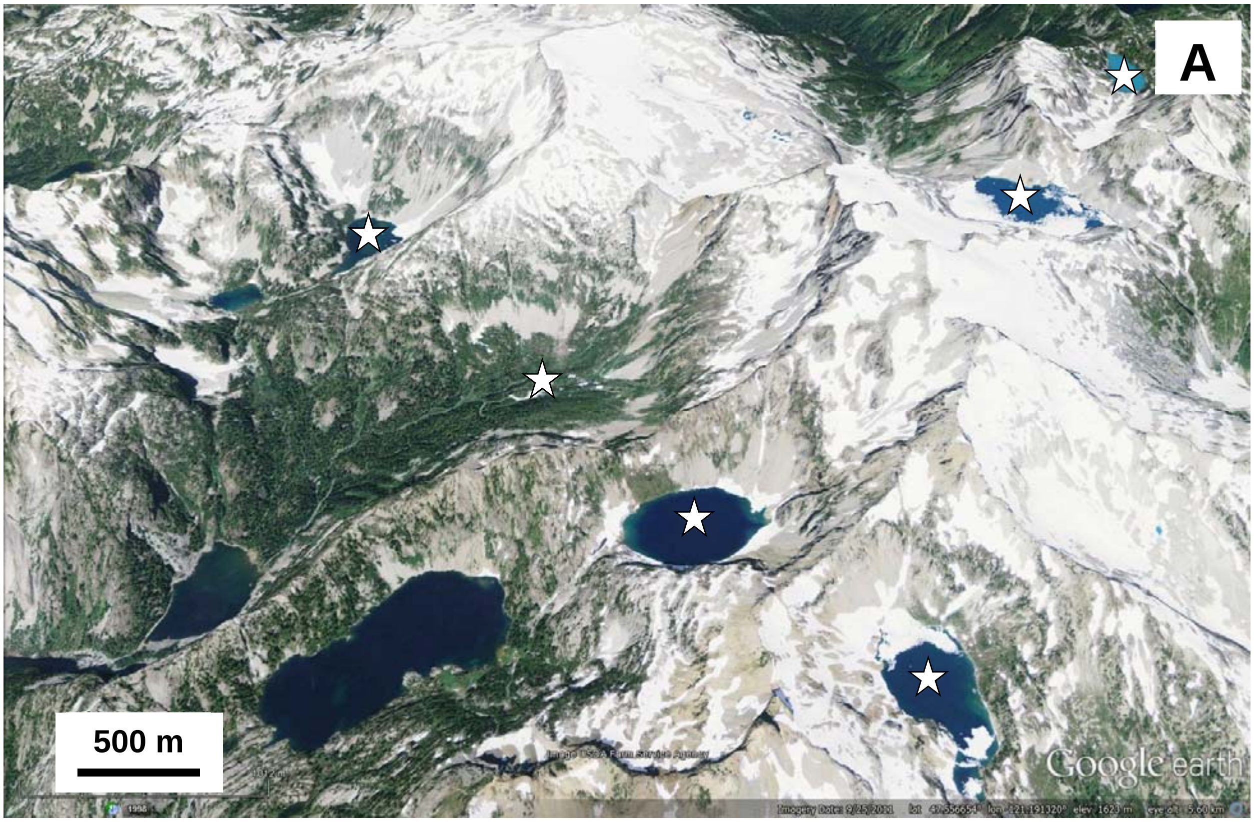
GSA DATA REPOSITORY 2015028

Supplemental Information for "Glacial cirques and the relationship between equilibrium line altitudes and mountain range height", by Mitchell and Humphries



