

Supporting Information for

Alteration at the base of the Siccar Point unconformity and further evidence for an alkaline source rock at Gale crater: Exploration of the Mount Sharp group, Greenheugh pediment cap rock contact with APXS

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Introduction

This supporting information document comprises:

Section S1: Details of the data and targets used in this study including Table S1, which comprises a list of targets used.

Section S2: Details of APXS data treatment, including the different statistical methods used to investigate trends and relationships. Tables of the results of statistical tests are included. Other derived datasets used to make various plots can be found in the data repository.

Section S3: Mastcam and MAHLI images of relevant pediment campaign APXS targets

Section S4: Images of previously encountered APXS targets with related compositions to pediment campaign targets

S1. Details of targets and data used in this study

See Table 1 in the paper for the Glasgow member, Hutton interval, Western butte cap float rock and pediment capping sandstone APXS targets and compositions. Table S1 lists other targets utilized in this study.

All MSL, raw data are available at the planetary data system:

<https://pds-geosciences.wustl.edu/missions/msl/index.htm>

<https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx>

Table S1: Bedrock and soil targets used in this study (GT – Glen Torridon).

List of GT Jura bedrock targets		List of GT Knockfarril Hill bedrock targets		List of Mount Sharp group targets related to Hutton interval	
Name	Sol	Name	Sol	Name	Sol
Kilmarie_drill_tailings_red	2404	Ecclefechan	2465	Ricardo_raster1_DRT	805
Kilmarie_drill_tailings_pale	2404	Tay	2463	Topanga_DRT_raster2	815
Kilmarie_dump_offset	2402	Feshie	2462	Mescal_DRT_raster1	820
Kilmarie_dump_centre	2402	Sligachan	2461	Puente_DRT	824
Aberlady_drill_tailings_pale	2380	Newtonhill	2458	Pickhandle_DRT	828
Aberlady_drill_tailings_red	2380	Magnus_Bay	2452	Telegraph_Peak_DT	922
Aberlady_dump_corrected	2380	Stack_of_Glencoul	2446	Oudam_tailings_APXS	1364
Mons_Graupius	2427	Beaully_DRT	2443	Mirabib_DRT	1275
Tobermory	2427	Balnakettle	2443	Inamagando_DRT	1355
Rutherglen	2359	Calgary_Bay	2442	List of Emerson and Naufluff plateau Stimson bedrock targets	
Longannet	2365	Blawhorn	2587	Ronan_DRT_2	998
Kilmarie	2382	Perth	2454	Ledger	1092
Kilmarie_offset	2382	Fetterangus	2478	Connption	1097
Seil	2377	Fetterangus_offset	2478	Big_Sky_DRT_raster2	1114
Aberlady_DRT	2367	Solway_Firth_DRT	2471	Big_Sky_DRT_raster1	1114
Aberlady_offset	2367	Kirbuster	2465	Big_Sky_mini_start_hole	1116
Aberlady_triage	2367	Oykel_DRT	2458	Big_Sky_full_drill_tailings	1123
Arbuthnott_DRT	2349	Glen_Etive_2_DRT	2483	Big_Sky_presieve_dump (off target)	1124
Fife	2347	Glen_Etive_1_tailings	2524	Big_Sky_presieve_dump_corrected	1126
Auchterarder	2333	Glen_Etive_1_dump_centre	2523	Big_Sky_postsieve_dump	1132
Alloa	2333	Glen_Etive_1_DRT	2482	Ennis	1151
Ladder_Hills	2320	Glen_Etive_1_offset	2482	Ellis_Canyon	1150
Curlew_DRT	2318	Glen_Etive_2_tailings	2553	Exshaw	1150
Gannet	2318	Glen_Etive_2_dump_corrected	2552	Bruckaros_DRT	1294
Tolsta	2449	Moine	2474	Sesriem_Canyon_DRT	1288
Hill_of_Skares	2431	Mither_Tap	2474	Sperrgebiet_raster2	1277
Crakaig	2422	East_Shetland_DRT	2472	Sperrgebiet_raster1	1277
Kinghorn	2419	Essendy	2472	Okoruso_DRT_centre	1130
Galashiels	2413	Nith	2470	Okoruso_DRT_offset	1130
Haddington	2408	Urr	2441	Okoruso_fulldrill_tailings	1137
Ardnamurchan	2363	Iapetus	2437	Okoruso_presieve_dump	1139
Ardmillan	2361	Ben_Hope	2570	Kwakwas_centre_DRT	1341
Crieff	2352	South_Ronaldsay_DRT	2567	Kwakwas_offset	1341
Snorre	2356	Shetland	2564	Groendraai	1351
Smooagro	2431	High_Plains	2557	Meob_DRT	1348
Paible	2468	Pobie_Bank	2577	Nomeib	1348
Gullane	2431	Nedd	2590	List of compositionally related targets to pediment caprocks	
Hillhead	2419	Gorgie	2587	South_Park_rp_apxs_twk	694
Kintore	2419	Inverurie_DRT	2601	Bell_Island_target9_night	117
Maud	2363	Latheron	2601	Howells	323
St_Fergus	2304	Everbay_DRT	2597	Eqalulik	323
Emerald_raster2	2315	Muckie_Flugga_DRT	2591	rocknest3_rp	102
Broad_Cairn_DRT	2415	Ard_Neakie	2591	Dismal_Lakes	304
Loch_Ness_DRT	2301	Glen_Doll	2591	Thimble_1	706
Puddledub	2301	Flow_Country_centre	2594	Stirling_RP	707
Linlithgow	2300	Ratio plot target		Ravalli	1082
Broad_Cairn_offset	2415	Lagrange	605	Little_Devil	942
Broad_Cairn_triage	2415			Bathurst_Inlet_Top_RP	54
				Minginish	2019

All raw APXS data used in this study, is available at the planetary data system: https://pds-geosciences.wustl.edu/msl/msl-m-apxs-4_5-rdr-v1/mslapx_1xxx/data/ and <http://doi.org/10.17189/1519440>

For details of the APXS targets used to investigate the Mount Sharp group, pre-Glen Torridon (not including high Si targets) see Thompson et al. (2020), and: *Thompson, L. (2020). Alpha Particle X-ray spectrometer geochemistry of the Murray formation and Vera Rubin ridge, Gale crater, Mars. <https://doi.org/10.25545/ZXDJZ7>, UNB, V1, UNF:6:bL/a2qTZBu6DNJlzkmgABg==[fileUNF].*

All tables within the manuscript and supporting information, as well as derived data can be found at: *Thompson, L. (2021). Alpha Particle X-ray spectrometer geochemistry of rocks associated with the Basal Siccar Point group unconformity, Glen Torridon region, Gale crater, Mars. Doi to be supplied upon final submission*

S2. Treatment of the data

S2.1. Average, median, minimum, maximum and 1σ standard deviation

Average, median, minimum, maximum and 1σ standard deviation values were calculated for different subsets of the data using Excel. See Table 1 in the manuscript for the results of these calculations. See repository for the derived datasets. The results of these calculations are represented in various plots, all created in Excel.

S2.2. F- and t-tests

F-tests were performed on select groupings of analyses to determine whether they showed equal or unequal variances using the “F-Test Two-Sample for Variances” analysis tool within the Data Analysis add-in for Excel, with a 95% confidence. If $F > F_{critical}$ one-tail, the two groupings have unequal variances. If $F < F_{critical}$ one-tail, the two groupings have equal variances.

Based on the results of the F-tests, t-tests were then performed on the same datasets to determine whether they are statistically the same or different. The “t-Test: Two Sample Assuming Unequal Variances” or “t-Test: Two Sample Assuming Equal Variances” analysis tool within the Data Analysis add-in for Excel was used. The t-tests determine whether the two groupings are statistically the same or different, with a 95% confidence level. If $t_{stat} > t_{critical}$ two-tail, the two groupings are statistically different. If $t_{stat} < t_{critical}$ two-tail, the two groupings are statistically the same.

F- and t-tests were performed on the following datasets for Si through Zn (Br is not included as it is highly variable throughout all datasets and appears to be primarily controlled by surface processes):

- 1) Comparison of Hutton interval targets with i) Mount Sharp group bedrock pre-Glen Torridon (GT), ii) GT Jura and Knockfarril Hill (KH) member bedrock targets (see Table S1 for the list of APXS targets), and iii) Glasgow member bedrock targets. See Table S2 for the results.
- 2) Comparison of Emerson and Naukluft plateau Stimson formation sandstones with i) basal pediment capping sandstones (platy; Gleann Beag interval), and ii) blocky pediment capping sandstones (Ladder and Edinburgh intervals). See Table S3 for the results.

S2.3. Log ratio plots

S2.3.1 Hutton interval

To examine the Hutton interval, log ratio plots were made in Excel by ratioing the data of interest to average Mount Sharp group bedrock encountered prior to Glen Torridon. The log ratioed maximum and minimum values derived for the Glen Torridon Jura and Knockfarril Hill members combined, and the Glen Torridon Glasgow member are plotted to show the range of compositions for those data subsets. Individual Hutton interval analyses and select Murray formation targets encountered earlier in the mission are plotted separately. See Figure 3a for the plot and the data repository for the derived data.

S2.3.1.1 Hutton interval diagenetic features

To investigate changes in chemistry associated with diagenetic features in the Glasgow member as Curiosity approached the pediment, log ratio plots were created in Excel whereby the target of interest is ratioed to a bedrock target in the same workspace (Figure 5). Derived data used for the plot can be found in the repository.

