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1 **ORIGIN AND COMPOSITION OF THREE HETEROLITHIC BOULDER- AND COBBLE-**
2 **BEARING DEPOSITS OVERLYING THE MURRAY AND STIMSON FORMATIONS,**
3 **GALE CRATER, MARS**

4
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- 36 • Gale crater
- 37 • Heterolithic unit
- 38 • Curiosity rover
- 39 • Stimson formation
- 40 • Murray formation
- 41 • Greenheugh pediment

42

43 **Highlights:**

- 44 • HiRISE images show heterolithic, bouldery units on the lower portion of Aeolis Mons
- 45 • Curiosity observed three such units with cobbles and boulders to > 2 m diameter
- 46 • Layered sandstones are similar to intact outcrops > 5 km distant, on Bradbury Rise
- 47 • Conglomerate clasts at Bimbe have compositions similar to the Stimson formation
- 48 • Conglomerates imply late fluvial activity during/after deposition of the Stimson

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50

51 **ABSTRACT**

52

53 Heterolithic, boulder-containing, pebble-strewn surfaces occur along the lower slopes of Aeolis
54 Mons (“Mt. Sharp”) in Gale crater, Mars. They were observed in HiRISE images acquired from orbit
55 prior to the landing of the Curiosity rover. The rover was used to investigate three of these units
56 named Blackfoot, Brandberg, and Bimbe between sols 1099 and 1410. These unconsolidated units
57 overlie the lower Murray formation that forms the base of Mt. Sharp, and consist of pebbles, cobbles
58 and boulders. Blackfoot also overlies portions of the Stimson formation, which consists of eolian
59 sandstone that is understood to significantly postdate the dominantly lacustrine deposition of the
60 Murray formation. Blackfoot is elliptical in shape (62 x 26 m), while Brandberg is nearly circular (50
61 x 55 m), and Bimbe is irregular in shape, covering about ten times the area of the other two. The
62 largest boulders are 1.5-2.5 m in size and are interpreted to be sandstones. As seen from orbit, some
63 boulders are light-toned and others are dark-toned. Rover-based observations show that both have the
64 same gray appearance from the ground and their apparently different albedos in orbital observations
65 result from relatively flat sky-facing surfaces.

66 Chemical observations show that two clasts of fine sandstone at Bimbe have similar compositions
67 and morphologies to nine ChemCam targets observed early in the mission, near Yellowknife Bay,
68 including the Bathurst Inlet outcrop, and to at least one target (Pyramid Hills, Sol 692) and possibly a
69 cap rock unit just north of Hidden Valley, locations that are several kilometers apart in distance and
70 tens of meters in elevation. These findings may suggest the earlier existence of draping strata, like
71 the Stimson formation, that would have overlain the current surface from Bimbe to Yellowknife Bay.
72 Compositionally these extinct strata could be related to the Siccar Point group to which the Stimson
73 formation belongs.

74 Dark, massive sandstone blocks at Bimbe are chemically distinct from blocks of similar morphology
75 at Bradbury Rise, except for a single float block, Oscar (Sol 516). Conglomerates observed along a
76 low, sinuous ridge at Bimbe consist of matrix and clasts with compositions similar to the Stimson
77 formation, suggesting that stream beds likely existed nearly contemporaneously with the dunes that
78 eventually formed the Stimson formation, or that they had the same source material. In either case,
79 they represent a later pulse of fluvial activity relative to the lakes associated with the Murray
80 formation.

81 These three units may be local remnants of infilled impact craters (especially circular-shaped
82 Brandberg), decayed buttes, patches of unconsolidated fluvial deposits, or residual mass movement
83 debris. Their incorporation of Stimson and Murray rocks, the lack of lithification, and appearance of
84 being erosional remnants suggest that they record erosion and deposition events that post-date the
85 exposure of the Stimson formation.

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87

1. INTRODUCTION

Since the Mars Science Laboratory (MSL) rover, Curiosity, landed on Mars in 2012, it has been used to explore the geologic record preserved within Gale (Fig. 1), a 154 km diameter impact crater located at the boundary between heavily cratered ancient highlands and younger, northern lowlands. Through investigation of Gale's ancient rock record—considered to be younger than 3.8 Ga and generally older than 3.2 Ga (Thomson et al., 2011; Le Deit et al., 2013)—the MSL team seeks to characterize the nature and evolution of early Martian environments and to understand their potential habitability (Grotzinger et al., 2013; Grotzinger et al., 2015).

