Supplementary Table 1. Detailed geomorphic descriptions of Black Mountain alluvial−fan surfaces.

Fan Surface Name	Surface [a]	Desert Pavement	Desert varnish[b]	Cracked Rocks	Dissolution of limestone	Lithology	Clast size	Clast angularity	Additional comments:
A (T1)	planar	Weak to none – soil is stripped down to Cc calcrete layer	Well−developed iridescent black.	Abundant cracked rock parts. No partnered rocks.	—	Basalt	Dominantly 20−30 cm b−axis diameter		Colorado River fines (likely correlative with the Bullhead Alluvium of House et al., 2005) exposed 15 m below top of fan surface. Soil stripped, surface on calcrete horizon.
B (Q1)	Planar with subtle curvature; has crown	Weak to none – soil is stripped down to Cc calcrete layer	Well−developed; vesicular basalt clasts are iridescent black; massive basalt clasts	Rare, but apparent that lots of rocks have cracked but aren't partnered rock clasts	—	Basalt, petrocalcic litter and pendants up to 10 cm in length	Bimodal; Gravel to boulders; dominantly 50 cm b−axis	Angular to subrounded; dominantly subangular	Some round patches of desert pavement made of calcrete rubble with few boulders.
B1 (Q2a)	Subdued B&S topography to Planar	Weak to none – soil is stripped down to Cc calcrete layer	Well−developed; vesicular basalt clasts are iridescent black; massive basalt clasts	Rare, but apparent are many boulders that have cracked and aren't partnered rock clasts	—	Basalt, petrocalcic litter and pendants up to 10 cm and 2 cm in length, respectively.	Bimodal; Gravel to boulders; dominantly 50 cm b−axis	Angular to subrounded; dominantly subangular	Surface has fault scarp at toe of deposit.
C (Q2a)	B & S; hummocky; 1−2 m relief	Swales filled in with desert pavement, mainly uniform grain size, occasional angular cobbles.	Well−developed, but less so than on Surface B. Vesicular basalt −black varnish; massive basalt − dark rusty brown varnish.	Rare; some rocks with cracks but not all the way through into separate rock pieces. More rhyolites are cracked.	—	Dominantly basalt, particularly larger rocks; purple rhyolites; some petrocalcic litter. Rare, thick Cc pendants.	Gravel to large boulders (60 cm b−axis); dominantly 20 cm and 40 cm basalt boulders.	Angular to subrounded; dominantly subrounded; Rhyolites – angular; Basalts – subangular to subrounded.	Rare well−rounded yellow chert pebbles (Colorado River). Overlies Bullhead Formation.
D (Q2b)	Very subdued B & S; swales are 10 m across; 0.5 m relief.	Swales filled with desert pavement made of uniform, angular to subangular clast size.	Developed; vesicular basalts approaching black; massive basalts have dark rusty brown.	Rare.	Rare pitted limestone cobbles.	Dominantly basalt; rare limestone; orange rhyolites; purple rhyolites; more	Pebbles to boulders (50 cm b−axis)	Subangular to rounded; dominantly subrounded.	1−2 m thick Colorado River sands 4−5 m below surface. Sands have undulating

						orange than purple.			surface; contain local, angular pebble layers, but dominantly uniform arkosic sand size.
E (Q2c)	B & S; swales are disturbed; no dissection on remnant, but active wash has created other Q2c remnants.	Weak. Interlocking non−uniform clast size; not flat surface.	Weak; rusty brown, no black, even on vesicular basalt boulders.	Rare.	—	Dominantly basalt. Purple rhyolite. More abundant petrocalcic litter than on Surface D.	Pebbles to boulders (1 m b−axis).	Subangular to subrounded; dominantly subrounded.	Rare well−rounded Colorado River yellow chert pebbles. 0.5 m below surface, clear undulating channel cut into Colorado River sands. Same unit as beneath Surface D, lower contact is at or below active wash level.
F (Q4)	B & S; sections of channlized, braided topography in sands. Gravel bars 10’s m in length with 1 m relief.	None.	None.	None.	—	At least 50% basalt; purple rhyolites.	Sands to boulders (1 m b−axis)	Angular to rounded; subrounded dominates.	Active wash sands may cover Q3 remnant (Surface G) that is 1 m above wash.
G (Q3)	B & S; dissection, other than by active wash.	Two 2x2 m patches of desert pavement of uniform grain size. Boulder bar has interlocking clasts but most clasts are stacked or imbricated on one another.	Weak rusty brown on most clasts. Some vesicular basalt boulders are developing black varnish.	Very few, other than limestone.	Boulders and cobbles cracked and degraded into fist−sized (or smaller) angular pieces still in original position of boulder.	Dominantly basalt; angular orange and purple rhyolites; more orange. Common limestone.	Pebbles to boulders (1 m b−axis)	Angular to rounded; dominantly subrounded.	Occasional well−rounded Colorado River yellow chert pebbles.
H (Q2c)	Single boulder bar; small patch of swale.	Interlocking clasts, but no singular flat surface, just patches with uniform grain size. Rocks in boulder bar are interlocking, imbricated and stacked.	Developed. Vesicular basalt has non−uniform black varnish. Massive basalt have dark rusty brown.	Bigger boulders have cracks all the way through the rock, but have not cracked into separate pieces.	Boulders and cobbles cracked, pitted, and degraded into fist−sized (or smaller) angular pieces still in original position of boulder.	Dominantly basalt; orange and purple rhyolites, more purple.	Pebbles to boulders (1 m b−axis)	Angular to rounded; dominantly subrounded; Rhyolites are typically angular, basalts subrounded.	Very rare well−rounded black, yellow Colorado River chert pebbles.
I	Subdued B&S;	Well−developed,	Black to dark	Common; Rocks	All limestone clasts	Dominantly	Pebbles to small	Angular to	Rare brown,