Table S2: Results of F- and t-tests for the Hutton interval comparisons (GT – Glen Torridon)

	Murray pre-GT vs Hutton interval						GT Jura and KH vs Hutton interval						Glasgow vs Hutton interval					
	F-tests			t-tests			F-tests			t-tests			F-tests			t-tests		
	F	F critical one tail		t Stat	t Critical two tail		F	F critical one tail		t Stat	t Critical two tail		F	F critical one tail		t Stat	t Critical two tail	
SiO ₂	2.29	3.68	equal	-0.67	1.97	same	2.78	3.71	equal	-1.90	1.98	same	2.11	4.50	equal	-1.25	2.03	same
TiO ₂	1.62	3.68	equal	1.22	1.97	same	1.08	2.19	equal	4.68	1.98	different	1.07	4.50	equal	1.28	2.03	same
Al ₂ O ₃	7.26	3.68	unequal	-0.10	2.31	same	2.97	3.71	equal	-2.28	1.98	different	1.85	4.50	equal	-2.21	2.03	different
Cr ₂ O ₃	6.77	3.68	unequal	5.18	2.31	different	4.20	3.71	unequal	7.48	2.23	different	7.00	4.50	unequal	1.99	2.09	same
FeO	5.43	3.68	unequal	-0.68	2.31	same	2.07	3.71	equal	2.23	1.98	different	2.49	4.50	equal	-1.94	2.03	same
MnO	11.88	3.68	unequal	-3.62	2.23	different	24.37	3.71	unequal	-1.48	2.03	same	15.70	4.50	unequal	-7.65	2.05	different
MgO	1.35	3.68	equal	-2.21	1.97	different	1.22	3.71	equal	-0.79	1.98	same	1.35	4.50	equal	-1.3	2.03	same
CaO	4.10	3.68	unequal	-4.16	2.36	different	8.46	3.71	unequal	-3.51	2.13	different	3.58	4.50	equal	-0.43	2.03	same
Na ₂ O	1.43	2.13	equal	-7.77	1.97	different	1.68	2.19	equal	-9.88	1.98	different	3.28	2.56	equal	-6.85	2.45	different
K ₂ O	25.75	3.68	unequal	-2.56	2.13	different	64.37	3.71	unequal	1.15	1.99	same	15.60	4.50	unequal	-3.45	2.05	different
P ₂ O ₅	34.72	3.68	unequal	-7.73	2.09	different	12.60	3.71	unequal	-12.90	2.09	different	5.20	4.50	unequal	-9.38	2.15	different
SO ₃	4.98	3.68	unequal	8.88	2.36	different	7.83	3.71	unequal	6.93	2.14	different	3.48	4.50	equal	5.81	2.03	different
Cl	5.72	3.68	unequal	3.41	2.31	different	3.04	3.71	equal	2.74	1.98	different	3.57	4.50	equal	1.21	2.03	same
Ni	13.09	3.68	unequal	8.10	2.23	different	4.90	3.71	unequal	6.35	2.20	different	18.64	4.50	unequal	5.57	2.05	different
Zn	2.19	3.68	equal	0.08	1.97	same	12.65	3.71	unequal	5.11	2.09	different	1.73	2.56	equal	-0.65	2.03	same

Table S3: Results of F- and t-tests for the Emerson and Naukluft plateau Stimson formation sandstones and pediment capping sandstones

	F-tests Stimson-Gleann Beag			t-tests Stimson-Gleann Beag			F-tests Stimson-Edinburgh/Ladder			t-tests Stimson-Edinburgh/Ladder		
	F	F critical one tail		t Stat	t Critical two tail		F	F critical one tail		t Stat	t Critical two tail	
SiO ₂	1.75	4.53	equal	5.19	2.04	different	1.04	2.74	equal	5.41	2.03	different
TiO ₂	1.02	4.53	equal	0.15	2.04	same	1.25	2.74	equal	4.81	2.03	different
Al ₂ O ₃	35.35	4.53	unequal	4.34	2.05	different	8.95	2.74	unequal	4.05	2.03	different
Cr ₂ O ₃	2.20	2.62	equal	0.82	2.04	same	1.04	2.25	equal	-2.5	2.03	different
FeO	1.49	4.53	equal	-0.25	2.04	same	1.7	2.74	equal	-3.88	2.03	different
MnO	5.46	2.62	unequal	0.63	2.45	same	1.23	2.74	equal	-11.11	2.03	different
MgO	1.17	4.53	equal	-0.44	2.04	same	2.56	2.74	equal	-1.39	2.03	same
CaO	3.80	4.53	equal	0.17	2.04	same	1.5	2.74	equal	0.54	2.03	same
Na ₂ O	3.30	4.53	equal	1.99	2.04	same	1	2.74	equal	-5.11	2.03	different
K ₂ O	1.99	4.53	equal	-1.52	2.04	same	1.82	2.25	equal	-20.78	2.03	different
P ₂ O ₅	5.70	4.53	unequal	-2.8	2.06	same	1.32	2.74	equal	5.58	2.03	different
SO ₃	4.05	2.62	unequal	-2.21	2.45	same	1.9	2.74	equal	-0.92	2.03	same
Cl	6.29	4.53	unequal	1.59	2.09	same	1.29	2.74	equal	0.03	2.03	same
Ni	6.63	4.53	unequal	-6.3	2.09	different	2.58	2.74	equal	4.59	2.03	different
Zn	2.52	4.53	equal	-3.42	2.04	different	1.54	2.25	equal	-2.5	2.03	different

2.3.2 Pediment cap rocks

To examine the pediment capping sandstones, log ratio plots were made by ratioing the data of interest to Lagrange (typical Gale soil analyzed by APXS on Sol 605) in Excel. The Lagrange, Gale soil target was chosen as the ratio plot comparison owing to the Mars soil-like composition of typical Stimson formation sandstones from the Emerson and Naukluft plateaus (Thompson et al., 2016). The ratioed maximum and minimum values derived for the Stimson formation sandstones encountered at the Emerson and Naukluft plateaus are plotted to illustrate the Stimson formation range of compositions. Individual pediment capping sandstone, Western butte float caprock and select targets encountered earlier in the mission are plotted separately. See Figure 6 for the plots and the data repository for the derived data used to construct the plots.

S2.4. Elevation versus composition

Select oxide and element concentrations are plotted versus elevation to highlight changes in the Glasgow member, Hutton interval as Curiosity neared the pediment contact (Figure 3b). Average and 1σ standard deviation for the Mount Sharp group pre-GT (Table 1) are shown for reference.

CaO and SO₃ concentrations versus elevation are plotted for the GT Mount Sharp group and Greenheugh pediment capping sandstones (Figure 12b). These plots highlight changes in Ca and S immediately below and above the Basal Siccar Point group unconformity at the pediment. Average and 1σ standard deviation for the Mount Sharp group pre-GT and Emerson/Naukluft Stimson formation (Table 1) are shown for reference.

S2.5. X-Y plots

CaO versus SO₃ concentrations are plotted for all Mount Sharp group bedrock pre-GT, GT Jura, GT Knockfarril Hill, and GT Glasgow with the Hutton interval and select Parhump Hills and Hartmanns Valley targets highlighted (Figure 3c). A CaSO₄ addition trend line is also shown. See Thompson et al., 2020 Section S2 for a discussion regarding CaSO₄ and the Murray formation.

Na₂O versus TiO₂ concentrations are plotted for all Mount Sharp group bedrock pre-GT (with Parhump Hills and gray/blue VRR Jura plotted separately), GT Jura and Knockfarril Hill, GT Glasgow and Hutton interval (Figure S1).

S2.6. %Increase and decrease calculations

Investigation of %increases and decreases for specific subsets of the data were computed using the following equation:

$$\% \Delta C = [(CI_x - CC_x)/CC_x] * 100$$

CI and CC are concentrations of the oxide of interest (x) and titanium (Ti) for the targets of interest and the comparison target respectively. Various plots were made using the derived data in Excel. See the data repository for the derived data used to make plots.

%increases and decreases in Na₂O concentration were calculated for all members of the Mount Sharp Group relative to average pre-GT, Mount Sharp group Na₂O and plotted in Figure 4a. This plot highlights which Mount Sharp group strata have the highest Na₂O concentrations relative to the average.

%increases and decreases were calculated for the Gleann Beag, Ladder and Edinburgh interval sandstones relative to average Stimson formation from the Naukluft and Emerson plateaus (Figure 7).

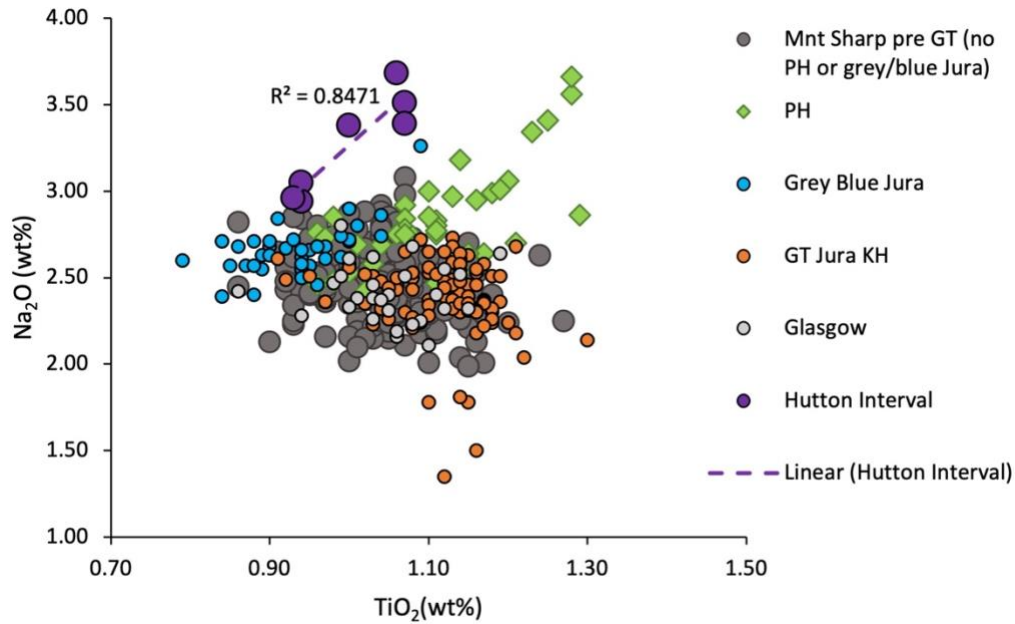


Figure S1. Na_2O versus TiO_2 for all Mount Sharp group bedrock pre-GT (with Pahump Hills and gray/blue VRR Jura plotted separately), GT Jura and Knockfarril Hill, GT Glasgow with the Hutton interval. Note the strong positive correlation for the Hutton interval and a number of Pahump Hills targets.