Here we present ground-based observations regarding a puzzling type of geological unit first observed prior to landing. Using ~25 cm/pixel High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) images acquired from the orbiting Mars Reconnaissance Orbiter (MRO), the team identified a suite of isolated features ranging in size from 10s to 100s of meters across that occur along the lower northern slopes of Aeolis Mons (informally, Mt. Sharp), the 5-km-high stratified mountain in Gale (Fig. 1). The strata of Aeolis Mons are sedimentary (Malin and Edgett, 2000; Anderson and Bell, 2010; Milliken et al., 2010). The puzzle was whether these isolated features are part of the sedimentary rock record (i.e., lithified units) or are younger, unconsolidated deposits.

These landforms exhibit a variety of shapes ranging from circular, elliptical, to irregular, but in HiRISE images all are relatively featureless in texture (at ~25 cm/pixel scale) and are of a uniform, intermediate to dark tone. In addition to these attributes, the landforms also contain concentrations of boulders to > 1 m in size. Some of the boulders seen in HiRISE images exhibit light tones; others are dark toned. Prior to encountering these units, it had been suggested that the apparent light-toned rocks are from the eolian lithology on upper Mt. Sharp (Milliken et al., 2010), or that they could be remnants of landslide or glacial till deposits. The team preliminarily interpreted these landforms to be depositional units because of their boulder-rich nature. These “heterolithic deposits” or “blocky units” are spatially distinct, span a ~200 m elevation range along the lower northern slopes of Aeolis Mons, and occur across a lateral distance of ~10 km. Although most of the heterolithic units are in direct contact with the lowermost exposed unit of Aeolis Mons, the Murray formation, several examples overlie the Stimson formation, which unconformably overlies an erosional paleoslope cut through the Murray formation on the lower portion of Mt. Sharp (Banham et al., 2018; Watkins et al., in revision).

To understand whether the heterolithic deposits are part of the ancient rock record in Gale crater, or whether they are modern, unconsolidated materials like the nearby eolian dunes, the MSL team used the tools and instruments of the Curiosity rover to investigate three of them that were encountered along the rover traverse (Fig. 1). In this paper we describe their setting, morphology, lithology, and compositional relationships using data acquired from orbit and on the ground. Based on these observations, we determine the stratigraphic context of the heterolithic deposits relative to the major geologic units investigated by the Curiosity rover, and discuss potential depositional origins and processes for these deposits. This work focuses exclusively on the three units studied by Curiosity, though many more exist in the area at the base of Mt. Sharp.

1.1. Geological Context

Curiosity landed on Bradbury Rise, at the distal end of the alluvial fan produced by Peace Vallis, a fluvial channel that descends from the crater rim (Fig. 1 inset; Palucis et al., 2014). Rocks of the Bradbury group include loose gravels, conglomerate beds, and sandstones deposited in a fluvial setting (Williams et al., 2013; Grotzinger et al., 2015). Upon reaching the Pahrump Hills around Sol 750, Curiosity entered the Murray formation (Grotzinger et al., 2015) of the Mt. Sharp group. This primarily lacustrine formation has been eroded to expose over 300 meters in vertical extent starting at Pahrump Hills and extending up at least through Vera Rubin ridge (VRR; Fraeman et al., in revision) and Glen Torridon (Fig. 1). The slope of the eroded Murray formation forms the base of Mt. Sharp. Draping over this erosional surface and forming patchy outcrops overlying the Murray is the Stimson formation, considered to be part of the Siccar Point group (Fraeman et al., 2016; Banham et al., 2018; Watkins et al., in revision). It consists of dark-gray sandstones containing cross-bedding ~1 m thick with cross laminations. It has a bimodal grain size centering on 250 μm and 710 μm (Banham et al., 2018). The Stimson formation was interpreted to be eolian (Banham et al., 2018). Subsequent lithification of the Stimson followed by canyon incision led to formation of the ~7-17 meters-high Murray buttes (Fig. 1 and Supplemental Material) in which the Stimson formation is exposed as buttes and mesas over the underlying Murray formation (Banham et al., 2019).