(Q2b)	little to no relief between bars and swales; local 0.25 m dissection close to slope break in Surface J. Surface is evened out by eolian inflation. Clasts are not stacked or imbricated.	more heavily varnished and interlocking than in Surface H pavement. Non−uniform clast size.	rusty brown. Some massive basalt boulders have iridescent black varnish like varnish on Q1 (Surface B) boulders.	broken into angular, separate pieces. Many rocks with cracks all the way through, not separate pieces.	are cracked/broken into smaller, sometimes pitted 3−4 cm pieces.	basalt; more in pavement clasts than younger fan surfaces. Orange and purple rhyolites, more orange.	boulders (50 cm b−axis); 30−40 cm diameter clasts dominate.	rounded; dominantly subrounded	red Colorado River well−rounded chert pebbles (larger than yellow cherts). Rare Quartzite clasts.
J (Q2a)	Planar; very subdued B& S. Long ridges of basalt boulders 10's m wide, 100 m long. Evened with eolian inflation. No dissection.	Well−developed, darkly varnished. Dominated by basalt; small patches of uniform clast size, but boulders and cobbles are in the pavement.	Dark rusty brown to iridescent black varnish, mostly black.	Abundant; at least one large (1 m b−axis diameter) basalt boulder is cracked and weathered flat, disintegrated into fist−sized pieces in form of and in original position of boulder. Cracking contributes to increased angularity and desert pavement clasts.	Rare, 2−8 cm pitted limestone cobbles.	Dominantly basalt; orange and purple rhyolites; more orange than purple. Cc litter.	Pebbles to small boulders; larger boulders are cracked into obvious angular, smaller clasts; 20−30 cm diameter rocks dominate.	Angular to subrounded; subangular dominates.	Very rare red chert pebbles. Darkest varnish appears to be on edge of slope break. Boulders look like they're settling into desert pavement; few rocks are stacked or imbricated.
K (Q2b)	Remnant B & S; hummocky, 0.5 m relief.	Patchy; lacks good interlocking of clasts; in boulder bar, clasts stacked on one another.	Dark rusty brown to black. Vesicular basalts are black.	Common. Boulders cracked into separate pieces in original position.	Rare, 6−8 cm diameter pitted limestone cobbles.	Dominantly basalt; orange and purple rhyolites.	Pebbles to small boulders (up to 70 cm b−axis); 30−40 cm boulders dominate.	Angular to Subrounded; dominantly subangular.	Rare yellow chert pebbles.
L (Q2c)	B & S; wavelength is few m's, swales are NE−SW and oblique to E−W drainage. 10 cm relief.	Weak; patches of interlocking clasts.	Weak; rusty brown to rare dark rusty brown, almost black.	Uncommon.	Rare, pitted, angular limestone cobbles.	25−30% purple rhyolite; 25−30% orange rhyolite; 40−50% basalt.	Pebbles to small boulders (30 cm b−axis).	Angular rhyolites; subangular to subrounded basalt.	Common rounded yellow chert pebbles. Some rounded black chert pebbles.
M (Q2b)	Planar with low−angle crown; remnant, subdued B & S. bars are diffuse, 20−30 m wide, not concentrated.	Well−developed interlocking clasts; petrocalcic litter.	Dark rusty brown to black on vesicular basalts. Massive basalts have medium rusty brown. Very little varnish on	Abundant. Many clasts are in form of and in original position of boulder.	Rare, pitted 6−8 cm limestone cobbles.	Dominantly basalt; orange and purple rhyolites; more orange.	Pebbles to sparse small boulders. 10 cm b−axis cobbles dominate.	Angular to subrounded; subangular dominates.	Occasional rounded Yellow, orange, red chert pebbles; rare well−rounded quartzites.

