AGU PUBLICATIONS

Tectonics

Supporting Information for

Reconnaissance basement geology and tectonics of South Zealandia

Andy Tulloch, Nick Mortimer,
GNS Science, Private Bag 1930, Dunedin, New Zealand

Trevor Ireland,
Research School of Earth Science, Australian National University, Canberra, Australia

Tod Waight
Department of Geosciences and Natural Resources Management (Geology Section), University of Copenhagen, Denmark

Roland Maas
School of Earth Sciences, University of Melbourne, Australia

Mike Palin,
Department of Geology, University of Otago, PO Box 56, Dunedin, New Zealand

Tusar Sahoo,
Hannu Seebeck,
Matt Sagar,
GNS Science, Lower Hutt, New Zealand

Andrea Barrier
Department of Geosciences, University of Canterbury, Christchurch, New Zealand

Rose Turnbull,
GNS Science, Private Bag 1930, Dunedin, New Zealand

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Introduction

This Supporting Information includes:

a) detailed descriptions of analytical methods that provide information on how data were collected, including calibration and secondary standard compositions, mass spectrometer operating conditions etc.

b) data files

c) reference to two separately uploaded data files

d) thin section photomacrographs of samples studies

e) Field photographs, and one cathodoluminescence image of zircon from Antipodes Is.

Text S1. Analytical Methods

Whole rock geochemistry

XRF analysis was undertaken by CRL Energy Ltd, Lower Hutt, NZ. Rock powders received are dried at 110 °C. A representative sample split is ignited at 1000 °C, providing a Loss-on-Ignition value. This ignited material is used to create a Lithium metaborate/tetraborate fused glass bead for analysis of the major oxide components. For trace element analysis (19 elements) a pressed-powder briquette, with appropriate binder (10% analytical-grade wax) is manufactured. Analysis is by X-ray fluorescence spectrometry, on a dedicated alumino-silicate calibrated analytical program, using the major oxide data for matrix correction. A SRS3000 Siemens/Bruker X-ray fluorescence spectrometer was used for both the major oxide and trace element analysis.

REE and other trace elements analysed by ICPMS. At Washington State University powdered samples were mixed with an equal amount of lithium tetraborate flux (typically 2 g), placed in a carbon crucible and fused at 1000° C in a muffle furnace for 30 minutes. The resultant fusion bead was briefly ground in a carbon-steel ring mill and a 250 mg portion was weighed into a 30 ml, screw-top Teflon PFA vial for a two-step dissolution that included HNO_3 (2 ml), HF (6 ml), and $HClO_4$ (2 ml) at 110 °C followed by addition of 10 ml of water, 3 ml HNO_3, 5 drops H_2O_2, 2 drops of HF and warmed on a hot plate until a clear solution was obtained. Solutions were analysed on an Agilent 4500 ICPMS; instrumental drift was corrected using Ru, In, and Re as internal standards. Standardization was accomplished by processing duplicates of three in-house rock standards interspersed within each batch of 18 unknowns. More detail is available at https://environment.wsu.edu/facilities/geoanalytical-lab/technical-notes/icp-ms-method/. At ALS a powdered sample (0.100 g) is added to lithium metaborate/lithium tetraborate flux, mixed well and fused in a furnace at 1025 °C. The resulting melt is then cooled and dissolved in an acid mixture containing nitric, hydrochloric and hydrofluoric acids. This solution is then analysed by ICPMS (code ME-MS81).

Radiogenic isotopes

Rb-Sr and Sm-Nd isotope compositions for five samples (four granitic rocks, one greywacke) were obtained by isotope dilution mass spectrometry at three different laboratories. In all cases, spiked samples were dissolved at high pressure, followed by element extraction using different combinations of cation exchange and Eichrom resins. At the University of Copenhagen and at University of California, Santa Barbara, the isotopic analyses were carried out on multi-collector TIMS instruments (VG Sector-54 at Copenhagen, Finnigan-MAT261 at UCSB); a Nu Plasma MC-ICPMS was used at the University of Melbourne. Further details are given in Scott et al. (2014) and Maas et al. (2015). All results were obtained by isotope dilution using mixed spike solutions. Sr isotope data are internally normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{87}Sr/^{86}Sr$ is reported to SRM987 = 0.71023. Internal precision is ± 0.00002 (se) or lower, while external precision is ± 0.00003-0.00004 (2sd); the external precision for $^{87}Rb/^{86}Sr$ is ±0.5% (2sd). Nd isotope data are internally normalized to $^{146}Nd/^{144}Nd = 0.7219$ (UC, UCSB) or