In addition to the Murray and Stimson formations, Curiosity encountered three heterolithic units (Fig. 1): Blackfoot (encountered by Curiosity on sols 1094-1104), Brandberg (sols 1158-1160), and Bimbe (sols 1400-1410), characterized by unconsolidated deposits of pebbles, cobbles and boulders that overlie the Murray formation, and in at least one case the Stimson formation. These units are clearly different from the surrounding surface exposures. Dark-toned, massive float rocks in particular are unique to these units relative to the surrounding surface, which have very few float rocks aside from those that clearly belong to the respective Murray and Stimson formations or are meteorites (Meslin et al., 2017). These three units occur between elevations of -4434 and -4419 m (relative to the Martian datum) within 1.2 km of each other and within ~0.5 km of a discontinuous scarp that marks a topographic transition between the flat plains (Aeolis Palus) and Mt. Sharp (Fig. 1).

The units are distinct from boulder and cobble deposits that occur on the slopes of mounds, buttes, mesas, and scarps in the region. In the latter cases, usually an intact, erosion-resistant cap rock (e.g., Stimson formation, in the case of Murray Buttes) overlies exposures of Murray-formation rock. It is also important to note that there are few to zero cobbles and boulders composed of fragments of these overlying rocks sitting on Murray-formation bedrock exposures more than 50 m (and usually not > 10 m) from the base of the buttes.

2. METHODS

2.1. Imaging

All HiRISE images acquired through 1-October-2017 of Blackfoot (24 images), Brandberg (23 images), and Bimbe (28 images) were used to observe the distribution pattern and relative tone of observable boulders. Typically, these are boulders ≥ 0.45 m in size; boulders smaller than ~1 m in size can be identified if they have a tone that contrasts with surroundings and/or cast a shadow. In addition, we illustrate our observations using the Calef and Parker (2016) mosaic of HiRISE images of the MSL investigation site compiled as a base map with the rover traverse overlain. Topographic

173 information comes from a digital elevation model (DEM) assembled by Parker and Calef (2016)
174 using HiRISE stereo pair images and correlated with Mars Global Surveyor (MGS) Mars Orbiter
175 Laser Altimeter (MOLA) topographic measurements, referenced to the Martian datum per the
176 approach outlined by Kirk et al. (2008).

177 Nearly all of Curiosity's cameras were used in this investigation. They consist of redundant dual
178 pairs of left and right stereo Navigation cameras (Navcams; Maki et al., 2012) and front and rear
179 Hazard cameras (Hazcams; Maki et al., 2012); two Mast cameras, one on the right side of the mast,
180 with a 100 mm focal length for long-range imaging, and one on the left side with a 34 mm focal
181 length for a larger field of view (Mastcam-34 and Mastcam-100; Malin et al., 2017); a Mars Descent
182 Camera (MARDI; Malin et al., 2017); a Remote Micro Imager (RMI; Maurice et al., 2012; Le
183 Mouelic et al., 2015); and a Mars Hand Lens Imager on the rover arm (MAHLI; Edgett et al., 2012).
184 Imaging via Curiosity's cameras can be considered to occur in two modes: (1) mono- and stereo-
185 context imaging and (2) high-resolution or close-up imaging. The rover's Mastcams, Navcams,
186 Hazcams, and MARDI provide contexts at a variety of scales as a function of distance from the
187 rover. The RMI and MAHLI provide close-up photography. As part of ChemCam (Wiens et al.,
188 2012; Maurice et al., 2012), the RMI provides panchromatic images with a spatial resolution of ~100
189 μm within 2.5 m distance. Typical MAHLI macrophotography provides color images over a 15–100
190 $\mu\text{m}/\text{pixel}$ range (Yingst et al., 2016).

191

192 2.2. Boulder and Cobble Lithology Interpretation

193 Stereo context imaging provides information on boulder and cobble dimensions that are generally
194 accurate to ± 1 cm (Maki et al., 2012). Boulder and cobble size classifications use the scheme of Blair
195 and McPherson (1999) and Terry and Goff (2014) over the 6.4–409.6 cm size range: fine cobbles
196 (6.4–12.8 cm), coarse cobbles (12.8–25.6 cm), fine boulders (25.6–51.2 cm), medium boulders (51.2
197 –102.4 cm), coarse boulders (102.4–204.8 cm), very coarse boulders (204.8 – 409.6 cm). Grains
198 smaller than cobbles and coarser than 4 mm are referred to as pebbles, while particles 2 to 4 mm are
199 granules (Wentworth, 1922). A detailed approach to both the Curiosity rover instruments and rock
200 classification is provided by Mangold et al. (2017).