			pavement clasts.						
N (Q2a)	Planar surface; extremely subdued B & S.	Reasonably tight pavement. Petrocalcic litter.	Moderate varnish.	Abundant.	—	Tributary deposit dominated by basalt.	Pebbles to small boulders; mostly angular 2−3 cm interlocking clasts in pavement. Scattered boulders and cobbles up to 25 cm b−axis.	—	Dispersed Colorado River rounded cherts.
O (Q2b)	Hummocky B & S with 0.5 m relief. Bar width – 10 m. and biggest boulders concentrated in bars.	Patches of well−developed pavement in swales; boulders still stacking on one another; very rare petrocalcic litter.	Medium rusty brown to almost black on vesicular basalt. No iridescence.	Rocks cracked all the way through, but not cracked into separate pieces. Few rocks cracked apart.	Rare small limestone cobbles dissolved in half (top, exposed half dissolved)	Dominantly basalt; orange, purple, and gray rhyolites; more orange (possibly).	Pebbles to small boulders (60 cm b−axis); 20−30 cm b−axis dominates.	Subangular to subrounded; subangular dominates.	No sands, no cherts.

Note: — indicates not applicable. Cc = soil carbonate; after Machette (1985).
[a] B &S = bar and swale topography.
[b] massive basalt indicates basalt clasts with rare to no vesicles.

Supplementary Table 2. Elemental Compositions and predicted amounts of associated nucleogenic and radiogenic ^3He and ^4He in Black Mountains whole−rock basalt and olivine and pyroxene therein obtained from basalt clasts collected on alluvial fans in this study.

	SiO_2 [wt.%]	Al_2O_3 [wt.%]	Fe_2O_3(T) [wt.%]	MnO [wt.%]	MgO [wt.%]	CaO [wt.%]	Na_2O [wt.%]	K_2O [wt.%]	TiO_2 [wt.%]	P_2O_5 [wt.%]	Th [ppm]	U [ppm]	Li [ppm]	P_3 [a] (at/g/yr)	P_4 [a] (10^6 at/g/yr)	P_3/ P_4 [a] ($*10^{-8}$)
Whole−rock Basalt																
L00−2−2M	45.52	15.45	9.19	0.152	5.39	13.59	2.70	0.85	1.153	0.16	2.6	0.7	12	0.033	2.02	1.63
AZ01−BM−101*	57.88	15.11	7.05	0.108	4.01	5.86	3.38	3.44	1.149	0.39	15.3	2.5	9	0.119 [b]	11.88[b]	1.00
AZ01−BM−103	49.77	16.41	10.07	0.158	6.47	9.84	3.18	0.98	1.187	0.25	3.1	0.5	9	0.025	2.41	1.06
AZ01−BM−105	48.13	15.06	11.27	0.196	6.14	11.08	3.20	0.91	1.616	0.38	2.8	0.7	10	0.026	2.17	1.20
AZ01−BM−106	49.13	16.90	9.56	0.176	6.62	10.34	3.03	0.87	1.416	0.37	3.6	0.6	17	0.054	2.79	1.94
AZ01−BM−120	48.55	16.49	9.00	0.146	6.87	11.18	2.94	0.99	1.261	0.22	3	0.5	8	0.023	2.33	0.99
AZ01−BM−126	47.80	16.39	8.93	0.147	7.48	10.86	2.95	0.98	1.215	0.26	2.4	0.6	10	0.027	1.86	1.47
AZ01−BM−135*	57.03	14.97	6.42	0.102	3.62	6.84	3.33	3.40	1.081	0.39	14.7	2.6	12	0.158 [b]	11.41 [b]	1.39
AZ01−BM−138	48.87	15.38	9.66	0.147	9.55	8.86	3.09	0.94	1.396	0.26	2.4	0.4	11	0.026	1.86	1.38
AZ01−BM−121	48.09	16.62	9.58	0.160	8.07	10.77	2.75	0.89	1.202	0.20	2.4	0.3	8	0.017	1.86	0.91
020903−04	45.69	16.10	11.29	0.176	5.71	11.53	2.93	0.64	1.415	0.24	1.5	0.6	10	0.018	1.16	1.58
020803−01*	56.59	15.62	6.39	0.124	3.58	6.80	3.34	3.17	1.023	0.59	15	2.7	12	0.163 [b]	11.64 [b]	1.40
020803−03	47.36	16.97	10.95	0.206	7.92	10.08	2.69	0.51	1.295	0.33	2.3	0.4	12	0.025	1.79	1.40
020803−02	49.13	16.33	9.94	0.166	7.60	10.48	2.85	0.65	1.232	0.17	2.3	0.3	9	0.018	1.79	1.01
AZ01−BM−136	49.03	15.57	8.98	0.141	6.31	11.65	3.20	1.09	1.052	0.29	3.6	0.6	8	0.027	2.79	0.96
020903−09	49.09	16.46	9.77	0.155	7.02	10.62	2.93	0.70	1.268	0.18	2.8	0.4	14	0.034	2.17	1.59
										Average	2.67	0.52	10.69	0.027	2.070	1.295
										± Standard Deviation	0.57	0.14	2.36	0.010	0.444	0.322
minerals																
020803−02	39.49	3.36	16.65	0.232	35.88	2.31	0.64	0.18	0.332	0.03	0.4	< 0.1	6	0.003	0.31	1.10
020903−10	49.81	3.81	14.24	0.370	17.88	10.23	0.83	0.60	0.694	0.65	3.4	0.5	62	0.112	2.64	4.26
AZ01−BM−113	50.76	3.70	14.61	0.380	18.79	8.85	0.75	0.46	0.594	0.08	1.8	0.3	12	0.015	1.40	1.06
020803−03	44.04	9.19	18.01	0.277	15.72	8.15	1.64	0.35	1.217	0.04	0.7	0.2	13	0.009	0.54	1.60
020803−04	40.46	6.72	19.82	0.311	8.33	13.54	1.61	0.38	3.559	0.03	0.9	0.4	10	0.007	0.70	0.96
L00−3−2M1	45.24	5.87	13.70	0.256	23.36	6.24	1.36	0.55	1.206	0.02	1.6	0.4	16	0.029	1.24	2.34
AZ−01−BM−114	46.30	8.99	13.99	0.216	17.01	7.19	1.91	0.60	1.400	0.03	3.2	0.4	16	0.038	2.48	1.53
AZ−01−BM−109	47.28	7.92	12.05	0.214	22.79	5.35	1.52	0.46	1.034	0.04	1.1	0.6	14	0.031	0.85	3.58
020903−11	45.51	6.15	14.52	0.274	25.25	4.28	1.30	0.29	0.722	0.03	0.6	0.2	17	0.015	0.47	3.11
										Average	1.54	0.41	12.43	0.036	1.19	2.77
										± Standard Deviation	1.00	0.14	3.55	0.034	0.77	1.74

