accreted to the Gondwana margin during subduction (Hada & Landis, 1995). The process is similar to that occurring where the Daiichi Kashima Seamount is presently collapsing upon entering the modern Japan trench (Lallemand, Corotta & von Huene, 1989). Burial and cycling of the olistostrome through the subduction complex and interaction with circulating fluids resulted in alteration-induced recrystallization of zircon grains within the analysed sample at about 230 Ma.

The Pacific margin of Gondwana occupied high southern latitudes during late Palaeozoic and Mesozoic times, with the Western Province of New Zealand generally depicted as being in the vicinity of the South Pole (Grunow, 1999; Lawver, Gahagan & Dalziel, 1998; Mukasa & Dalziel, 2000; Powell & Li, 1994). Thus the transfer of the intra-oceanic warm-water Tethyan limestone to the Gondwana margin within 15 m.y. of limestone deposition indicates that it was not initially accreted at its present location across strike from Western Province of New Zealand. Rather it was initially accreted at a low-latitude and has been subsequently translated along the margin. In addition, significant differences in the age signatures of the detrital zircons as well as sandstone composition of the Te Akatarawa Terrane relative to inferred time-equivalent strata in the Torlesse Terrane (Fig. 5b) argue strongly against initial accretion adjacent to these Torlesse sequences.

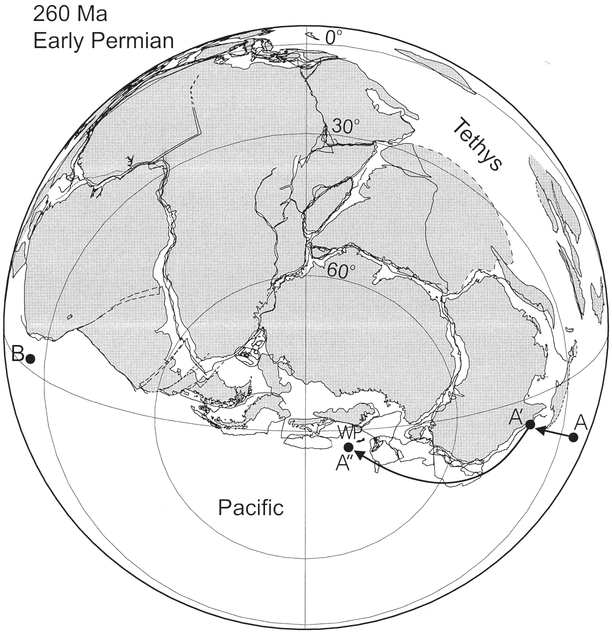

Figure 7. Palaeogeographic reconstruction for Gondwana at 260 Ma showing two possible locations (A and B) for the site of formation of the fusulinid limestone in the Te Akatarawa Formation. Site A' shows a potential location for accretion of the limestone to the Gondwana margin (Late Permian) and A" shows the final location with respect to New Zealand's Western Province (WP) in the Late Cretaceous. Unshaded areas enclosed by solid lines are submerged continental crust.

Figure 7 shows two possible sites for accumulation of the fusulinid limestone. Each site accounts for the warm-water open-ocean setting of the limestone and its subsequent rapid accretion to the Pacific margin of Gondwana. Both locations place the limestone at low latitudes, around 20° S, with the first (A, Fig. 7) lying off the northeast coast of Australia and the second (B, Fig. 7) off the Peruvian coast of South America. Both locations lie less than 1500 km from the Gondwana continental margin, enabling accretion of the limestone within 15 m.y. of its formation given geologically reasonable rates of convergence between the Pacific and Gondwana plates of 5–10 cm/yr. Either location can account for the presence of Permian zircon detritus related to syn-depositional convergent margin activity, and similarly the Gondwana hinterland of each could provide a source for the Neoproterozoic and Mesoproterozoic detritus.

However, only location A provides a substantial source for the Carboniferous–Devonian detritus of the analysed sample. The New England Orogen of northeast Australia preserves an extensive mid-late Palaeozoic arc-trench complex (Cawood, 1991; Cawood & Leitch, 1985; Holcombe *et al.* 1997; Korsch, 1984). The Karamea Batholith of New Zealand (Muir *et al.* 1996*a*,*b*; Tulloch, 1988) and several plutons from

Marie Byrd Land (Mukasa & Dalziel, 2000) are correlatives. Detrital zircons from modern beach sands along the northeastern Australian coastline show age spectra indicating derivation from the New England Orogen, showing clustering of data at 400–300 Ma as well as 290–200 Ma and 700–500 Ma (Sircombe, 1999). In particular, we note the most northern of the beach sands analysed by Sircombe (1999) from Hummock Hill Island in North Queensland are remarkably similar in zircon age distribution to that of the Te Akatarawa sample.