201 Most of the boulders, cobbles, and pebbles observed at Blackfoot, Brandberg, and Bimbe were
202 investigated only through contextual images obtained by MRO HiRISE and Curiosity's Mastcams,
203 Navcams, and Hazcams. In these cases, identification of rock type is limited to comparisons with
204 other, more closely examined rocks along the Gale-crater traverse since 2012. Additional context
205 images were obtained by MARDI and MAHLI (wheel inspection and landscape images), particularly
206 when the rover drove across Blackfoot. A few boulders and cobbles were examined in greater detail
207 using MAHLI for macrophotography; the Alpha Particle X-ray Spectrometer (APXS; Campbell et al.
208 2012) was used for geochemistry on one cobble at Blackfoot and two boulders at Bimbe. ChemCam
209 RMI images and laser-induced breakdown spectroscopy (LIBS) were used to investigate three targets
210 at Blackfoot, three targets at Brandberg, and 16 targets (several of which are on the same boulder) at
211 Bimbe. As described below, the compositions derived from ChemCam LIBS and APXS are used in
212 the interpretations of the boulders and cobbles.

213 Image interpretation of boulder and cobble lithology is based on experience gained from Curiosity's
214 exploration in Gale crater to date. All of the >350 m of observed in-place strata appear to be
215 sedimentary rocks. Further, the nearly 5 km of stratigraphy above, on Mt. Sharp, are also interpreted
216 to be dominated by sedimentary rock (e.g., Malin and Edgett, 2000; Anderson and Bell, 2010;

217 Milliken et al., 2010). The strata encountered along the traverse include conglomerates interpreted to
218 be fluvial sediments (Williams et al., 2013, Mangold et al., 2016); sandstones interpreted to be
219 fluvial, deltaic, and lacustrine (Grotzinger et al., 2013; Grotzinger et al., 2015; Rice et al., 2017);
220 sandstones interpreted to be eolian (Banham et al., 2018); and rocks finer-grained than fine sand,
221 interpreted largely to be lacustrine mudstones (e.g., Grotzinger et al., 2015). Clasts interpreted as
222 being derived from igneous processes or perhaps impact-generated melts have been confined to
223 coarse cobbles and smaller sizes (Williams et al. 2013; Sautter et al., 2014, 2015, 2016; Mangold et
224 al., 2016; Cousin et al., 2017a); these are interpreted as having been liberated by rock decay
225 processes from exposures of conglomerate and pebbly sandstone, likely transported in streams from
226 the crater walls and rim (e.g., Williams et al., 2013; Sautter et al., 2016).

227 The experience in Gale crater includes observations of bedrock properties and landscape evolution
228 that pertain to indicators of Blackfoot, Brandberg, and Bimbe boulder and cobble lithology as a
229 function of color, shape, sedimentary texture (e.g., clastic, clast properties, fabric), and sedimentary
230 structure (bedding, bedding plane features, soft sediment deformation). Concretions and nodules
231 (Stack et al. 2014; Nachon et al., 2017; Wiens et al., 2017; Sun et al., 2019) as well as fracture-
232 associated diagenetic features such as veins (Nachon et al., 2014, 2017; Kronyak et al., 2019) and
233 alteration halos (Frydenvang et al., 2017; Yen et al., 2017) also occur in the sedimentary rocks of
234 Gale; their presence in a boulder or cobble can also aid in lithological identification. Color is helpful
235 because the majority of sandstones coarser than very fine sand observed in Gale are medium to dark
236 gray (almost black). Conglomerates are generally gray with clasts of varied sizes from sand to small
237 cobbles of various shades of gray from white to black. Mudstones and very fine sandstones which
238 make up the majority of the stratigraphy encountered by Curiosity, occur mostly in various shades of
239 medium to light-gray, purple-gray, and various shades of red.

240 Thus a first-order comparative approach emerges for lithologic interpretation of boulders and cobbles
241 at Blackfoot, Brandberg, and Bimbe that are only seen in context images.