$^{146}Nd/^{145}Nd$ = 2.0719425 (UM), and $^{143}Nd/^{144}Nd$ is reported relative to the La Jolla standard ($^{143}Nd/^{144}Nd$ = 0.511860). Internal precision is ± 0.000010 (se) or lower, while external precision is ±0.000020 (2sd); the external precision for $^{147}Sm/^{144}Nd$ is ± 0.2% (2sd). ε_{Nd} values are for a modern CHUR with $^{147}Sm/^{144}Nd$ = 0.1960 and $^{143}Nd/^{144}Nd$ = 0.512630 (Bouvier et al., 2008) and Nd model ages (T_{DM}) are based on a model depleted mantle with $^{147}Sm/^{144}Nd$ = 0.2129 and $^{143}Nd/^{144}Nd$ = 0.513145 (equivalent to ε_{Nd} = +10). Decay constants:$^{87}Rb = 0.01395 \times 10^{-11}$/yr; $^{147}Sm = 0.00654 \times 10^{-12}$/yr.

U-Pb geochronology

LA–ICPMS zircon dating was undertaken in the Centre for Trace Element Analysis at the University of Otago. The facility incorporates a Resonetics RESOlution M-50-LR laser ablation system with a Coherent CompexPro 102 193 nm ArF excimer laser and Laurin Technic M50A two-volume sample cell input to an Agilent 7500cs quadrupole ICPMS. The laser was operated in dynamic voltage mode (~28 kV) with a transmittance of 12.5% to maintain a constant laser energy of ~126 mJ, corresponding to a fluence of ~2.5 Jcm^{-2}. High purity He and Ar gases were added to the sample cell at rates of ~0.3 L/min and ~0.9 L/min, respectively, to carry ablated material to the ICPMS. Mercury traps were fitted to the upstream end of both the He and Ar gas lines. High-purity N_2 gas was added at ~0.03 L/min to increase sensitivity. Abundances of 18 masses were measured in time-resolved mode. The 40-s duration of each spot analysis allowed for ~100 mass scans (40 s/0.375 s). The ICPMS was tuned to maximise ^{238}U sensitivity, while minimising production of doubly charged species, CaO, ThO, and $^{238}U/^{232}Th$ mass fractionation.

Raw data (counts per second) were processed with the U–Pb geochronology data reduction scheme (DRS) in Iolite 3.36 (Paton et al. 2011) using an exponential downhole fractionation correction (Paton et al. 2010). Baseline levels of all masses were subtracted using their abundances measured immediately prior to each spot analysis (step forward spline). Outlier data >3 standard deviations from mean values were excluded. The sequence in which the samples were analysed remained constant within an analytical session so that U–Th–Pb–TE data could be corrected using mean values for TEMORA 2 and NIST SRM 610 within each session. The isotopic ratios and $^{206}Pb/^{238}U$ age (417.26 ± 0.47 Ma) of TEMORA 2 used for data processing were uncorrected for common Pb as recommended by Horstwood et al. (2016). Trace element data were calibrated against NIST SRM 610 (Jochum et al. 2011) using the stoichiometric Si content of zircon (14.76 wt%). Selection of the appropriate data interval for processing was based on downhole age zonation indicated by $^{206}Pb/^{238}U$ ratio variation and the presence or absence of inclusions indicated by spikes in trace element content. For example, spikes in ^{31}P were interpreted to indicate analysis of apatite inclusions. The ^{238}U, ^{235}U and ^{232}Th decay constants and $^{238}U/^{235}U$ ratio used are those recommended by the International Union of Geological Sciences geochronology sub-commission (Jaffey et al. 1971; Steiger & Jäger 1977). Uncertainties include variation in primary reference materials (TEMORA 2 zircon and NIST SRM 610 glass) within each analytical session.

SHRIMP U-Pb zircon measurements were carried out on SHRIMP I at the Australian National University, with the exception of Antipodes Island granite xenolith (P52539), which was carried out on SHRIMP-RG at Stanford University. Methods followed standard measurement protocols (Muir et al. 1996). For the drill core samples, both U concentrations and U/Pb ratios were determined relative to the SL13 reference zircon (572 Ma, 238 ppm U). For Antipodes Island and Bounty Island samples, U concentration was calibrated to SL13, but U/Pb was calibrated to AS3. Both SL13 and AS3 have some issues with U/Pb calibration and their use has been discontinued (Ireland and Williams 2003). However, these issues are at the level of only a few percent and will not greatly affect the conclusions in this study. For SL13 normalisation, there is an apparent over calibration resulting in U-Pb ratios that are 0-2% high. For AS3, variable Pb loss (Schmitz et al. 2003) results in calibration to a low mean $^{206}Pb/^{238}U$, also pushing the resulting unknowns to higher ages, typically up to 2%. Overall, the zircon analyses from these samples are typically over dispersed with MSWD ranging from 3.4 to 14.4.