In contrast to the New England region, the South American margin of Gondwana during the Devonian and Carboniferous represented an overall passive margin until about 300 Ma (Bahlburg & Hervé, 1997; López-Gamundi *et al.* 1994). Pre-Permian igneous activity is generally absent from this segment of the margin, and although minor within-plate volcanic rocks of Early Carboniferous age occur in northern Chile (Breitkreuz *et al.* 1989), they are not sufficiently extensive to provide the source for the Devonian to Carboniferous zircon detritus (390–300 Ma) within the Te Akatarawa Formation.

Accretion of the Te Akatarawa limestone to the northeast Australian segment of the Gondwana margin requires it to have undergone approximately 5000 km of subsequent dextral strike-slip movement to reach its current location. The time frame over which this translation took place is poorly constrained. Assuming rates of plate motion involving lateral movement of around 5 cm/yr, this translation would require at least 100 m.y. and hence have continued until at least the Late Jurassic (160 Ma). Although translation is unlikely to have been either continuous or constant over such a protracted time period, such calculations provide a minimum age framework to constrain palaeogeographic reconstructions. A younger limit on the time of final emplacement of the formation is provided by widespread Late Cretaceous passive margin planation and deposition of quartz-rich sandstones in southern New Zealand, and the development of the Great South Basin (Beggs, 1993; LeMasurier & Landis, 1996). These deposits span the Livingstone Fault system which separates the Torlesse and other subduction accretion terranes from arc flanking basin terranes further west (Fig. 1; Bishop, Bradshaw & Landis, 1985). Mid-Cretaceous regional termination of convergent plate motion along the East Gondwana margin (~105 Ma; Bradshaw, 1989) provides a more likely younger limit on significant lateral translation along the margin. This time is also close to the age of final movement (~110 Ma) along the Median Tectonic Zone separating the Eastern and Western provinces of New Zealand (cf. Kimbrough *et al.* 1994). One possible interpretation of the ~110 Ma zircon grains in the Te Akatarawa Formation (Pickard, Adams & Barley, 2000) is that they record a localized hydrothermal or tectonothermal event related to final emplacement and exhumation of the unit at its current site within the Torlesse Terrane.

In addition to the Te Akatarawa location, fusulinid limestones have also been recorded in New Zealand from Glenfalloch Stream in the South Island and Marble Bay in the North Island (Fig. 1). The Glenfalloch Stream locality consists of an isolated limestone boulder containing Middle Permian fusulinid fauna similar to the Te Akatarawa location (Hornibrook, Brazier & Strong, 1989; Leven & Campbell, 1998). Although not known from outcrop, the limestone was possibly eroded from a nearby deformed volcanic association within the Torlesse Terrane (Whitehouse & Bradshaw, 1988). The fusulinid limestone at Marble Bay within the Waipapa Terrane of the North Island of New Zealand occurs in association with an intra-oceanic assemblage of basalt, chert and argillite. Sandstones stratigraphically overlie this assemblage and the entire sequence has been repeated by thrust imbrication (Spörli & Gregory, 1981). Fusulinids indicate a Late Permian age (Capitanian, Midian: Leven & Grant-Mackie, 1997; Vachard & Ferriere, 1991) implying an absolute age of around 262 Ma. Notably, however, the fauna and inferred palaeolatitude are different from that of the Te Akatarawa Terrane (Hada *et al.* 2001). Radiolarians from limestones and cherts in the Bay of Island–Whangaroa area, Northland, include late Middle to early Late Permian forms of low latitude affinities (Takemura *et al.* 1999) whereas radiolarians from phosphatic nodules are of Middle Triassic age and non-Tethyan, high-latitude, character (Aita & Bragin, 1999). The Marble Bay locality has been interpreted as an ocean floor assemblage which was imbricated within the Waipapa subduction complex (Spörli & Gregory, 1981). The age of accretion is not accurately known but may be as late as Early Cretaceous (Aita & Spörli, 1992). Analysis of detrital zircons from siliciclastic rocks elsewhere within the Waipapa Terrane reveals the presence of the characteristic Neoproterozoic and Mesoproterozoic Gondwana margin age components recognized in the Torlesse and Te Akatarawa samples (Cawood *et al.* 1999; Lindsay *et al.* 1994).

6. Source of the Torlesse Terrane sediments

MacKinnon (1983), from a detailed petrographic analysis, concluded sandstones of the South Island Torlesse Terrane were derived from a Western Province–West Antarctica magmatic arc complex situated along the continental margin of Gondwana. Recently, this view has been challenged with the suggestion that the entire Torlesse Terrane, including the enclosed Te Akatarawa Terrane, comprises sands derived from the New England Orogen that accumulated off northeast Australia, and was subsequently tectonically transported south along the Gondwana margin (Adams *et al.* 1998; Adams & Kelley, 1998; Pickard, Adams &

Barley, 2000; Veevers, 2000). Permian age strata of the Torlesse Terrane underlie a large area adjoining the Te Akatarawa Terrane (e.g. MacKinnon, 1983) to the east and north and are envisaged by these authors as being deposited off, and sourced from, the North Queensland segment of the New England Orogen. Successively younger Triassic and Jurassic elements of the Torlesse Terrane are interpreted as accumulating at progressively higher latitudes during southward translation of the terrane (Pickard, Adams & Barley, 2000).