Note: Major, trace, and rare−earth elements were determined through a lithium metaborate/tetraborate fusion technique and measured by ICP and ICP−MS. Li concentrations were measured by ICP following a total digestion chemical method, which employs HCl, HNO_3, perchloric, and HF acids.

[a] Not included in the average and standard deviation.

[b] P_3 = predicted amount of nucleogenic ^{3}He; P_4 = predicted amount of radiogenic ^{4}He; Calculated from equations from Andrews (1985) and Li, U, and Th elemental concentrations in olivine or pyroxene in this study.

Supplementary Table 3. Summary of predicted amounts of nucleogenic and radiogenic helium contributed to Black Mountain olivine and pyroxene over the past 20 Ma, based on equations of Andrews (1985).

	P_3 [a] (10^6at/g/yr)	P_4 [a] (10^6at/g/yr)	P_3/P_4 [b] (10^{-8})	P_3 After 15 Ma (10^6at/g)	P_4 After 15 Ma (10^{12}at/g)	P_3 After 20 Ma (10^6at/g)	P_4 After 20 Ma (10^{12}at/g)	Measured ^{3}He total (10^6at/g) [c]	Measured ^{4}He total (10^{12}at/g) [c]
Whole−rock basalt	0.017 − 0.16	1.16 − 11.8	0.91 − 1.94	0.3 − 2	17 − 178	0.34 – 3.2	23−236	−	−
Olivine or pyroxene	0.003 − 0.11	0.31−2.64	0.96 − 6.1	0.05 − 2	5 – 40	**0.06 – 2.2**	6 − 53	**19−358**	0.42 − 47

[a] P_3 = predicted amount of nucleogenic ^{3}He; P_4 = predicted amount of radiogenic ^{4}He; Calculated from equations from Andrews (1985) and Li, U, and Th elemental concentrations in olivine or pyroxene in this study.

[b] $P_3/P_4 = {}^3He_{nu}/{}^4He_{r.}$

[c] Actual measured/calculated values of ^{3}He and ^{4}He within olivine and pyroxene from this study, determined by mass spectrometric analysis. See Table 2 in text for details.