- 242 • Conglomerate cobbles and boulders have a gray matrix and abundant pebble clasts. In some
243 cases, pebbles liberated from their surfaces litter the adjacent ground. Pebbles were normally
244 interpreted as igneous from their coarse-grained or massive texture, at least on Bradbury Rise
245 (e.g., Williams et al., 2013).
- 246 • Cobbles and boulders interpreted as sandstone are dark gray, can exhibit bedding structures and
247 sand-, granule-, or minor pebble-sized clasts as viewed in the highest spatial resolution context
248 images (e.g., Mastcam-100 data). Some of the dark-gray sandstones in Gale have concretions
249 (like the object liberated from Stimson eolian sandstone studied by Van Bommel et al., 2017),
250 fracture fills (veins), or fracture-parallel alteration “halos.”
- 251 • Mudstone cobbles and boulders are expected to be rare, given their poorer resistance to erosion.
252 However, angular fine cobbles of mudstone do occur and have been identified along Curiosity’s
253 traverse (e.g., Lamoose target noted by Morris et al., 2016, and a large number of dislodged slabs
254 observed in the upper Murray formation below VRR, and smaller pebbles on the ridge itself).
255 Fine laminae and diagenetic features, especially veins and concretions, are common in the
256 mudstones in Gale (e.g., Sun et al., 2019). Color might actually be the most helpful clue, as none
257 of the mudstones identified thus far have been as dark gray as the sandstones and their colors
258 include reddish, golden brown, and purplish strata.

259 2.3. Elemental Compositions and Reflectance Spectroscopy

260 ChemCam uses LIBS at distances of 2–7 meters from the rover’s remote sensing mast to determine
261 elemental chemistry (Wiens et al., 2012; Maurice et al., 2012). Laser pulses of 14 mJ energy and 5 ns
262 duration are focused on observation points (0.3-0.6 mm diameter) on the targets. The first few laser
263 pulses remove dust from the surface. Individual spectra from pulses 6–30 at each targeted point are
264 averaged and processed to remove ambient-light background, noise, and electron continuum, leaving
265 the atomic emission spectrum (Wiens et al., 2013). These are further processed through a calibration
266 algorithm that normalizes the spectra, correcting for variable distance (Wiens et al., 2013), and yields
267 the abundances of the major elements as oxide weight percent (Clegg et al., 2017). Trace elements
268 Li, Rb, and Sr are processed by calibrating the area of an emission peak of the respective element,
269 slightly revised from Payré et al. (2017).

270 Accuracies are estimated using the calibration algorithm on a separate test set of standards over a
271 variety of compositions, yielding accuracies as functions of abundances for each major element and
272 trace element. Precisions are determined by comparing repeated observations of onboard calibration
273 targets carried out over a number of different days (Blaney et al., 2014) or by comparing repeated
274 observations of a homogeneous lithologic unit such as the Sheepbed mudstone in Gale crater
275 (Mangold et al., 2015). The latter is more realistic in that it is done over various instrument-to-target
276 distances, but it is a worst-case measurement of precision, as it includes any heterogeneity that may
277 exist in the bedrock at the scale of the beam. Overall, the two determinations of precision are
278 comparable. Finally, for each observation point, the averaging of 25 spectra, and the resulting
279 standard deviation, allows us to determine the stability of the composition within the evolving laser
280 pit. This standard deviation is another measure of precision and is equivalent in its nature to the error
281 reported with APXS observations. An exception is that, because the laser creates a depth profile into
282 the target, the standard deviation includes the heterogeneity of the target over the depth of laser
283 pulses 6 to 30. Normally this is not a significant consideration but sometimes the composition does
284 change over the course of the 25 laser pulses, resulting in a higher standard deviation that is
285 unrelated to instrument stability.

286 All ChemCam statistics, including abundances, accuracies, and standard deviations are provided in
287 the data submitted to the Planetary Data System. Quantification limits for the trace elements Li, Rb,
288 and Sr are 5, 26, and 96 ppm, respectively. While accuracies vary with abundances, observations
289 presented here were generally within ± 5 , ± 30 , and ± 150 ppm, respectively.

290 For all targets, Fe is not separated by oxidation state, but is computed as total iron as FeO (“FeO_T”).
291 The major elements are not normalized to 100% to allow for contributions from minor elements such
292 as S, P, Cl, F, and H. In most cases the major-element total is in the mid-90s in wt. %, but in a few
293 cases the minor elements appear to comprise up to ~12 wt. %.

294 APXS was used to analyze four targets: Badlands in the Blackfoot area and targets Sonneblom,
295 Funda, and Zambezi at Bimbe (Sonneblom and Zambezi were on the same boulder). Funda was
296 analyzed by a 4-point raster, while the other three targets were single analyses. Badlands, Zambezi,
297 and Sonneblom were overnight integrations. The Dust Removal Tool was not used on any of the
298 targets. The footprint of APXS is ~1.7 cm in diameter.