TIMS zircon grains were air-abraded (Krogh, 1982) prior to dissolution and column chemistry in a clean lab at Otago University, Dunedin, utilising a mixed ^{205}Pb-$^{235}U^{233}U$ spike. Isotopic measurements were subsequently made on a Finigan MAT 261 mass spectrometer at Brown University, Rhode Island (Getty and Gromet, 1992).

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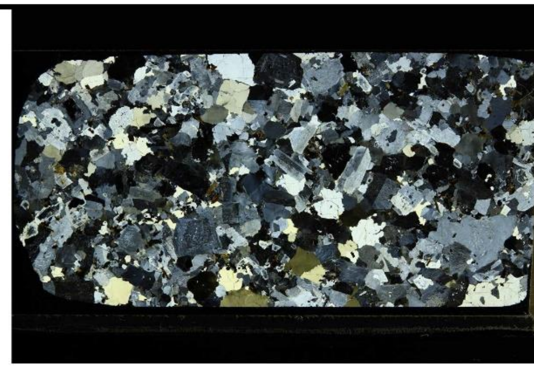

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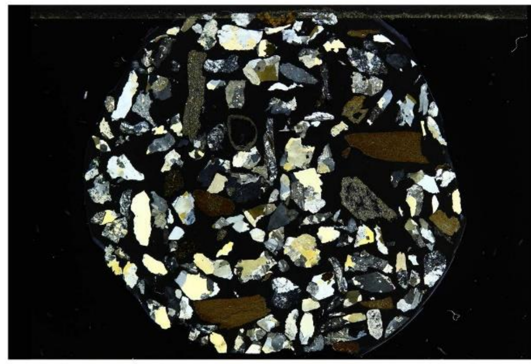

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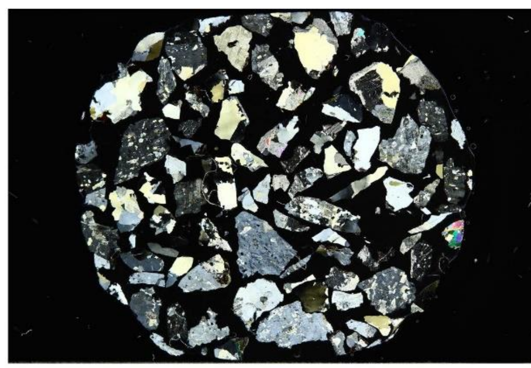

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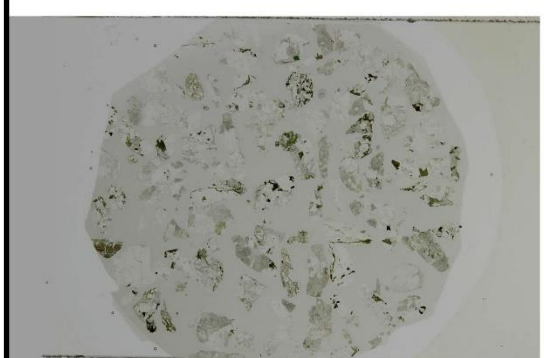

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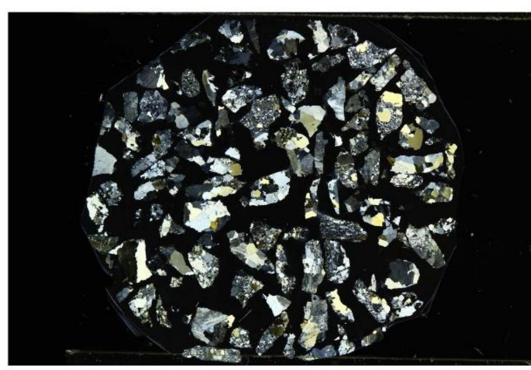