S2.7. Mass balance calculations

Mass balance calculations were performed using the following equation (Brimhall & Dietrich, 1987):

$$\% \Delta C = [(C_x * CC_{Ti}) / (CC_x * C_{Ti}) - 1] * 100$$

C_I and CC are concentrations of the oxide of interest (x) and titanium (Ti) for the targets of interest and the comparison target respectively. See Thompson et al. (2020) for a discussion of the use of Ti as the conservative oxide. Calculations were made to look at gains and losses associated with the potential alteration of the Hutton interval targets versus the Glasgow DRT target, and the Gleann Beag high S, pediment capping sandstones versus Galloway Hills.

The Hutton interval targets are compared to the Glasgow DRT target, as this represents typical Glasgow member bedrock and was also a drill target (Figure 4b). The high S, capping sandstone targets exposed at the contact with the underlying Glasgow member, as well as the more nodular sandstones within the Gleann Baeg interval are compared to the relatively nodule-free Galloway Hills target, which represents the least altered Gleann Baeg interval sandstone (Figure 12a).

See the data repository for the derived data used to make plots.

S2.8. Errors for mass balance and %increase and decrease plots

Propagated errors for the mass balance plots and %increase and decrease plots are calculated using the general equation:

$$\frac{\delta Q}{|Q|} = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2 + \dots}$$

Where $\frac{\delta q}{|q|}$ is the propagated error, δa = error associated with the concentration of the element of interest, a = first concentration, δb = error associated with the second concentration, b = second concentration.

S3. Images of relevant pediment campaign APXS targets (Image credit for Mastcam and MAHLI images: NASA/Caltech-JPL/MSSS)

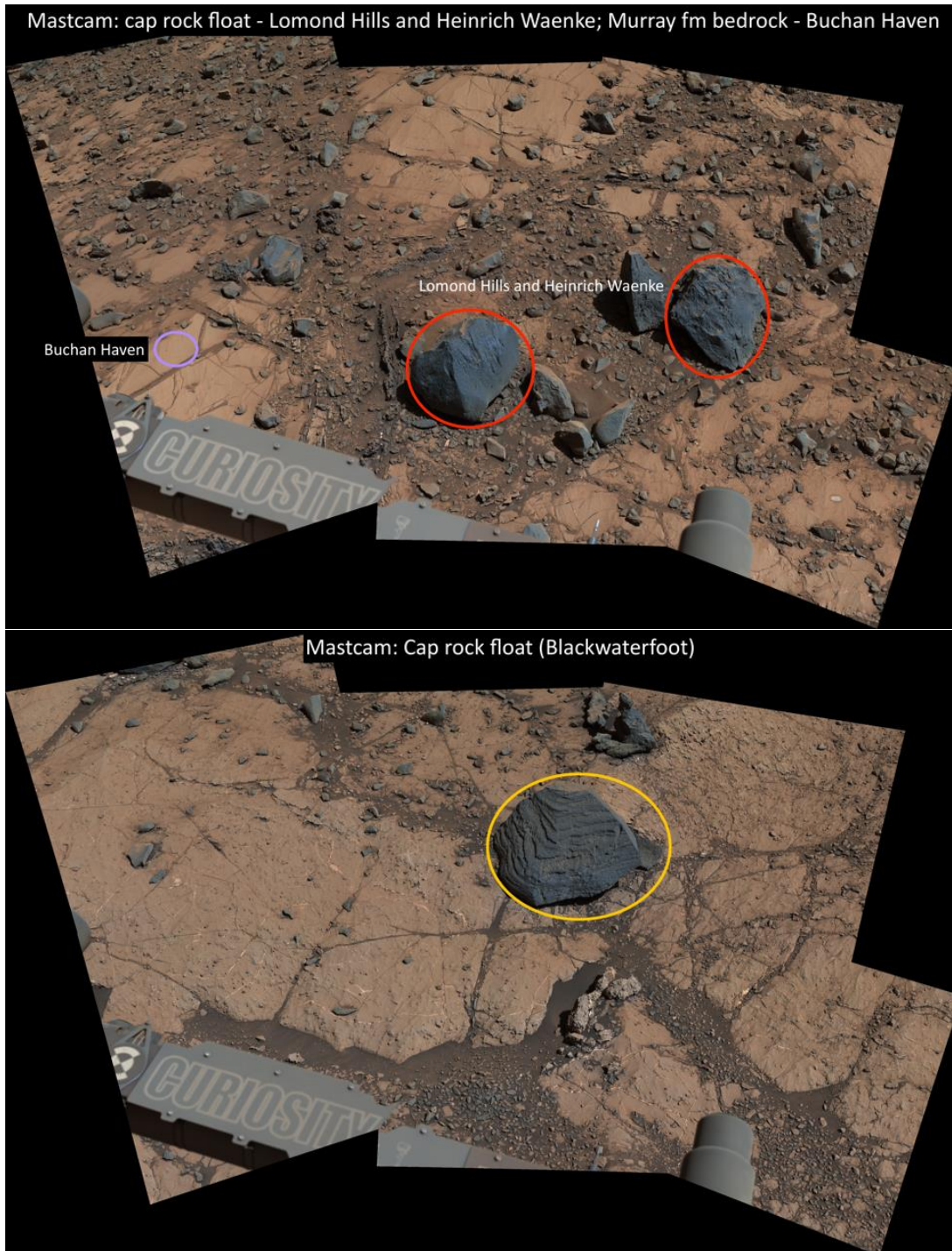


Figure S2. Mastcam workspace mosaics from Western butte showing: **top** - the Hutton interval bedrock target, Buchan Haven, and the two float caprock targets Lomond Hills and Heinrich Waenke (Sol 2633, mcam013793); **bottom** - the Blackwaterfoot float caprock (Sol 2618, mcam013759)

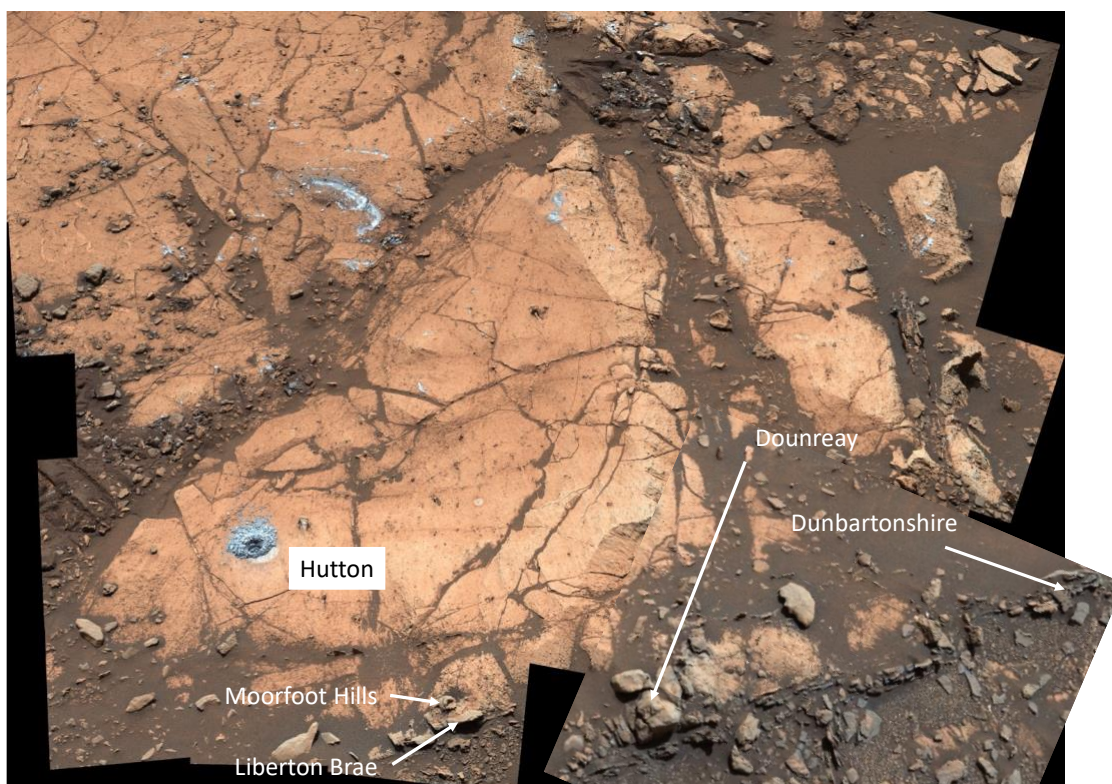


Figure S3. Mastcam mosaics (Sol 2680, mcam014031; Sol 2666, mcam013985) of the Hutton drill site workspace, including the diagenetic targets; Moorfoot Hills, Liberton Brae, Dounreay and Dunbartonshire.