299 Johnson et al. (2015) demonstrated that radiance spectra acquired using ChemCam without the laser
300 provides sufficient signal to allow measurement of reflected sunlight from soil and rock targets.
301 Calibration of such data was accomplished by dividing the scene radiance spectrum by a calibration
302 target radiance spectrum with known reflectance properties (Wiens et al., 2013). This provided an

303 estimate of relative reflectance with uncertainties of <10% (Johnson et al., 2015). Typically, such
304 passive observations were acquired after laser shots, which served to minimize dust contamination in
305 the measurement's field of view.

306 The rover's interior mineralogical and geochemical laboratories, Chemistry and Mineralogy
307 (CheMin) and Sample Analysis at Mars (SAM), were not used to investigate Blackfoot, Brandberg,
308 and Bimbe.

309 **3. RESULTS**

310 **3.1. Blackfoot Image Observations**

311 **3.1.1. Field site and Stratigraphic Position**

312 Of the three heterolithic units that were investigated, Blackfoot was the only one that the Curiosity
313 rover drove across. The route went southwest across the long dimension of Blackfoot between sols
314 1099 and 1104 (09–14 September 2015). Curiosity parked at two spots on Blackfoot (Fig. 2a) to
315 briefly investigate the surface. ChemCam observed targets named Sunburst and Swan at the Sol
316 1099–1100 site and targets Jefferson, Madison, and Lincoln, at the Sol 1100–1104 site. APXS and
317 MAHLI were deployed on Sol 1102 to study an angular, coarse cobble named Badlands at the Sol
318 1100–1104 parking spot. Early views of Blackfoot were acquired on Sol 1094 (04 September 2015)
319 and later views were obtained from the Big Sky and Greenhorn drill sites (Fig. 1; see Yen et al.,
320 2017) as late as Sol 1144 (25 October, 2015). HiRISE captured an image of the Curiosity rover on
321 Sol 1094 (Fig. 2a).

322 Blackfoot covers about 1730 m² in a semi-elliptical area that has a long dimension of ~62 m oriented
323 northeast-southwest and a short dimension of ~26 m perpendicular to that. It occurs between
324 elevations –4434 and –4432 m on the lower north-facing slope of Mt. Sharp. Excluding the largest
325 boulder, the unit has < ~1.1 m relief and its overall surface slopes upward ~1.2° toward the
326 southwest (i.e., elevation gain of ~1.4 m over 62 m). At the northeast end, the gravels, cobbles, and
327 boulders of which it is composed are in contact with the cross-bedded sandstone facies of the
328 Stimson formation (Fig. 2d, e). At its southwest end it is in contact with mudstones of the Murray
329 formation (Fig. 2h). The Blackfoot unit cross-cuts and bridges the pattern of parallel ridges (Banham
330 et al., 2018) separated by troughs > 4 m deep that are exhibited by the underlying Stimson and
331 Murray-formation rocks (Fig. 2a, Supplementary Fig. 1-1). Its topography and contact relations with
332 underlying bedrock suggest a near-uniform thickness of the order of a few tens of centimeters. No
333 intact rock unit overlies Blackfoot; it is not emergent from beneath superposed rock strata.

334 **3.1.2. Physical Sedimentology of the Blackfoot Deposit**

335 The surface of Blackfoot is pebbly with scattered occurrences of cobbles and boulders of a variety of
336 sizes, shapes, and orientations relative to their internal bedding structures (Fig. 2f, i). Some of the
337 boulders and cobbles are resting on the surface of Blackfoot, while others protrude from the deposit.
338 The loose, pebbly surface includes a few minor superimposed patches of unconsolidated eolian sand.
339 The largest boulders are ~1.5–2.5 m in size; boulders of sizes ~0.45 to ~1.8 m can also be observed
340 in the highest quality HiRISE images of Blackfoot (e.g., PSP_009294_1750 and
341 ESP_018854_1755), as well as the images acquired during the rover's visit to the area. Most—but,
342 importantly, not all—boulders and cobbles are clustered on the downward slopes around the unit
343 margins; some of these clasts have apparently moved down onto nearby, subjacent rock surfaces.