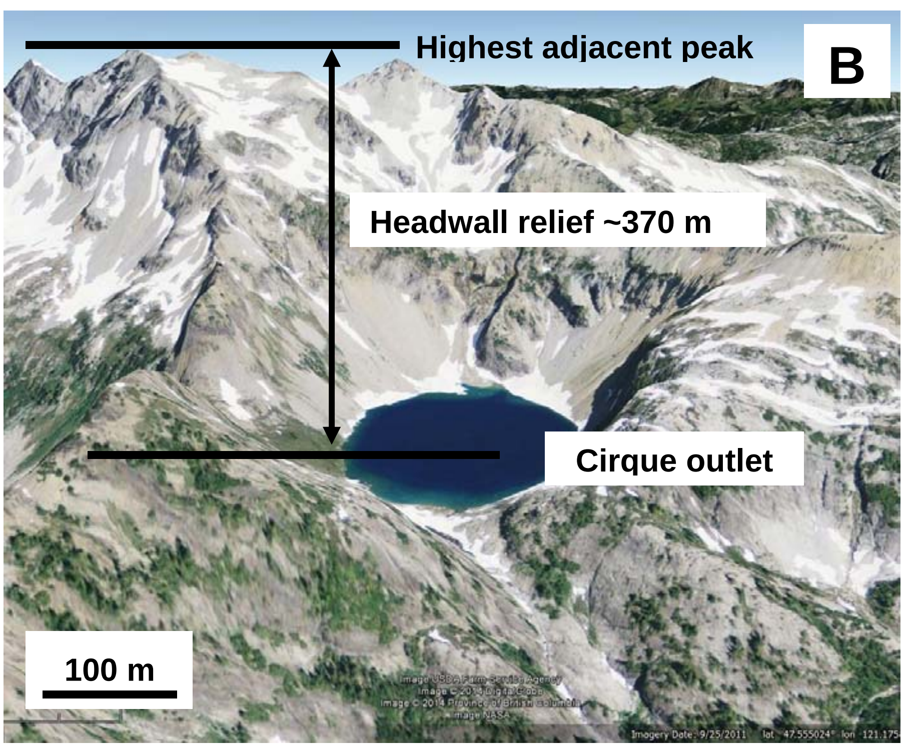


Figure DR 1. A. The glacially carved, alpine topography in the central Washington Cascade Range (47.55°N, 121.18°W) is an example of the cirque-rich landscapes analyzed for this study. This image shows at least five cirques (marked with stars) as defined in the methods. Only the highest cirque in a drainage was measured, unless lower cirques had a separate, well-defined headwall. The modern ELA is at or just above the peaks and the cirques are not presently occupied by glaciers. Cirque floors (technically tarn surfaces or cirque outlets) in this area formed in a zone centered around the Quaternary average ELA and peaks rise an average of ~370 m above cirque floors. B. Cirque headwall relief is a function of the highest adjacent peak altitude and the outlet altitude. Images are from Google Earth (photograph date: 11/2011).

Table DR1. Locations, cirque altitudes, relief, peak altitudes, precipitation rates, tectonic regime, shortening rate, and data sources.