Figure S4. Mastcam workspace mosaic (Sol 2693, mcam014090) showing the location of the Gleann Beag interval, high S, APXS targets (Clach Glas and Huttons Section).

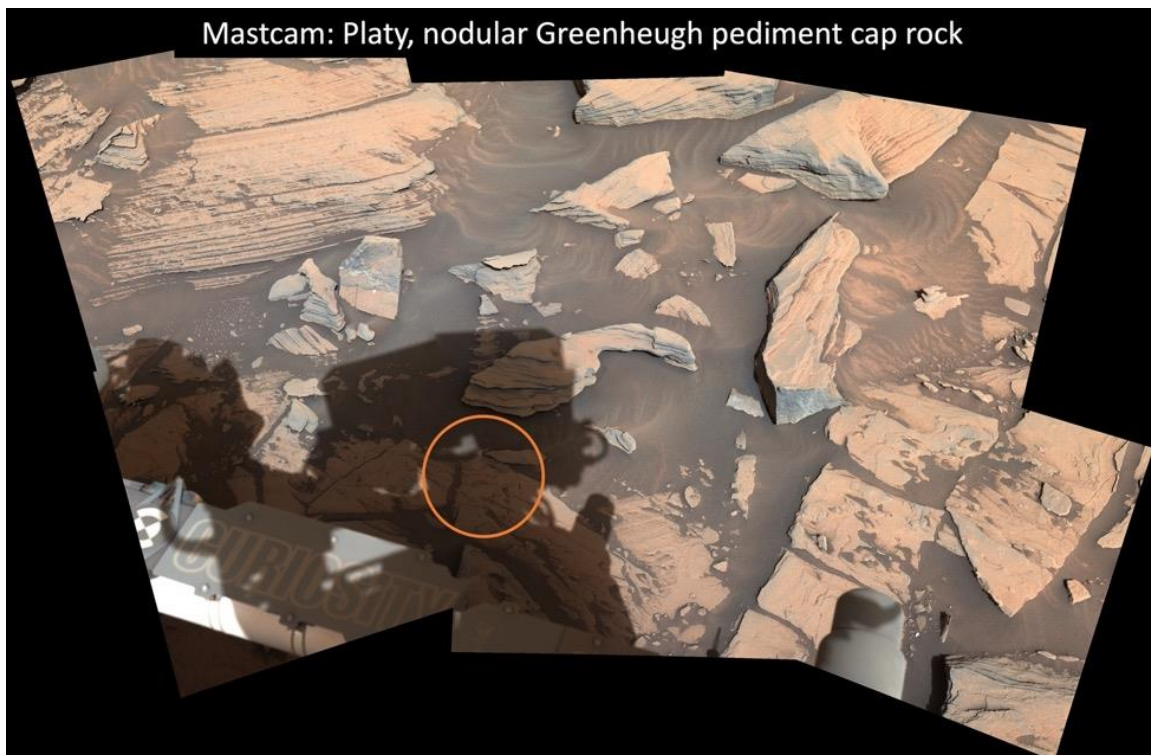


Figure S5. Mastcam workspace mosaic (Sol 2695, mcam014100) of the Galloway Hills, Gleann Beag interval sandstone target.

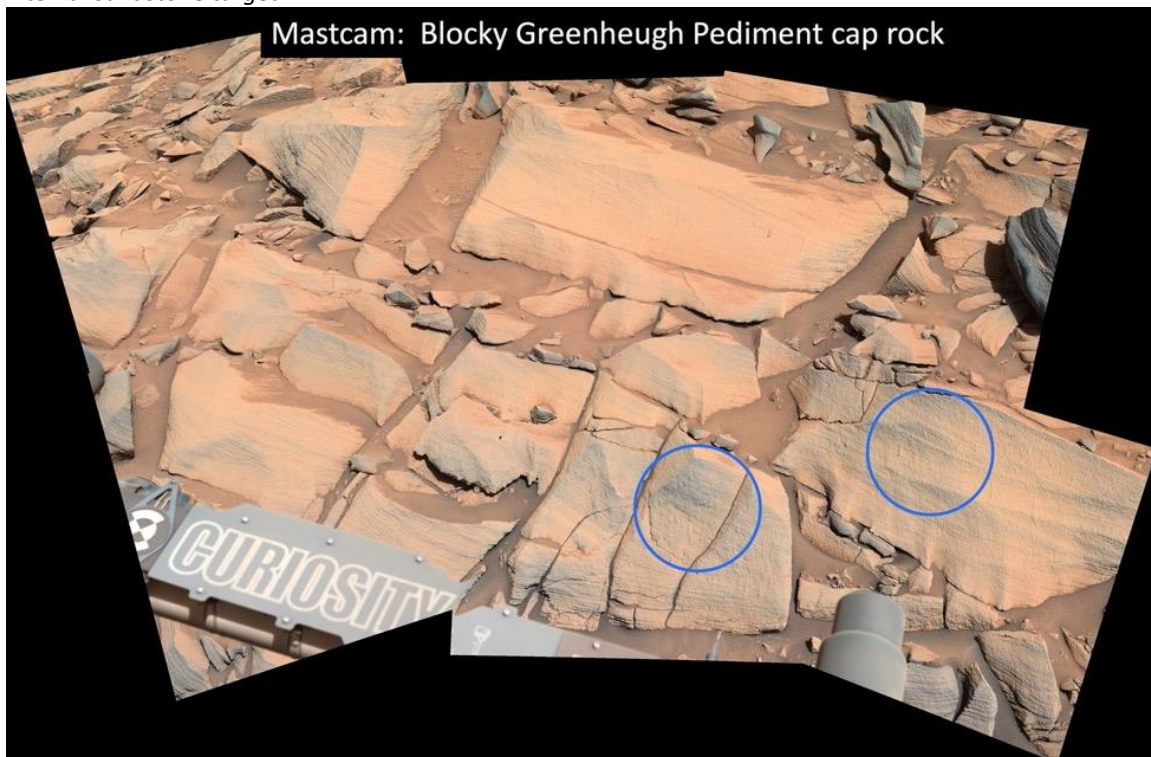


Figure S6. Mastcam workspace mosaic (Sol 2698, mcam014122) of the Ladder interval sandstone targets Forsinard Flows (right) and Machir Bay (left).

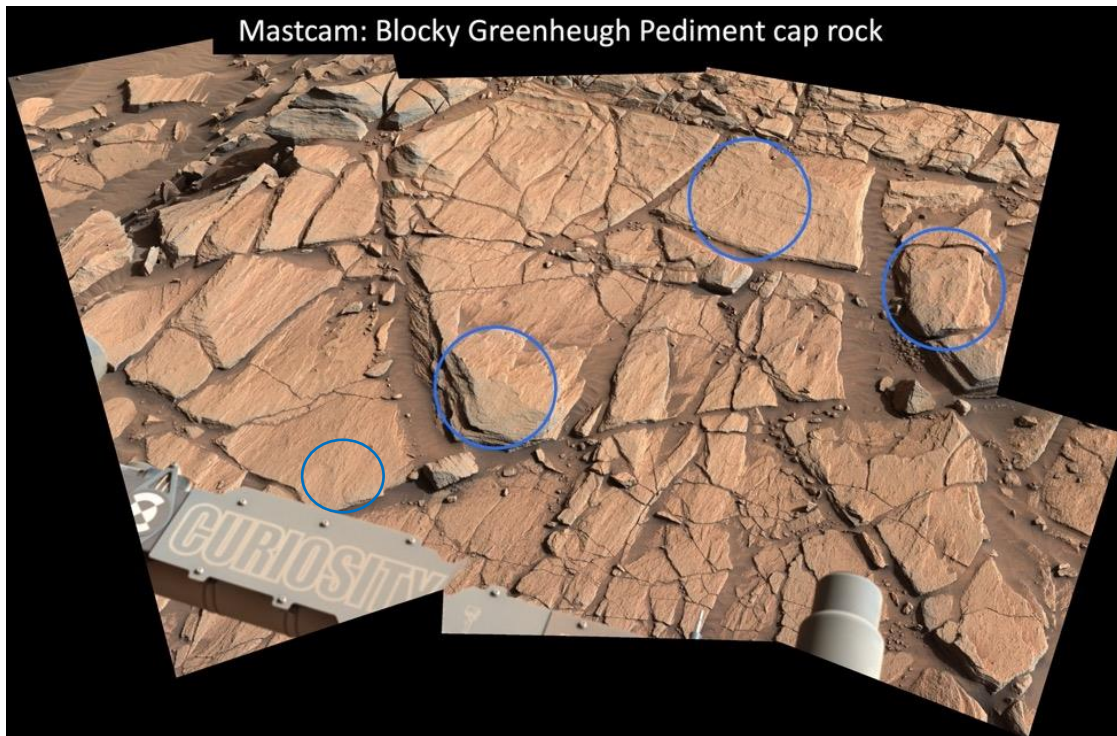


Figure S7. Mastcam workspace mosaic Sol 2700, mcam014136 of the Ladder interval sandstone targets Glen Feshie (left), Assynt Window (middle), Edinburgh (top), and Eshaness (right).