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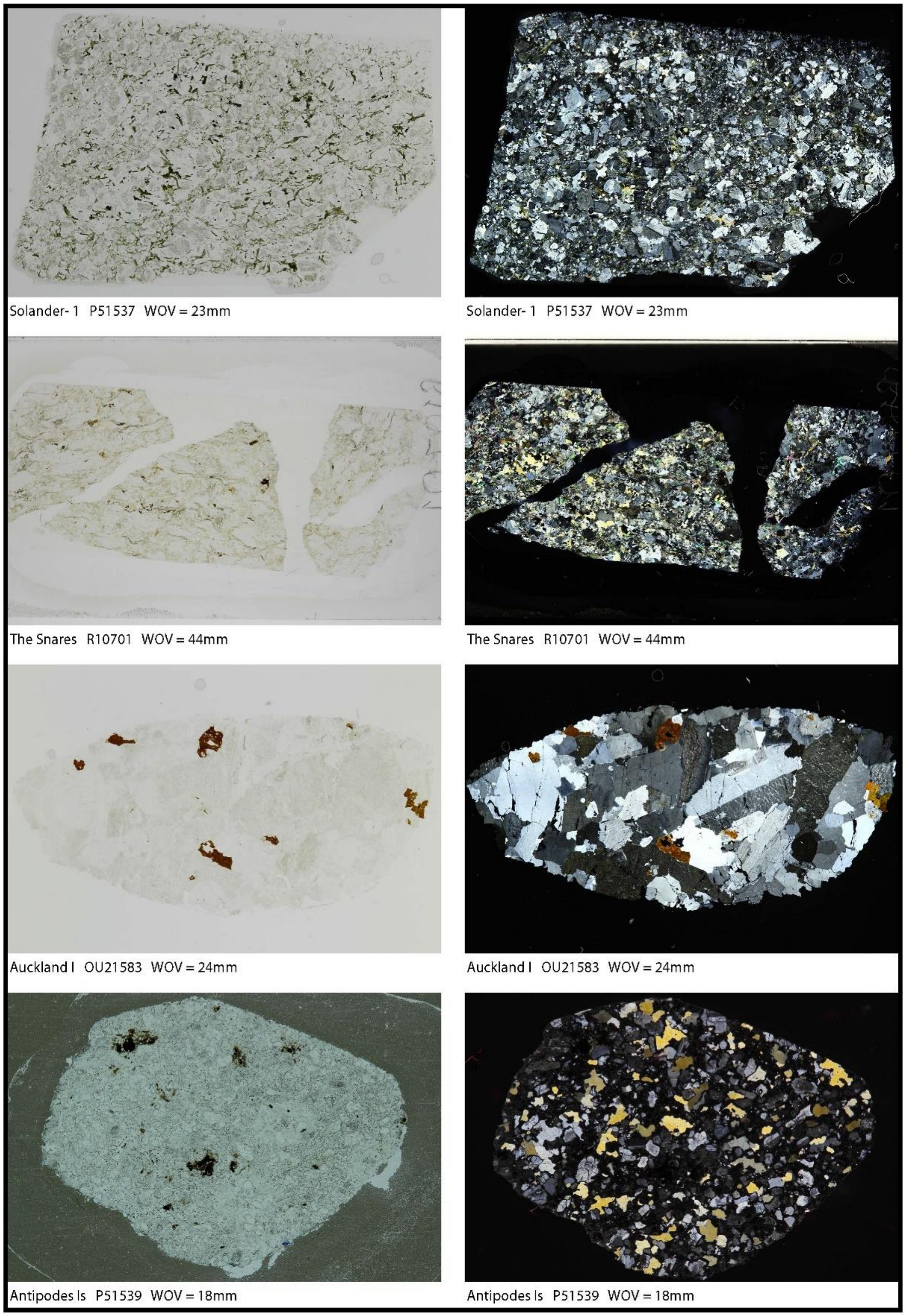
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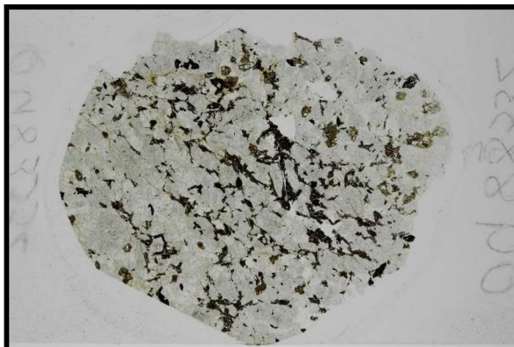
Solander- 1 P51537 WOV = 23mm
The Snares R10701 WOV = 44mm
The Snares R10701 WOV = 44mm
Auckland I OU21583 WOV = 24mm
Auckland I OU21583 WOV = 24mm
Antipodes Is P51539 WOV = 18mm
Antipodes Is P51539 WOV = 18mm