Mountain Range Name and Country	Map Code (Figure 1)	Lat. (DD)	Long. (DD)	N of cirq.	Mean ± 1σ Cirque Floor Altitude (m)	Mean ± 1σ Relief (m)	Mean ± 1σ Peak Altitude (m)	*Modern average precip. (mm/yr)	Tectonic regime	†Short. rate (mm/yr)	Data Source
Caledonian Mountains, Norway	1	69.25	19.22	539	§590	400 ± 182	1091	710	Passive margin	0	Hassinen, 1998
Ogilvie Mtns., Canada	2	64.5	-138.833	128	1444	292	1780	324	Continental Interior	ND	Nelson and Jackson, 2003
Crag Mountain Upland, Canada	3	63.75	-140.667	54	1232	152	1498	247	Continental Interior	ND	Nelson and Jackson, 2003
Alaska Eastern Range, USA	4	63.39	-147.12	82	1549 ± 213	389 ± 105	1938 ± 218	270	Continental Interior	2	#USGS NED
Glenlyon Range, Canada	5	62.5	-134.5	52	1667 ± 122	214	1881	305	Continental Interior	ND	Nelson and Jackson, 2003
Northern Dawson Range, Canada	6	62.333	-137.667	31	1433 ± 125	168	1601	229	Continental Interior	ND	Nelson and Jackson, 2003
Southern Dawson Range, Canada	7	61.366	-138	66	1451 ± 117	135	1586	282	Continental Interior	ND	Nelson and Jackson, 2003
Torngat Range, Labrador, Canada	8	59.17	-63.95	246	614 ± 214	266 ± 81	880 ± 233	566	Passive margin	ND	USGS NED
Sredinny Mountains, Russia	9	56.00	160.00	3520	988 ± 274	420	1408	787	Active margin	ND	Barr and Spagnolo, 2013
Northern England, United Kingdom	10	54.43	-3.20	73	§520	ND	ND	1235	Passive margin	ND	Temple, 1965
Wales, United Kingdom	11	53.07	-3.83	260	§400	221	597	1113	Passive margin	ND	Evans, 2006
Canadian Cordillera, Canada	12	52.50	-118.00	1244	2299 ± 243	ND	ND	639	Continental Interior	2.1	Trenhaile, 1975
Coast Ranges, Canada	13	50.49	-123.79	384	1598 ± 435	445 ± 119	2042 ± 387	907	Active margin	3	USGS NED
Tatry Mountains, Slovakia	14	49.17	20.13	116	1921 ± 159	311 ± 99	2232	1150	Continental Interior	ND	Krizek and Mida, 2013
Glacier National Park, USA	15	48.71	-113.70	131	1997 ± 190	644 ± 256	2641 ± 226	671	Continental Interior	2	USGS NED
Olympic Mountains, USA	16	47.75	-123.48	114	1414 ± 282	312 ± 127	1727 ± 297	2661	Active margin	ND	USGS NED
Cascade Range, Washington, USA	17	47.63	-121.40	373	1462 ± 295	380 ± 190	1838 ± 309	2249	Active margin	ND	Mitchell and Montgomery, 2006
Carpathians, Romania	18	46.5	24	631	§1938	279	2217	949	Continental Interior	ND	Mindrescu et al., 2010
Ticino Alps, Switzerland	19	46.49	8.94	500	2435 ± 285	370 ± 175	2805 ± 617	1559.5	Continental Interior	0	Anders et al., 2010
Bitterroot Mountains, USA	20	45.53	-113.69	39	2658	248	2906	396	Continental Interior	ND	Foster et al., 2008
Wallowa Mountains, USA	21	45.20	-117.39	93	2348 ± 154	319 ± 103	2667 ± 161	728	Continental Interior	ND	USGS NED
Oregon Cascades, USA	22	44.48	-122.09	117	1381 ± 287	258 ± 84	1638 ± 293	2143	Active margin	ND	USGS NED
Beaverhead Mountains, USA	23	44.35	-112.84	38	2814	205	3019	441	Continental Interior	ND	Foster et al., 2008
Lemhi Range, USA	24	44.28	-113.59	146	2815	350	3165	362	Continental Interior	ND	Foster et al., 2008
Maritime Alps, France and Italy	25	44.07	7.45	432	2347 ± 227	355	2702	1198	Continental Interior	0	Federici and Spagnolo, 2004