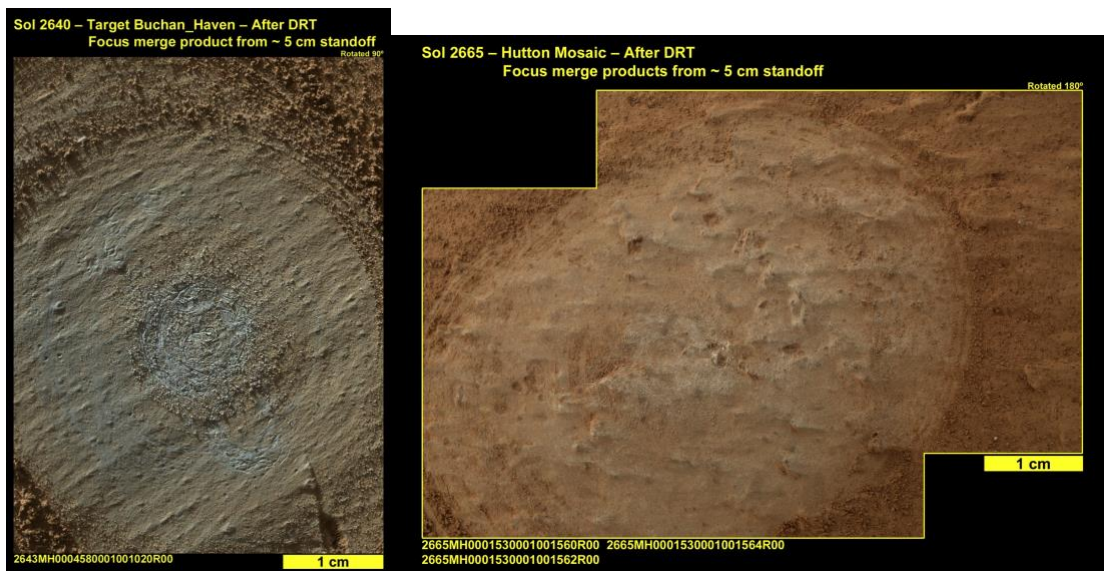


Figure S8. ~5 cm standoff MAHLI images of the Hutton interval targets Buchan Haven (Western butte – left) and Hutton (right) after DRT

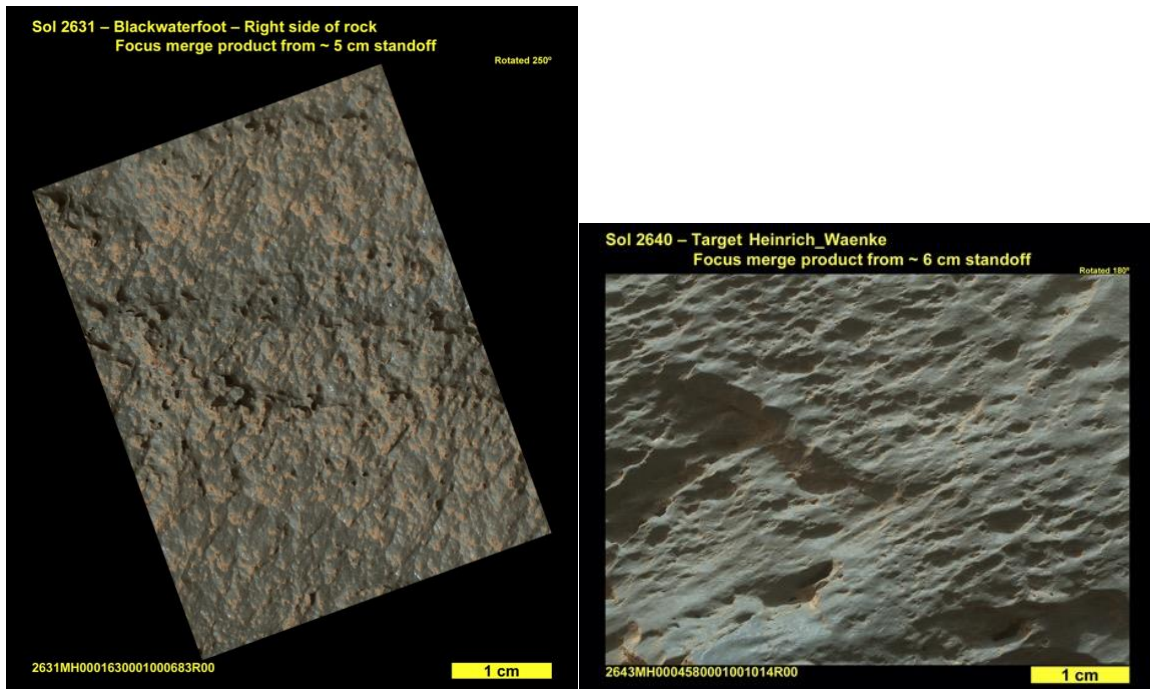


Figure S9. ~5-6 cm standoff MAHLI images of Western butte float cap rock targets Blackwaterfoot (left) and Heinrich Waenke (right).

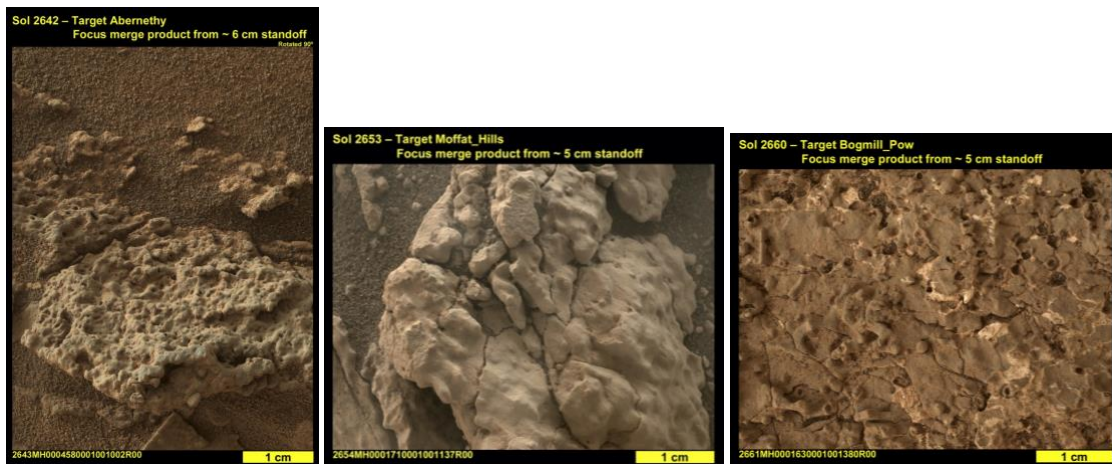


Figure S10. ~5-6 cm standoff MAHLI images of diagenetic features within upper Glasgow member bedrock; Abernethy (Western butte, Buchan Haven workspace, left), Moffat Hills (Trossachs workspace, middle), Bogmill Pow (Cullivoe workspace).

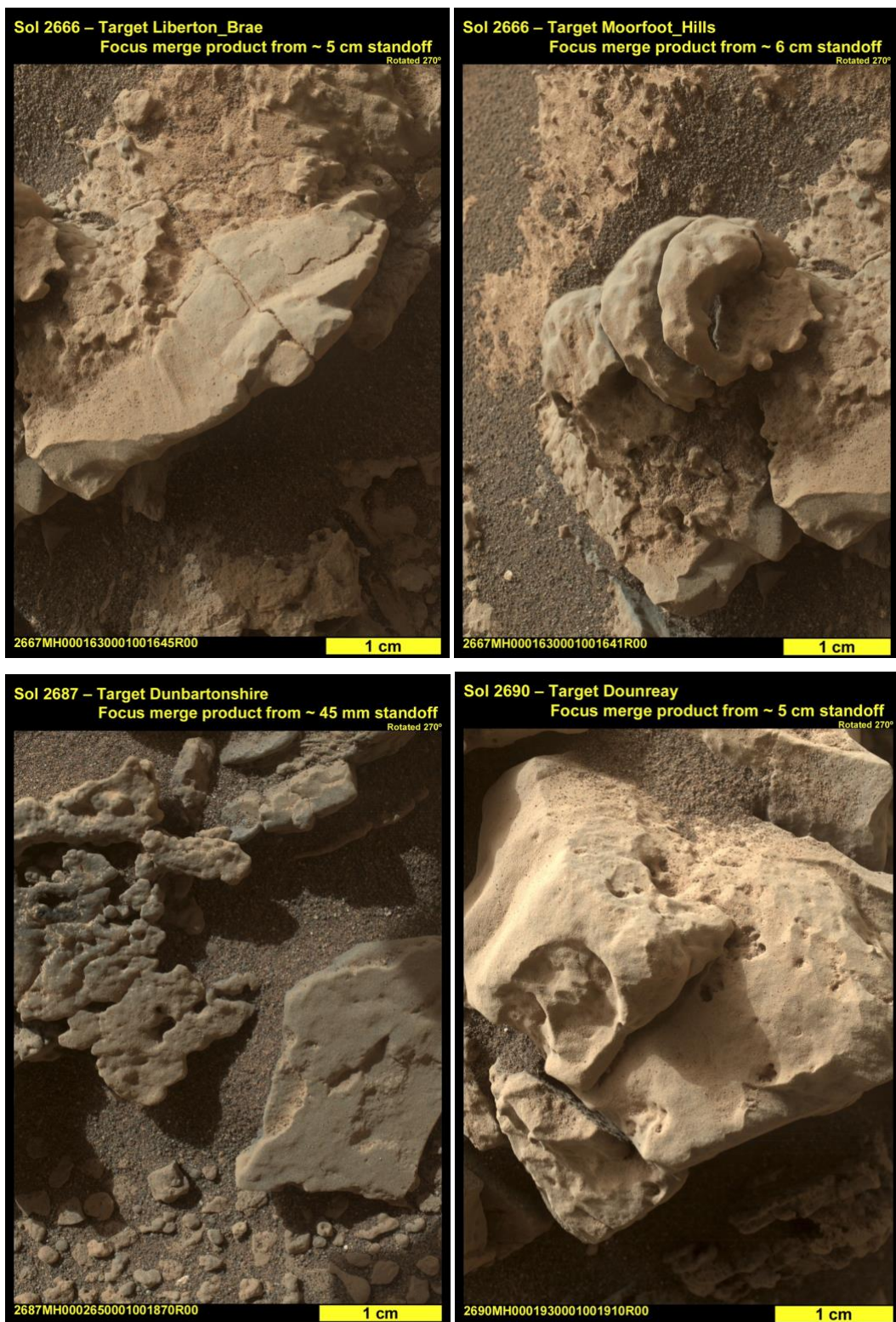


Figure S11. ~4.5-6 cm standoff MAHLI images of diagenetic features within Hutton workspace; Liberton Brae, top left), Moorfoot Hills (top right), Dunbartonshire (bottom left), and Dounraey (bottom right).