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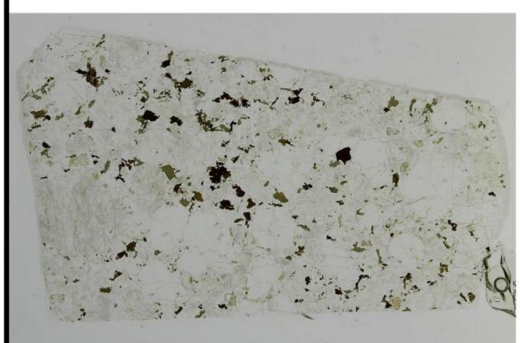
Antipodes Is OU83332 WOV = 42mm

Bounty Is P28371 WOV = 55mm

Bounty Is P28371 WOV = 55mm



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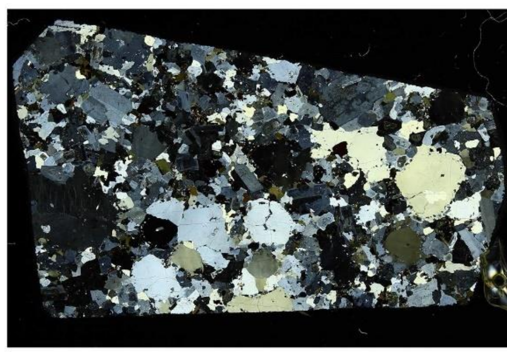