344 The northeast end of Blackfoot exhibits an exposure that gives a glimpse of its internal sedimentary
345 structure (Fig. 2f). The framework clasts in this few tens-of-centimeters-thick exposure are angular

346 to sub-rounded pebbles and cobbles; matrix clasts — i.e., grains finer than pebbles in the interstices
347 between pebbles and cobbles — are not resolved in the highest resolution images acquired. Sorting
348 in this apparent exposure is poor and laminae or beds within individual cobbles are randomly
349 oriented. Although the subjacent Stimson and Murray-formation rocks are cut by fractures (some of
350 which are filled with minerals, i.e., veins), the Blackfoot material is not; furthermore, some fractures
351 in Stimson formation rocks terminate at the boundary with the Blackfoot unit (Fig. 2g). Particle size
352 analysis of Blackfoot (Supplementary Material, Section 2) indicate a median size (D50) of 16 mm,
353 and 84th percentile (D84) of 40 mm and a 16th percentile (D16) of 7 mm (Supplementary Material,
354 Section 2, Supplementary Fig. 2-3).

355 3.1.3. Evidence of Lithologic Diversity

356 The lithologic diversity of Blackfoot was suspected for several years before the rover arrived, based
357 on mapping during traverse planning. This notion was due to the tone of the two largest boulders at
358 Blackfoot relative to the surrounding terrain as seen in HiRISE images. As labeled in Fig. 2a,
359 boulder A has a dark tone and boulder B has a light tone in this perspective from orbit. As seen from
360 the ground, the only relatively light-toned rocks encountered along the traverse to that point were
361 light-gray mudstones of poorer erosion resistance (e.g., Grotzinger et al., 2013; Grotzinger et al.,
362 2015; Morris et al., 2016; Schieber et al., 2016). In addition to these few light-toned rocks, light-
363 toned fracture-associated halos occur in the Stimson formation (Frydenvang et al., 2017; Yen et al.,
364 2017), but the affected portion of these sandstones is small relative to the size of boulder B. In
365 addition, white vein minerals, interpreted based on ChemCam and APXS observations to be calcium
366 sulfates, are abundant throughout Curiosity's field site (Nachon et al., 2014, 2017; Kronyak et al.,
367 2019). Clasts formed from the breakdown of exposed, eroding veins along the traverse have been of
368 pebble size and smaller (e.g., Newsom et al., 2018).

369 The light-toned (orbital perspective) boulder B was imaged on the ground using the Mastcams from
370 four different locations on sols 1094, 1098, 1100, and 1144 (e.g., Fig. 2c), and it was also captured in
371 a MAHLI rover wheel inspection image from Sol 1102, as well as in engineering camera data. The
372 boulder's dimensions are approximately 2.7 by 1.6 m. The Mastcam images provide eight important
373 observations about boulder B: (1) the rock is actually not light-toned as seen from the ground; it is
374 dark gray, (2) it is angular, (3) it is tabular with a relatively flat skyward-facing surface, (4) its
375 skyward-facing surface is coated with brownish-orange eolian dust, (5) its skyward-facing surface is
376 smooth at centimeter scale, (6) it exhibits sedimentary structure in the form of bedding, (7) the
377 bedding thickness is < 1 cm (i.e., of the order of a few millimeters), and (8) the bedding is at an angle
378 of about 50° relative to the top of the boulder and relative to the surface on which the boulder rests.
379 On the basis of bedding and color, boulder B is interpreted to be a sandstone, similar to other
380 sandstones observed in the area and in Gale crater in general. The light tone observed from orbit
381 (Fig. 2a), and also to some extent as observed from a distance with rover cameras, is entirely the
382 result of the combination of a dust coating and a skyward-facing surface that is smooth at centimeter
383 and perhaps millimeter scales.

384 Boulder A was imaged using Curiosity's Mastcams and engineering cameras from four different
385 locations on sols 1094, 1098, 1100, and 1144 (e.g., Fig. 2b). Boulder A differs from boulder B; it is
386 smaller (~1.2 m across), but stands higher above the surface owing to its greater sphericity. Like
387 boulder B, it is dark gray in color, but it is rougher at a centimeter scale. Boulder A, too, has dust on
388 its skyward-facing surfaces, but the combination of shape and centimeter-scale roughness renders it
389 dark-toned when viewed from above in HiRISE images.

390 The images acquired during Curiosity’s traverse across Blackfoot show the range of boulder and
391 cobble lithologies present at its surface. Generally, on the basis of color, tone, texture, and
392 sedimentary structure, the boulders can all be interpreted as sandstones. Some of the cobbles can also
393 be interpreted as likely sandstones, on the same basis, but some cobbles are pebbly conglomerates or
394 pebbly sandstones (Fig. 3). The lithology of pebble clasts and smaller grains are not interpreted here
395 owing to insufficient spatial resolution in the images acquired.