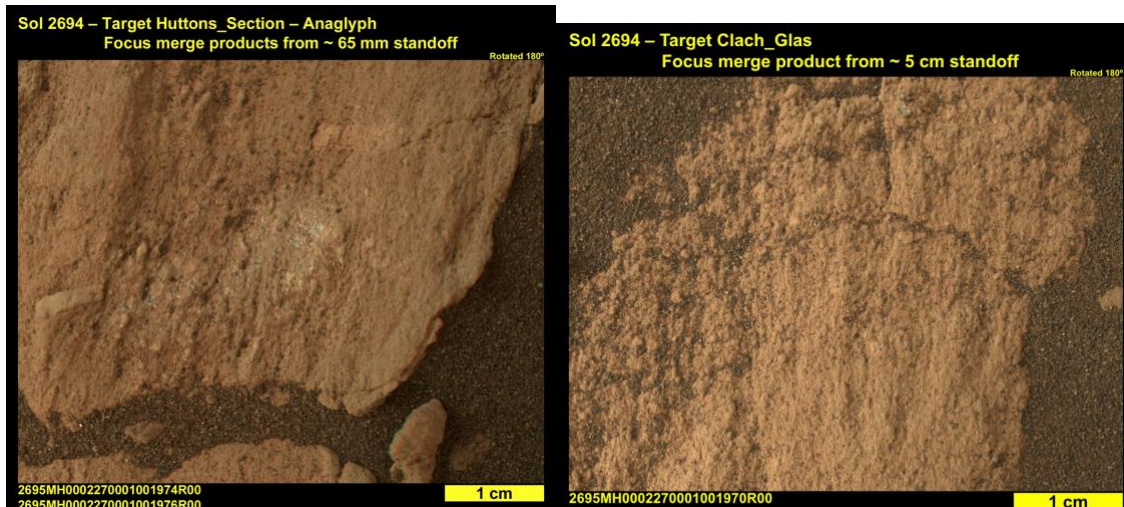


Figure S12. ~5 - 6 cm standoff MAHLI images of Gleann Beag pediment capping sandstone immediately at the contact with the underlying Hutton interval; Huttons Section (left) and Clach Glas (right).

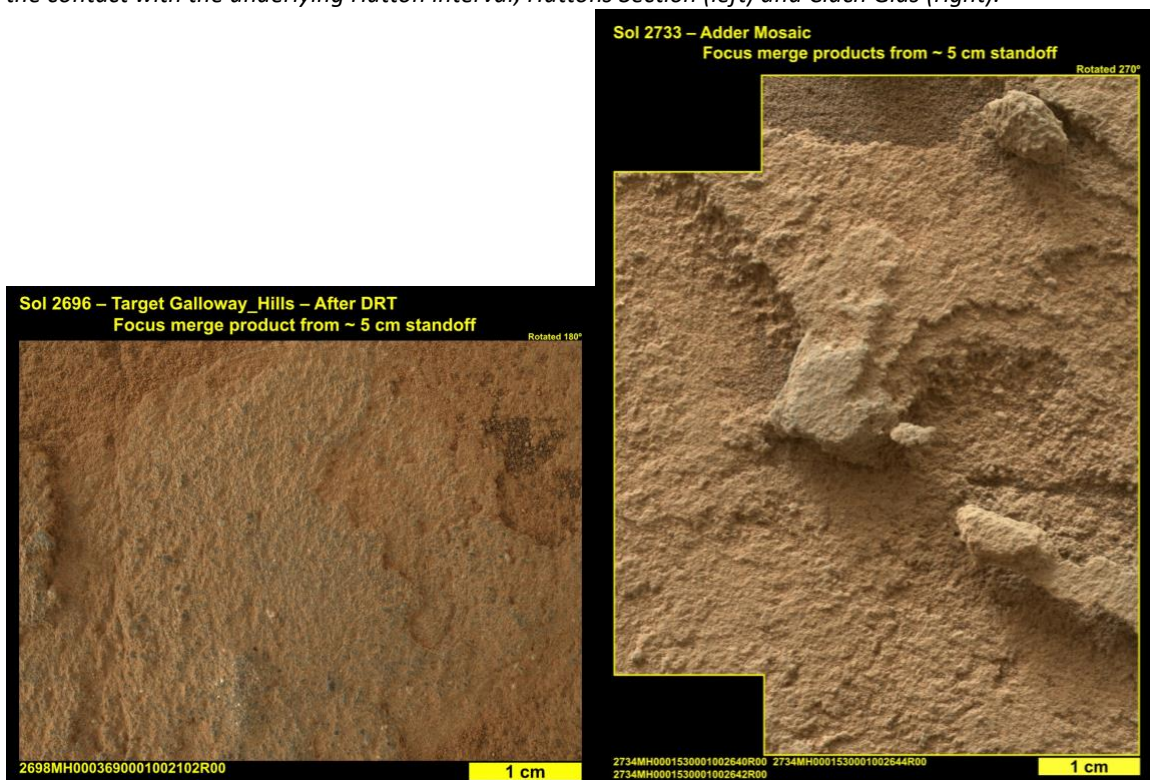


Figure S13. ~5 cm standoff MAHLI images of Gleann Beag pediment capping sandstone targets; Galloway Hills (left) and nodular Adder (right).

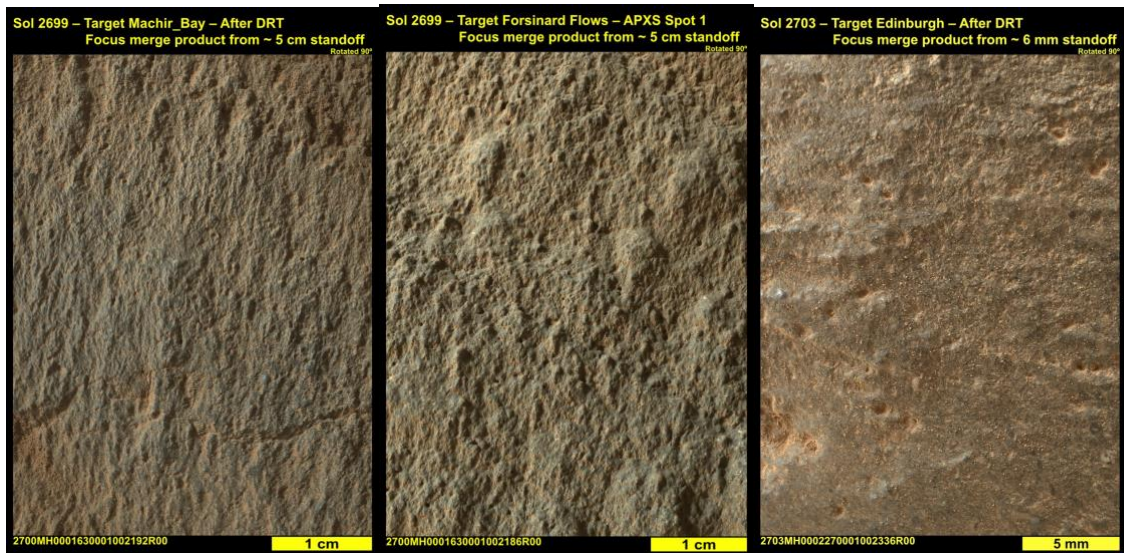


Figure S14. ~5-6 cm standoff MAHLI images of Ladder and Edinburgh interval pediment capping sandstone targets; Machir Bay(left), Forsinard Flows (middle), and Edinburgh (right).

Section S4: Images of previously encountered APXS targets with related compositions to pediment campaign targets (Image credit for Mastcam and MAHLI images: NASA/Caltech-JPL/MSSS)

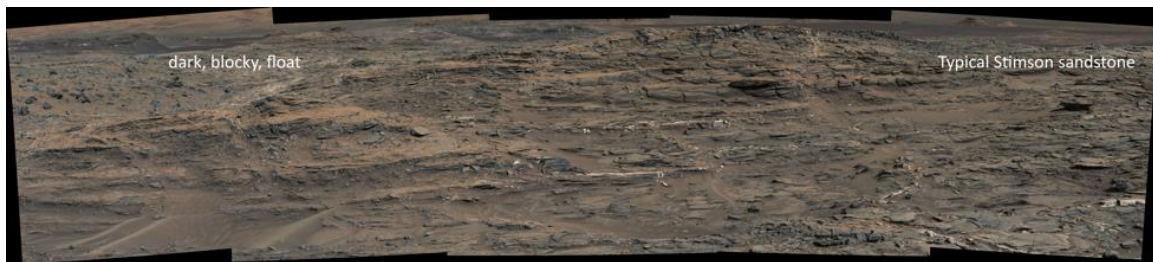


Figure S15. Mastcam mosaic (mcam04764) showing an outcrop is typical Stimson formation sandstone on the Emerson Plateau and associated dark, block float rocks.