Bounty Is P28372 WOV = 38mm

Bounty Platform P51222 WOV = 60mm

Bounty Platform P51222 WOV = 60mm

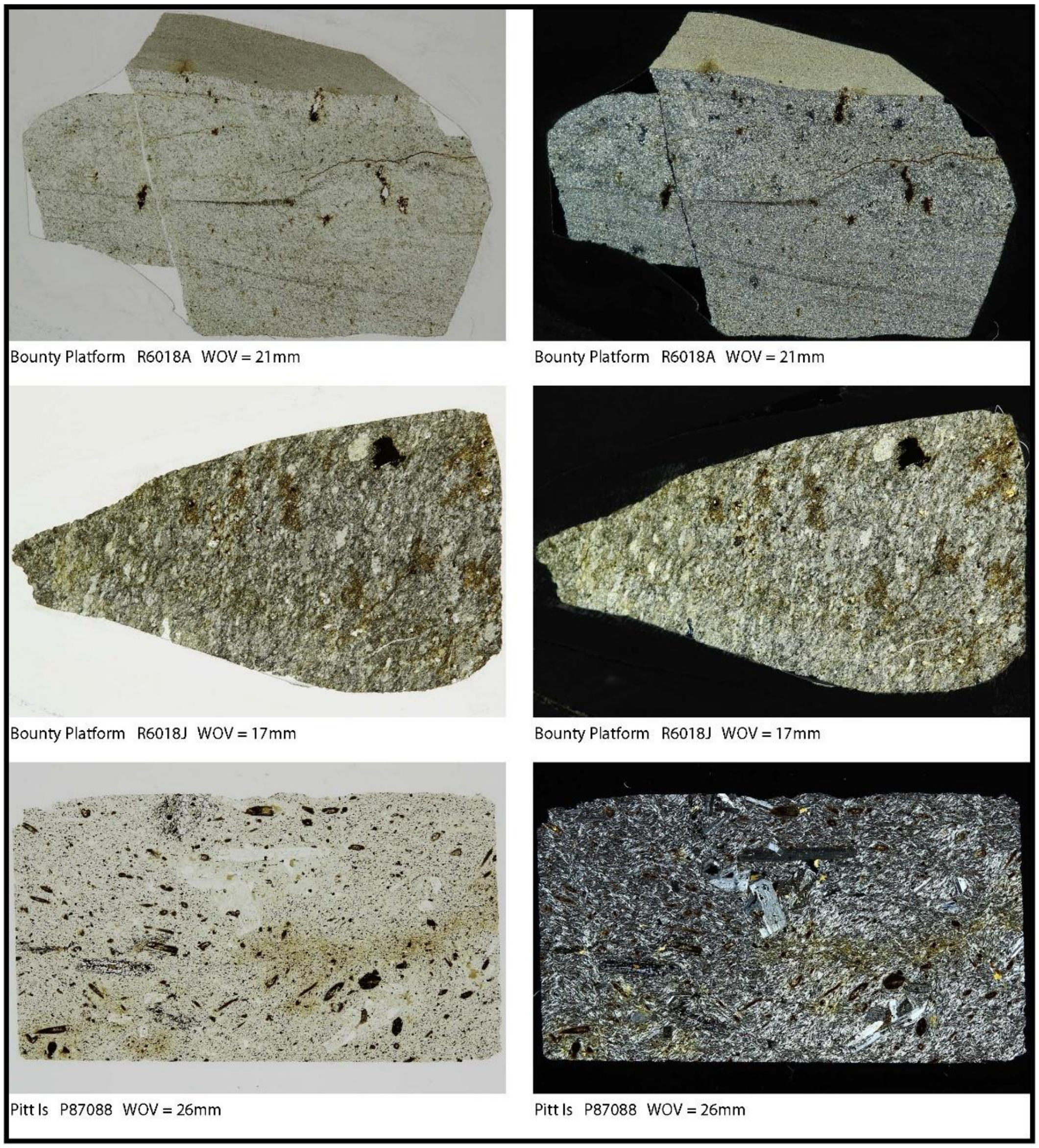

Figure S1. Photomacrographs of whole thin sections of most samples studied were taken on a digital SLR camera with a 60mm macro lens of thin sections sitting on a 70 x 70mm transmitted light illuminator. The light source comprised an array of 60 LED chips, producing a total of c. 1000 lumens. Left hand images are plain light and the righthand images are with crossed polarized light. WOV is width of view.

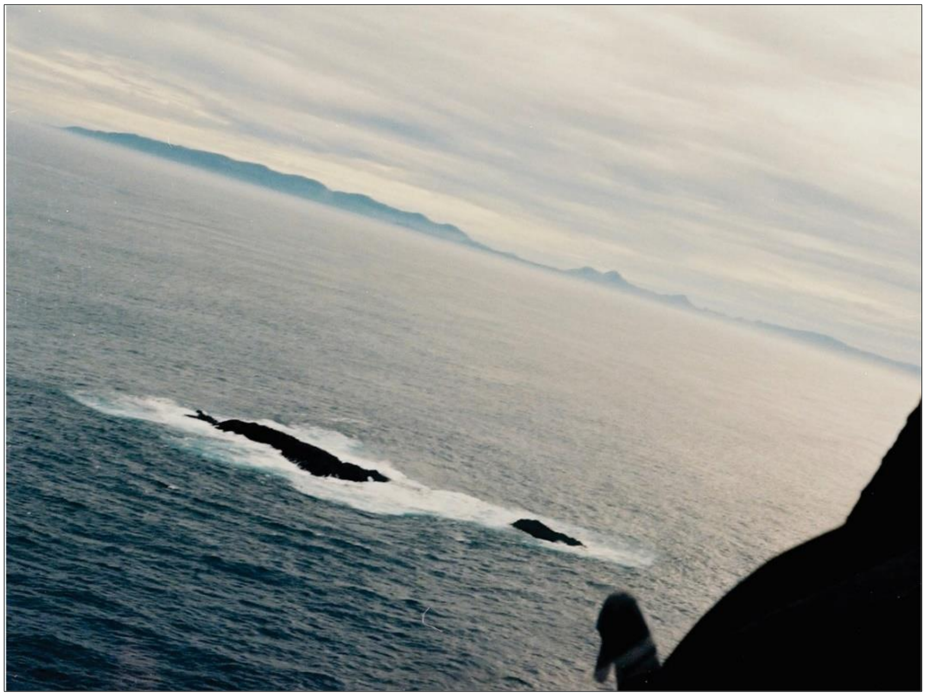

Figure S2. Sampled reef within the northern group of The Traps, looking WNW towards southernmost Stewart Island. Rock on the left is about 10m long, and the tide is low. These reefs represent the only exposures of unmetamorphosed, unaltered, plutonic rocks in the hanging wall of the Sisters Shear Zone.

Historical note: In 1770 the British explorer James Cook sailed away from New Zealand having failed to find the great southern continent that Europeans believed must exist to balance the major continental masses of the northern hemisphere. As he did so he nearly came to grief on rocks he named The Traps. Little did he know that they were a hint to a continent beneath the waves.