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Lost River Range, USA	26	43.98	-113.67	83	2940	352	3292	330	Continental Interior	ND	Foster et al., 2008
Teton Mountains, USA	27	43.44	-110.83	142	2890	342	3232	521	Continental Interior	ND	Foster et al., 2008
Pyrenees, Spain	28	42.79	0.50	206	2100	364 ± 138	2464	1281	Continental Interior	0	Garcia-Ruiz et al, 2000
Uinta Mountains, USA	29	40.74	-110.51	247	3309 ± 161	374 ± 110	3683 ± 231	697	Continental Interior	0	USGS NED
Mt. Evans and Medicine Bow Range, USA	30	40.12	-105.75	164	3495 ± 169	384 ± 141	3879 ± 181	705	Continental Interior	0	USGS NED
Elk, Mosquito, and Sawatch Ranges, USA	31	39.20	-106.53	298	3598 ± 183	359 ± 106	3957 ± 194	570	Continental Interior	0	USGS NED
Northern Sierra Nevada, USA	32	39.00	-120.22	74	2380 ± 213	314 ± 124	2694 ± 269	1456	Continental Interior	0	USGS NED
Sangre de Cristo Mountains, Colorado, USA	33	37.99	-105.62	60	3653 ± 117	447 ± 101	4100 ± 118	552	Continental Interior	0	USGS NED
Central Sierra Nevada, USA	34	37.88	-119.40	175	3076 ± 252	367 ± 136	3443 ± 290	1039	Continental Interior	0	USGS NED
San Juan Mountains, USA	35	37.66	-107.35	201	3658 ± 185	315 ± 107	3973 ± 199	887	Continental Interior	0	USGS NED
Culebra Mountains, USA	36	37.12	-105.20	17	3673 ± 100	367 ± 119	4040 ± 136	674	Continental Interior	0	USGS NED
Southern Sierra Nevada, USA	37	36.97	-118.64	575	3338 ± 262	413 ± 133	3751 ± 313	755	Continental Interior	0	USGS NED
Wheeler Peak, USA	38	36.55	-105.41	16	3527 ± 114	315 ± 116	3842 ± 134	711	Continental Interior	0	USGS NED
Sangre de Cristos, New Mexico, USA	39	35.92	-105.64	26	3472 ± 141	313 ± 81	3785 ± 146	772	Continental Interior	0	USGS NED
Lidder Valley, Himalaya, India	40	34.17	75.37	81	3593 ± 358	182 ± 271	3776 ± 494	500	Active margin		Kaul, 1990
High Atlas Mountains, Morocco	41	31.48	-6.63	18	3210 ± 513	431 ± 86	3642 ± 502	570	Continental Interior	ND	**ASTER GDEM V1
Cerro Chirripo, Costa Rica	42	9.48	-83.49	7	3562 ± 55	185 ± 77	3747 ± 53	3337	Active margin	ND	††SRTM DEM in Google Earth
Rwenzori, Uganda and Democratic Republic of Congo	43	0.45	29.94	5	4113 ± 112	425 ± 135	4538 ± 196	1887	Continental Interior	ND	ASTER GDEM V1
Mount Kenya, Kenya	44	-0.15	37.31	13	4380 ± 78	592 ± 87	4971 ± 86	1641.5	Volcanic	ND	Wielochowski, 2007
Andes Mountains, Ecuador	45	-0.51	-78.21	116	3726 ± 330	342 ± 125	4068 ± 293	1286	Active margin	6	ASTER GDEM V1
Mount Wilhelm, Papua New Guinea	46	-5.79	145.00	7	3718 ± 32	525 ± 177	4243 ± 192	2389	Active margin	ND	SRTM DEM in Google Earth
Andes Mountains, Chile and Argentina	47	-30.17	-70.27	147	4003 ± 346	386 ± 86	4390 ± 385	97	Active margin	3	ASTER GDEM V1
Andes Mountains, Chile	48	-40.47	-71.80	406	1390 ± 201	385 ± 108	1774 ± 188	1328	Active margin	ND	ASTER GDEM V1
Northern Southern Alps, New Zealand	49	-42.00	172.75	289	1420 ± 249	287 ± 100	1707 ± 233	2124	Active margin	9	§§ LINZ, Geographix
Ben Ohau Range, New Zealand	50	-44.00	170.00	92	§1843 ± 250	157	2000	3702	Active margin	9.1	Brook et al., 2006
Central Southern Alps, New Zealand	51	-44.00	169.50	399	1544 ± 378	363 ± 178	1906 ± 366	3702	Active margin	9	LINZ, Geographix
Andes Mountains, Chile	52	-45.38	-72.83	225	1046 ± 243	387 ± 103	1434 ± 251	2225	Active margin	0	ASTER GDEM V1