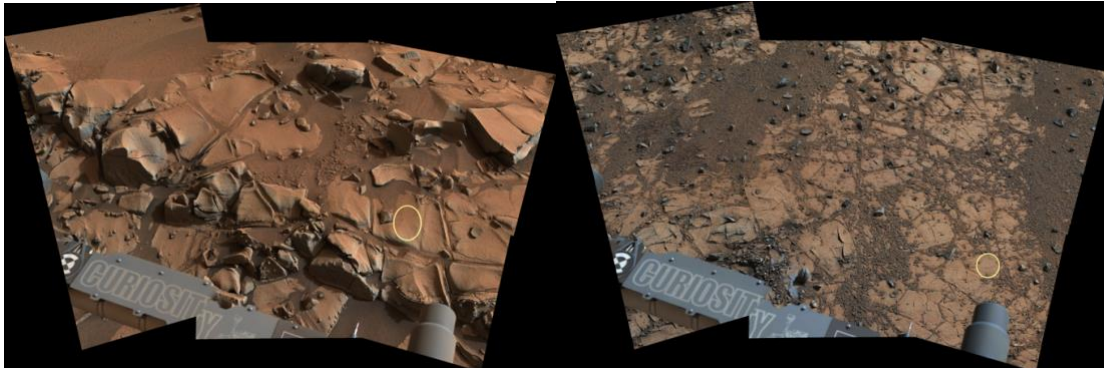


Figure S16. Mastcam mosaics showing workspaces for lower Mount Sharp group targets Mescal (left, mcam03600), and Telegraph Peak (right, mcam03953).

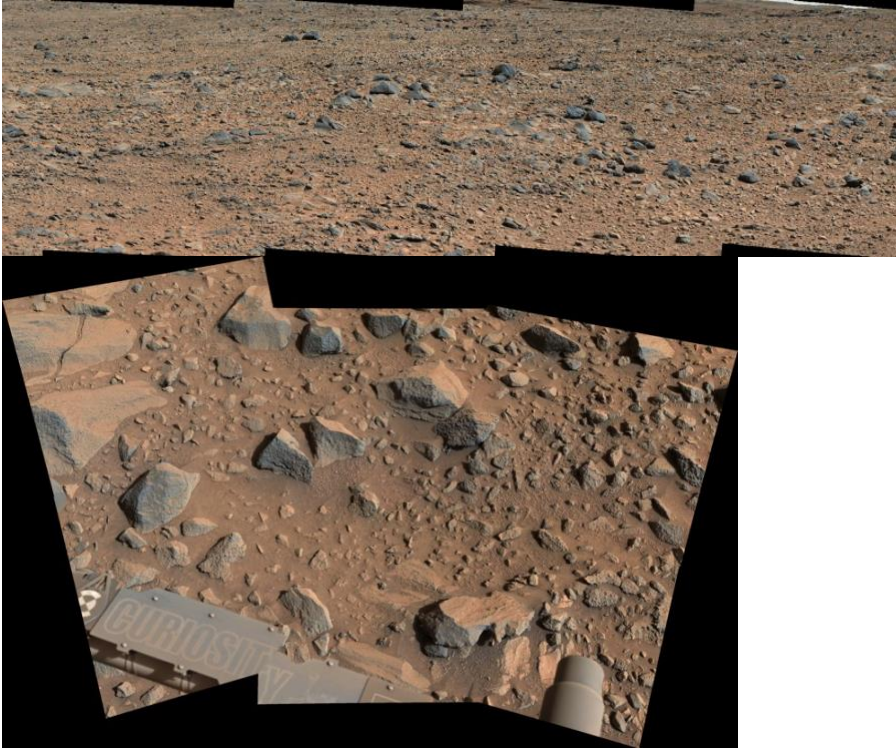


Figure S17. Mastcam mosaics showing: context for the Bradbury group, South Park cap rock target (top, mcam02925); and the South Park workspace (bottom, mcam02931).

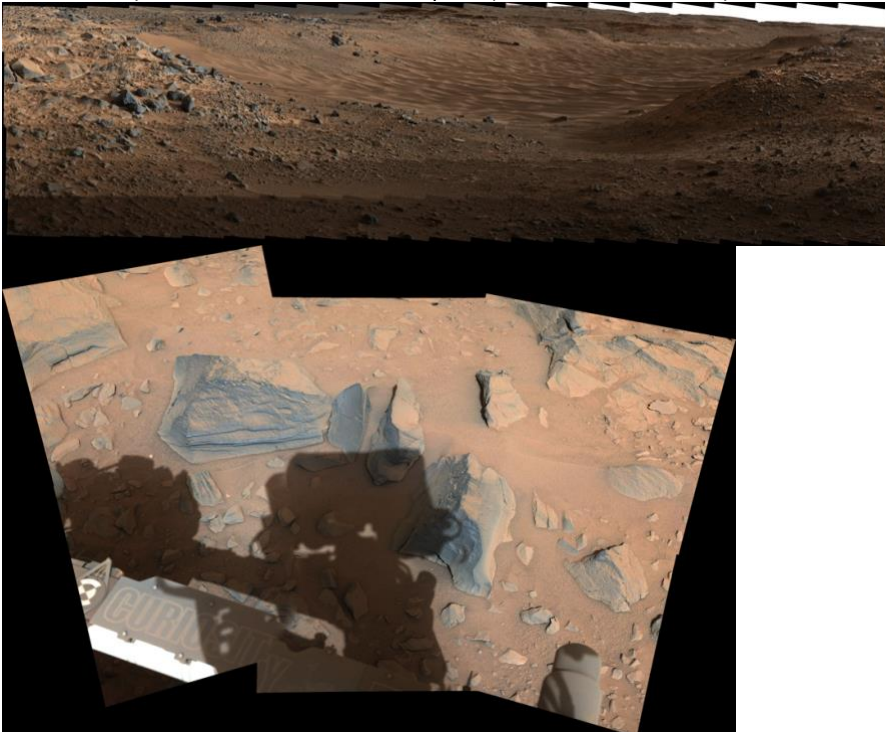


Figure S18. Mastcam mosaics showing: context for the Bradbury group, Thimble and Stirling cap rock targets (top, mcam02977); and their workspace (bottom, mcam02994).

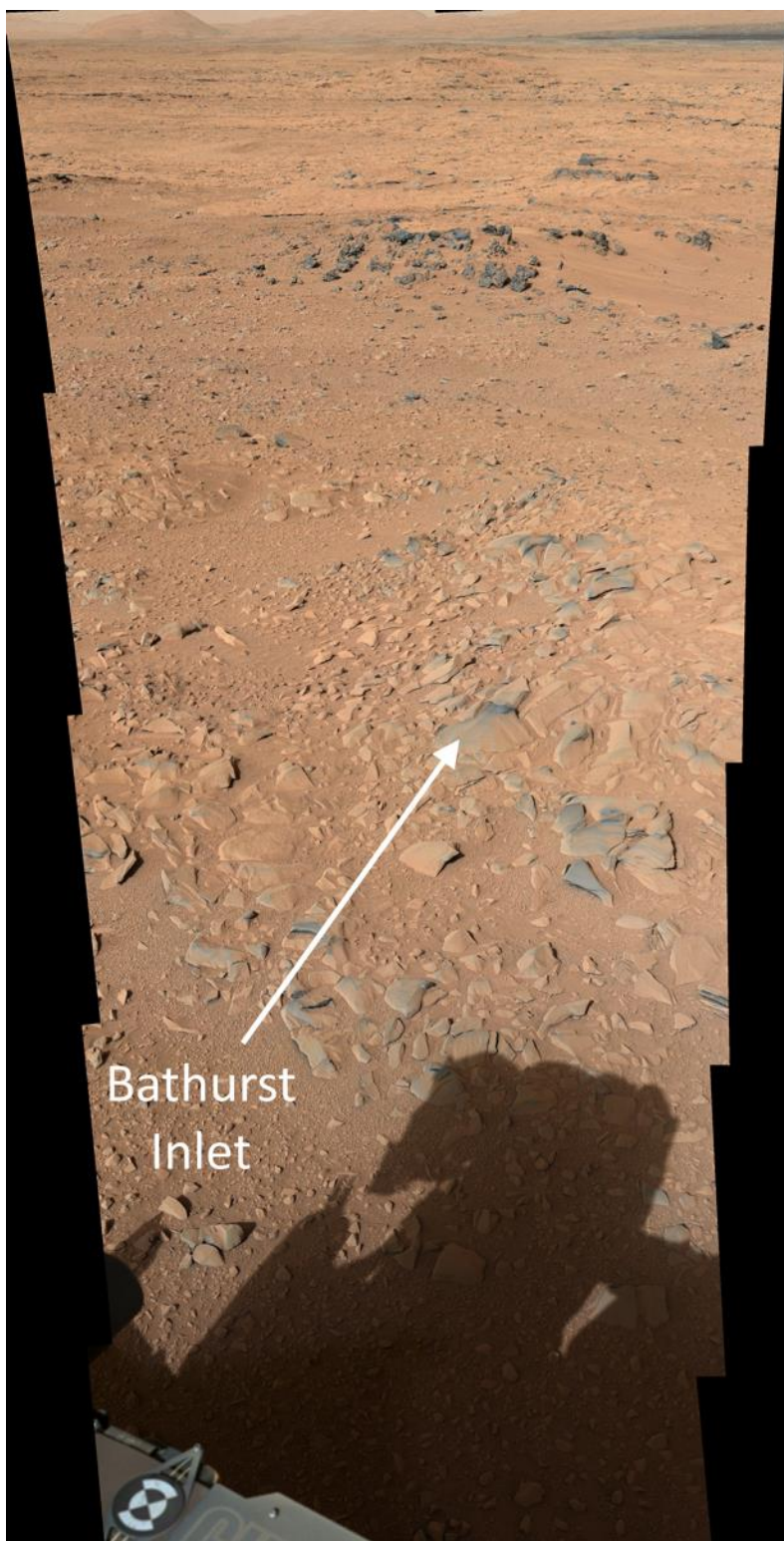


Figure S19. Mastcam mosaic showing context for the Bradbury group, Bathurst Inlet target (mcam00240).