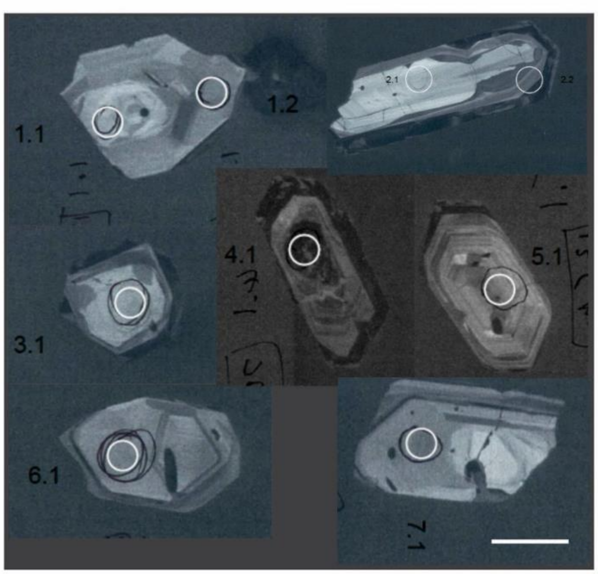

Figure S3. Cathodoluminescence images of zircon from Antipodes sample P51539. SHRIMP analysis sites maked; scale bar 50 µm.

Figure S4. Google Earth image of Bounty Islands, main group. Predominant brittle fracture direction is 060°**.**


Figure S5. Trachytic dykes striking c.160°, SW Pitt Is (Chatham Is group). High points on rear ridge are c. 170 m above sea level.

Table S1. LA-ICPMS zircon U-Pb isotope age and TE, U analyses for South Zealandia samples_180301

	The Traps	Snares Is	Snares	Auckland Is	Colbeck Trough		Antipodes xenoliths		Bounty Is
	P62424	P63138	R10701	OU21583	D2-2	D2-47	P51539	OU83332	R6180
Ba	521	149	284	65			597	183	539
Ce	72.7	30.5	17.6	104.70	364.20	300.40	33.85	46.8	45.6
Cs	7.96	18.35	5.89	2.75			4.14	4.22	7.67
Dy	5.03	5.42	1.74	6.62			0.73	3.35	2.59
Er	2.57	3.21	0.86	3.44			0.4	1.96	1.58
Eu	0.68	0.51	0.36	0.40	1.28	1.65	0.47	1.39	0.68
Gd	4.99	3.84	1.59	7.33			1.21	3.94	2.73
Hf	6.1	2.4	1.9	3.97			3.41	6.7	3.8
Ho	0.94	1.07	0.31	1.29			0.15	0.67	0.55
La	32.9	13.1	8.1	47.39	129.00	113.00	20.08	18.1	21.6
Lu	0.4	0.66	0.12	0.48	0.25	0.24	0.09	0.31	0.29
Nb	18.4	19	18.3	14.65			2.54	10.3	8.9
Nd	30.1	13.3	7.5	42.35	144.40	106.00	10.52	20.7	17
Pr	7.98	3.66	2.01	11.75			3.18	5.03	5.14
Rb	214	278	298	230.5			174.3	71.1	164
Sm	6.44	4.02	1.9	9.14	16.98	12.98	1.79	4.16	3.46
Sr	243	69.4	97.9	79			198	408	188.5
Ta	3.7	1.6	3.1	3.08			1.24	0.9	1.4
Tb	0.79	0.84	0.3	1.14	1.10	1.03	0.15	0.54	0.45
Th	20.5	7.45	2.76	43.71			23.2	13.85	12.85
Tm	0.41	0.59	0.12	0.52			0.06	0.31	0.31
U	3.92	1.9	4.17	2.69			7.64	3.73	2.04
Y	26.3	33.6	9.4	33.96			4.18	18.7	16.2
Yb	2.65	4.06	0.91	3.08	2.40	2.60	0.45	1.91	1.79
Zr	202	53	36	118				264	123

P51539 analysed at Washington State University, Pulman; Colbeck samples by INAA at Oregan State Univ.; all other samples analysed at ALS, Brisbane.

Table S2. ICPMS trace element analyses of Whole rock samples from South Zealandia. Elements in ppm.

Sample name	location	lithology	age t, Ma	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$^{87}Sr/^{86}Sr(t)$	$\varepsilon_{Nd(t)}$	T_{DM}, Ga
P62424^	The Traps	granite	120	189.5	231.5	2.368	0.70943	6.03	28.63	0.1271	0.512478	0.70546	-1.9	1.18
OU21583^	Auckland Is	granite	96	228.9	91	7.285	0.71760	8.72	43.24	0.1217	0.512211	0.70784	-7.3	1.56
P51539*	Antipodes Is	granite xenolith	130	140.1	160.3	2.53	0.70972	1.68	11.17	0.0910	0.512622	0.70513	1.6	0.65
P83332^	Antipodes Is	granodiorite xenolitl	120	65.4	432	0.438	0.70655	15.82	79.74	0.1197	0.512530	0.70582	-0.8	1.01
R6019#	Bounty Platform	greywacke	490	191.7	114.1	4.884	0.74322	8.53	42.43	0.1216	0.512170	0.70972	-4.3	1.62

Analyzed by laboratories at ^University of Copnehagen, * University of California at Santa Barbara, # University of Melbourne. Procedures are reported in Supporting Information.