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Southern Southern Alps, New Zealand	53	-46.00	167.00	555	1129 ± 315	386 ± 132	1491 ± 281	2145	Active margin	9	LINZ, Geographix
Andes Mountains, Chile	54	-47.48	-73.42	88	1022 ± 398	428 ± 113	1450 ± 400	1470	Active margin	0	ASTER GDEM V1
Falkland Islands, Great Britain	55	-51.75	-59.50	49	§440 ± 100	160	600	542	Passive margin	ND	Clapperton, 1971
Taylor Valley, Antarctica	56	-77.38	161.75	52	174	515	1650	ND	Passive margin	ND	Aniya and Welch 1981

* Mean Annual Precipitation from summed monthly 10-arc-minute normals for 1950-2000 WorldClim (Hijmans et al., 2005)

† Shortening rates compiled by Champagnac et al., 2012

§ Cirque altitudes derived from graphs rather than tabular data

USGS NED refers to data from United States Geological Survey National Map program, http://nationalmap.gov, accessed between June 2011 and February 2014.

**Data from The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 1 (V1). These data were obtained through the online data pool at the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov/data_access), in June and July, 2011.

†† Data obtained from 90-m digital elevation model from the Shuttle Radar and Tomography Mission (SRTM), accessed via Google Earth in January and February, 2014.

§§ 100-m digital elevation models derived from 1:50,000 scale digital topographic maps from Land Information New Zealand (LINZ) (www.linz.govt.nz/topography/topographic-data) and distributed by Geographx (http://geographx.co.nz), accessed June and July, 2011.

Analysis of residuals

The residuals for cirque altitude and QAEP ELA have a mean = -117 m with 1σ = 478 m (Fig. DR2 and DR3). The residuals do not differ from a normal distribution (Kolmogorov-Smirnov p-value > 0.2; Shapiro-Wilk p-value = 0.407). A one-sample T-test further demonstrates that the mean of the distribution is not significantly different from zero (t-statistic = -1.836; sig. = 0.072).

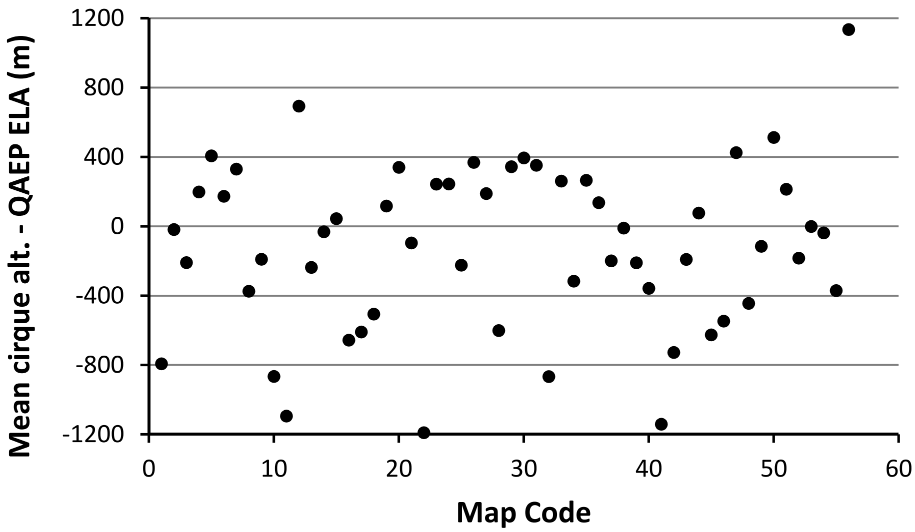

Figure DR2. Residuals for cirque altitude and EP ELA for the 56 study locations. Map codes correspond to Figures 1 and DR1.