Figure S20. Mastcam mosaic showing context for the Bradbury group, Shaler outcrop, Egaluik target (mcam01304).



Figure S21. Mastcam mosaic showing context for the Bradbury group, Rocknest 3 target (mcam00666).

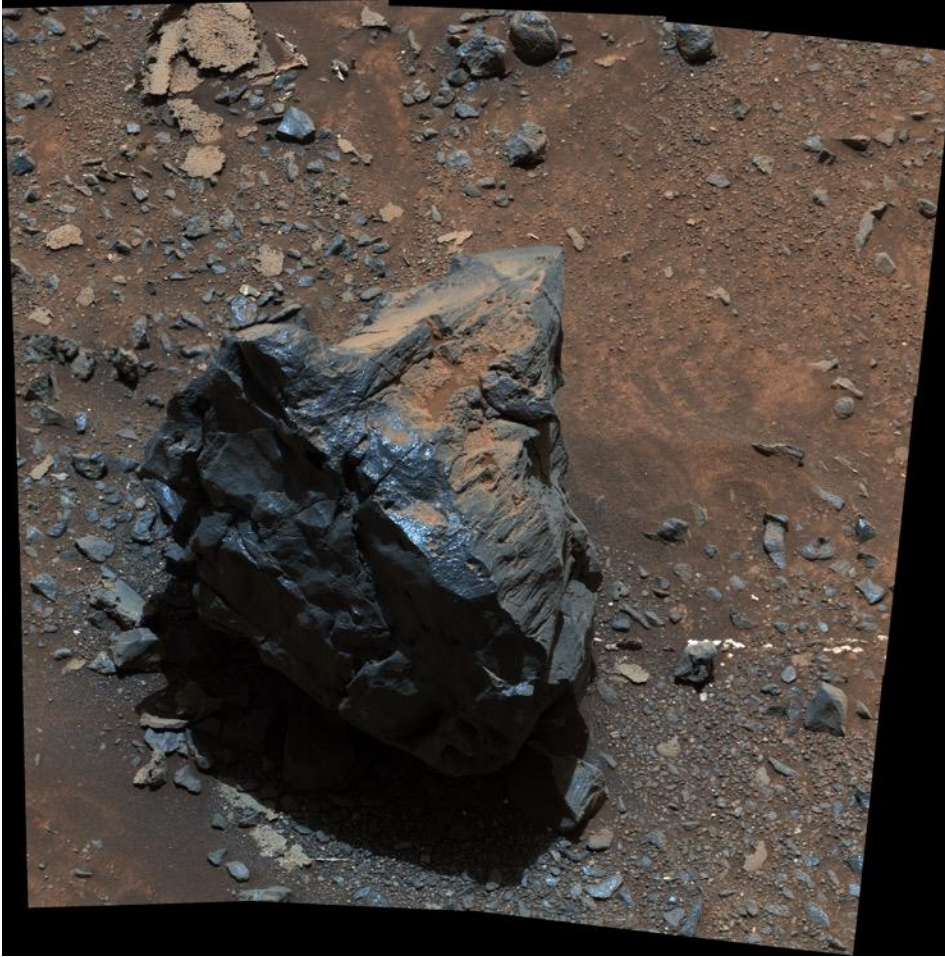


Figure S22. Mastcam mosaic showing context for the Little Devil float cap rock target derived from the Salsberry Peak capping sandstones at Pahrump Hills (mcam04132).

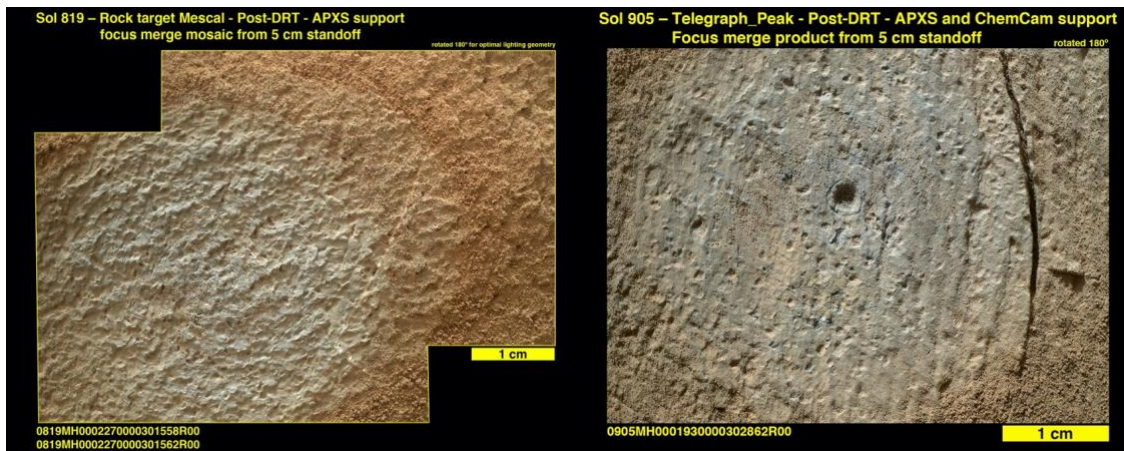


Figure S23. ~5 cm standoff MAHLI images of the lower Mount Sharp group, Pahrump Hills targets; Mescal (left), and Telegraph Peak (right).

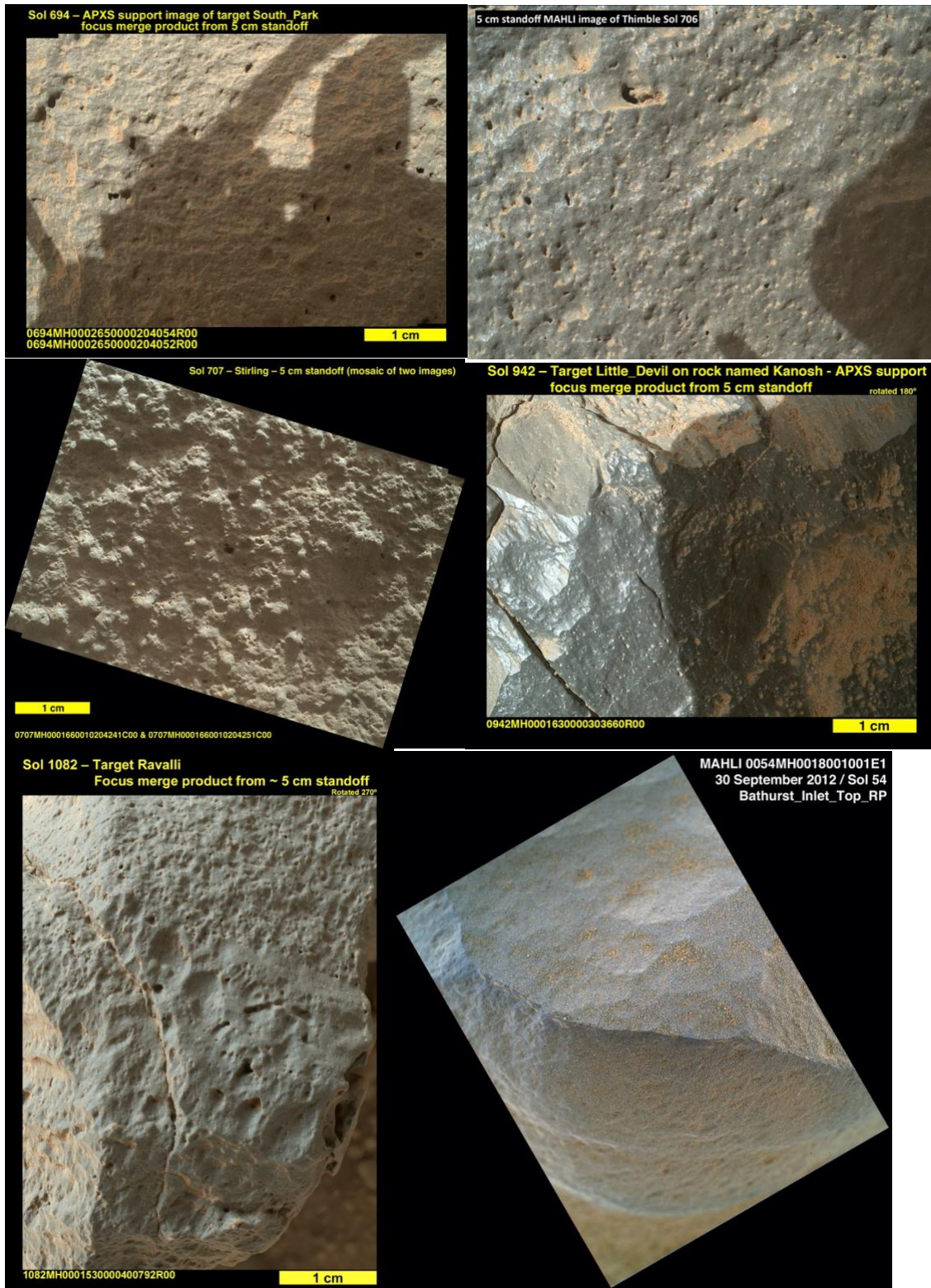


Figure S24. ~5 cm standoff MAHLI images of 1) Bradbury group targets: South Park (top left), Thimble (top right), and Stirling (middle left), 2) float rock targets encountered along the Mount Sharp group traverse: Little Devil (middle right), and Ravalli (bottom left), 3) Bradbury group Bathurst Inlet sandstone target (bottom right).