Adams and co-workers (Adams *et al.* 1998; Adams & Kelley, 1998; Pickard, Adams & Barley, 2000) have shown that the detrital zircon age signatures of the Torlesse sandstones are dominated by a 300–200 Ma age cluster, which they related to derivation from subduction-related magmatic rocks of this age in the New England Orogen (cf. Cawood, 1984). A flaw in this argument is that activity of this age is not unique to New England but extends some 10 000 km along the entire Pacific margin of Gondwana from New Guinea to South America (Cawood, 1984; Kimbrough *et al.* 1994; López-Gamundi *et al.* 1994; Mukasa & Dalziel, 2000) forming the Gondwanide Orogen.

Veevers (2000) maintains that the age population of Torlesse sandstones is similar to modern northeastern Australian beach sands and to the Early Triassic Terrigal Formation of the Sydney Basin (Sircombe, 1999), both of which he considers to be derived from the New England Orogen. He believes that this confirms the contention of Adams and co-workers (Adams *et al.* 1998; Adams & Kelley, 1998; Pickard, Adams & Barley, 2000) who argue for a New England Orogen source and the subsequent southward tectonic transport of the Torlesse Terrane. The beach sands and Terrigal Formation are characterized by a prominent cluster of detrital zircon ages between 400–300 Ma (Sircombe, 1999) which corresponds to a period of subduction-related arc magmatism within the New England Orogen (Cawood & Leitch, 1985; Korsch, 1984). In contrast to the conclusions of Veevers (2000), this age component is poorly developed in the Torlesse samples and thus the zircon data argue against, rather than for, a New England source (cf. Cawood *et al.* 1999).

The contrasts in detrital zircon age signature between the Te Akatarawa Formation and the Torlesse Terrane, and in particular the lack of a detrital age signature related to the New England Orogen of northeast Australia, argue against accumulation of the Torlesse outboard of that region. In addition, Roser & Korsch (1999) show from geochemical and petrographic data that the majority of the New England and associated granitoids are distinct from the Torlesse sediments and thus the former cannot have acted as a source for the latter. In contrast, Te Akatarawa Terrane zircon data do permit a source in northeast Australia.

Petrographic study of the Permian to Early Triassic sandstones of the Bowen Basin, Central Queensland (Michaelsen & Henderson, 2000) shows that these rocks do not resemble contemporaneous strata of either the Te Akatarawa or the Torlesse terranes. The Bowen Basin strata contain consistently more quartz and lithic fragments than any of the New Zealand correlatives. Michaelsen & Henderson (2000) regard the Late Permian–Early Triassic Bowen Basin as representing a foreland basin west of the New England Orogen. An active volcanic arc lay within this source area. Both arc and orogenic uplands sources now appear to have lain east of the present eastern Australian coastline. Referring to the proposed Queensland source for the New Zealand Permian–Mesozoic sediments (Adams & Kelley, 1998), the Bowen Basin comprises the sequence closest to the inferred depositional site of the contemporaneous Torlesse and Te Akatarawa terranes. In addition, the Bowen Basin sediment has been derived from the north where New Zealand strata are proposed to have originally lain. Although the Bowen Basin is situated on the continental side of the arc while the Torlesse Terrane is inferred to have lain on the oceanic side, we can envisage no weathering or transport mechanism which could produce such consistently and profoundly different compositions (e.g. Dickinson, 1985). Thus on the basis of all available data, we conclude that whereas the northern part of the New England Orogen provides a most likely source for the Te Akatarawa sandstones, it is unlikely to have supplied the contemporaneous Torlesse sandstones.

Although the provenance of the Torlesse Terrane clearly indicates derivation from Gondwana (MacKinnon, 1983), the lateral continuity of rock units along the Pacific margin of the supercontinent makes definition of the exact location of the source difficult. We have long noted the similarity in the geological history of the New Zealand and New England segments of the margin (Cawood, 1984), but available geochemical, modal and zircon age data make New England an unlikely source for the Torlesse sediments (Cawood *et al.* 1999). The inferred cold-water affinities of the faunas in Permian and Triassic sedimentary rocks of the Torlesse Terrane (Shi & Grunt, 2000) suggest that accumulation took place at high southern latitudes probably near to the present day Antarctic segment of Gondwana.

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