Table S3. Radiogenic isotope analyses of whole rock samples from South Zealandia

Table S4. SHRIMP zircon U-Pb isotope age analyses from South Zealandia samples

size fraction	weight (mg, est.)	Pb (ppm)	U (ppm)	206/204	206*/238	%error	207*/235	Radiogenic %error	Rho	ratios 207*/206*	%error
Mulitfaceted	0.01	5.94	316.4	972	0.0183157	0.602	0.122825	1.35	0.51	0.0486364	1.17
Prism, 150m	0.01	7.59	114.13	390.5	0.061515	1.12	0.424892	3.23	0.43	0.0500953	2.93
Prism, 125m	0.01	165.96	531.65	998.4	0.267978	0.379	1.83794	0.416	0.92	0.0497427	0.167

	apparent ages (Ma)				
	206*/238	207*/235	207*/206*	(±)	S&K (Ma)
Mulitfaceted	117.00	117.63	130.34	1.52	120
Prism, 150m	359.54	384.83	199.42	5.84	120
Prism, 125m	1530.5	1059.1	182.99	0.31	120

Single grains prepared at GNS/Otago University, Dunedin and analysed by Nick Walker at Brown University, RI, USA using a ^{205}Pb-^{233}U-^{235}U tracer.
Total procedural blanks are ~2 picograms for U and ~8 picograms for Pb. Measured isotopic ratios corrected for mass fractionation of ~ 0.11% per atomic mass unit based on analyses of NIST SRM 981 and 982 and adjusted for small amount of ^{206}Pb in tracer

+Total Pb concentration includes blank Pb, common Pb in zircon and radiogenic Pb. Total procedural blanks are ~2 picograms for U and ~8 picograms forPb.
Measured isotopic ratios corrected for massfractionationof ~ 0.11% per atomic mass unit based on analyses of NIST SRM981 and 982 and adjusted for small amount of 206Pb in tracer.
Uncertainty in the calculated ages is stated at the two-sigma
level and estimated from combineduncertainties in calibrations of mixed 205Pb - 233U - 235U tracer, measurement of isotopic ratios
of Pb and U, common and laboratory blank Pb isotopic ratios, Pb and U mass fractionation corrections, and reproducibility in measurement of NIST Pb and U standards.

Table S5. TIMS zircon U-Pb isotope age analyses from Antipodes is granite xenolith P51539

Sample	Sample type	Locality	Latitude	Longitude	Site Description
OU21583	Surface	Auckland Is	-50.81096272	166.0605119	W side of Crab Bay, Musgrave Peninsula
OU83332	Surface	Antipodes Is	-49.70746644	178.7448174	South coast
P28371	Surface	Bounty Is	-47.75	179	approx lat-long, Bounty Island
P28372	Surface	Bounty Is	-47.75	179	approx lat-long, Bounty Island
P51222	Dredge	Offshore Bounty I	-47.68333333	179.05	Bounty Is offshore, dredge 121m, Cruise 506
P51537	Drillcore	Solander-1	-46.355	167.1566667	
P51539	Surface	Antipodes Is	-40.94187774	172.9002512	Wavecut platform, coast between South and Stack Bays
P57234	Drill cuttings	Parara-1	-46.62476944	167.1719833	
P57235	Drill cuttings	Pakaha-1	-48.2475	169.5495556	
P57236	Drill cuttings	Pukaki-1	-48.557225	170.1520417	
P62424	Surface	The Traps	-47.37	167.8843333	North Traps, main rock, w end, NZ Offshore
R10701	Surface	North coast	-48.01822005	166.5333128	Snares Islands
R6018J	Dredge	Offshore Bounty I	-47.7	179.45	NZOI (NIWA) seafloor station, 35 km E of Bounty Is
R6180	Surface	Bounty Islands	-47.75136284	179.0264751	summit of eastern islet of NW Group (Tunnel Island)

P, R, GNS Science collections; OU, Otago University collection

Table S6. Location information for analyzed rock samples from South Zealandia, downloaded from Petlab.