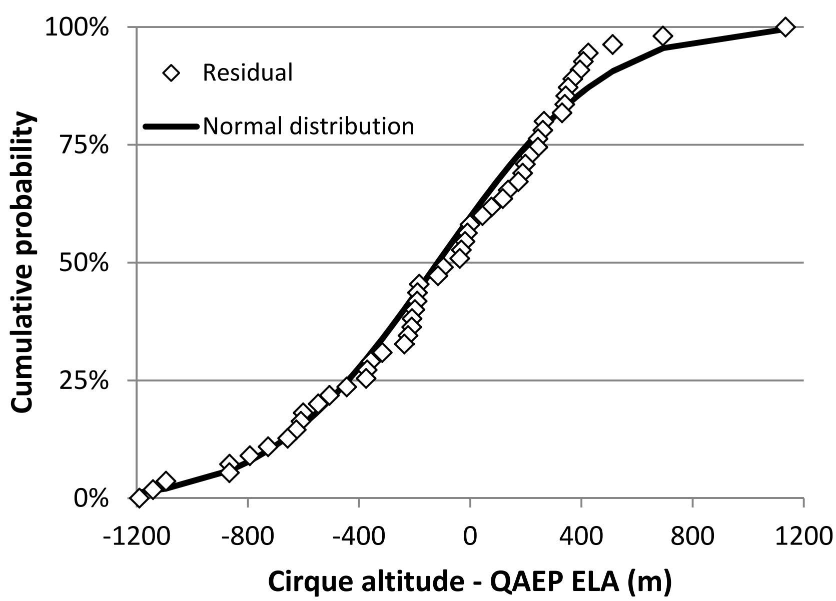

Figure DR3. Cumulative probability function for residuals. Symbols are our data, the line represents a normal distribution with the same mean and 1σ.

To determine whether average cirque altitudes were preferentially above or below the QAEP ELA depending on modern annual precipitation or average adjacent peak height, we did linear regressions. When we compare cirque altitude and QAEP ELA residuals to modern average annual precipitation, we see that mean cirques altitudes are more likely to be higher than the QAEP ELA where precipitation is low than where precipitation is high, but the low r^2 value indicates a very weak correlation (Fig. DR4).

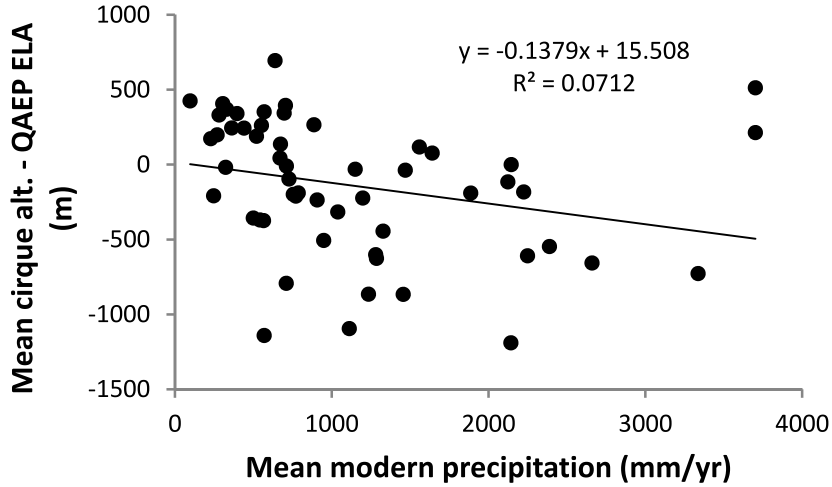

Figure DR4. Average cirque altitude – QAEP ELA vs. modern average annual precipitation in mm. Precipitation data from WorldClim (Hijmans et al., 2005).

Cirques are slightly higher with respect to the QAEP ELA on higher peaks, but again the r^2 value is low and thus the correlation is weak (Fig. DR5). Differences between the QAEP ELA and each study location's actual QA ELA may account for the correlation weakness.

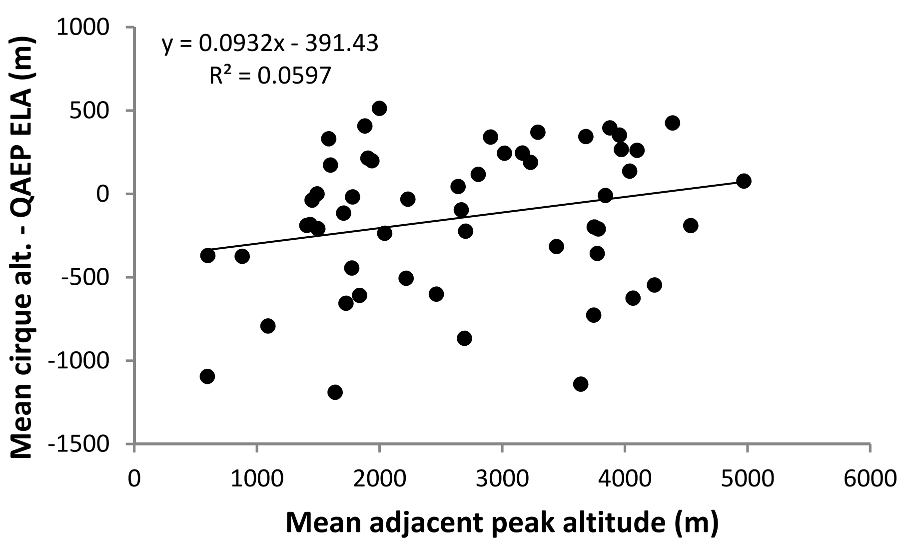

Figure DR5. Average cirque altitude – QAEP ELA vs. mean adjacent peak height.

Cirque floor altitudes are, on average, lower than the QAEP ELA for active and passive margins, while those in continental interiors are centered on the QAEP ELA (Figure DR6). The difference in residuals for passive margins compared with active margins and continental interiors are statistically insignificant (Mann-Whitney U-test p-values = 0.509 and 0.1 respectively). The difference between active margins and continental interiors is significant (p-value = 0.019) at the 0.05 level, but not with the more stringent significance level (P = 0.0167) of the Bonferroni correction for multiple tests.

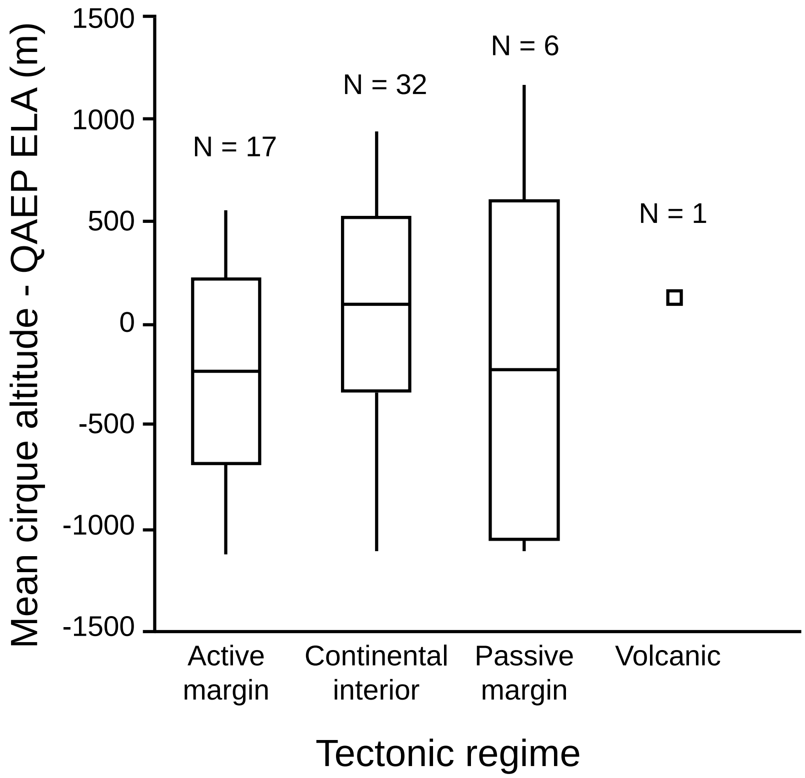

Figure DR6. Box and whisker plot of the mean ± 1 σ and extreme values of residuals for each of the tectonic regimes. Differences in residuals between groups are not highly significant.

References Cited

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Wielochowski, A.L., ed., 2007, Mount Kenya 1:50,000 Map and Guide, 4th edition: EWP.