396 Fig. 3 shows various examples of the rocks interpreted to be conglomerates and sandstones at
397 Blackfoot. Mastcam and RMI images of select targets, such as Swan, Sunburst, Lincoln, Jefferson,
398 and Madison show that sand grains are present in these rocks (Fig. 3b,e), all of which are interpreted
399 to be dark gray, erosion-resistant sandstones. Their individual characteristics vary; for example
400 Madison and Sunburst include light-toned sand grains (Fig. 3b, e) and Sunburst exhibits cross-
401 stratification (Fig. 3a). MAHLI images of the rock target Badlands also show sand grains (Fig. 3f).
402 Some of the rocks observed at Blackfoot are light gray to white in color (Fig. 3g); some of these
403 might have been eroded from fracture-associated altered sandstones that occur in the Stimson
404 formation (see Frydenvang et al. 2017; Yen et al. 2017).

405 None of the boulders and cobbles observed at Blackfoot resemble or are lithic fragments of the
406 Murray formation. As well as can be determined from the images acquired by the Mastcams, RMI,
407 Navcams, Hazcams, MARDI, and MAHLI, none are as finely (< 1 mm) laminated as typical
408 Murray-formation rock, nor are they of one of the colors—light grays, grayish purples, brownish and
409 yellowish reds—observed in Murray-formation strata.

410 In summary, Blackfoot is a relatively thin accumulation of poorly sorted pebbles to boulder-size
411 clasts; the angular to well-rounded pebble-sized lithic fragments appear to serve as matrix to the
412 coarser rocks. The boulders and cobbles exhibit random orientations relative to their internal
413 sedimentary structure (bedding); some of them protrude from the deposit and others rest on its
414 surface. The deposit overlies both Stimson and Murray-formation rocks and is not lithified. The
415 surface is largely a pebbly lag with very little superimposed eolian dust and sand. Boulder and
416 cobble shapes include angular clasts; these are suggestive that they were not transported far from
417 their bedrock source. The boulders are generally dark-gray apparent sandstones; the gray
418 conglomerates are a sub-set of a population of otherwise dark gray (and a few light gray to white)
419 sandstone cobbles.

420

421 3.2. Brandberg Image Observations

422 3.2.1. Field Site and Stratigraphic Position

423 Brandberg is a nearly circular (~50 x 55 m) landform. The MSL team parked the rover next to the
424 eastern edge of Brandberg on Sol 1158 for a limited investigation. The Navcams, Hazcams,
425 Mastcams, and ChemCam were all used to examine nearby cobbles and boulders of Brandberg from
426 this vantage point over sols 1158–1160 (09–11 November 2015). HiRISE captured an image of
427 Curiosity parked at the site on Sol 1159, 10 November 2015 (Fig. 4a). Brandberg was also visible in
428 Mastcam mosaics acquired during the drive toward and away from Brandberg over the sol 1115–
429 1163 period (25 September – 14 November 2015).

430 Covering about 2300 m², Brandberg occurs between elevations –4435 and –4432 m on the lower
431 north-facing slope of Mt. Sharp. Not only is it nearly circular, an arcuate ridge of about 1–2 m height
432 occurs about 15–20 m to its east (Fig. 4f). A Sol 1160 Mastcam mosaic (sequence mcam05248)

433 shows that the ridge is composed of purple-ish Murray-formation bedrock. As viewed in planform in
434 HiRISE images, Brandberg has a surface speckled with light- and dark-toned boulders (Fig. 4a). The
435 overall surface is also dark-toned, similar in HiRISE images to nearby eolian dunes such as the
436 Namib and High dunes explored via Curiosity (Bridges and Ehlmann, 2018) after departing
437 Brandberg. The HiRISE views of Brandberg also show that it has a discontinuous, meter-scale
438 parallel ridged texture that runs approximately northeast-southwest (Fig. 4a). In HiRISE images and
439 all of the acquired Mastcam and Navcam mosaics of Brandberg, this unit is seen to be elevated above
440 and in contact with Murray-formation rocks, all around its circumference. It does not contact the
441 Stimson formation and there are no overlying rock units. Supplementary Fig. 1-2 shows that
442 Brandberg and Blackfoot occur at the same elevation and have a similar thickness.

443 3.2.2. Physical Sedimentology of the Brandberg Deposit

444 The surface of Brandberg exhibits scattered boulders, cobbles, and pebbles, interspersed with dark-
445 gray, windblown sand and granules (Fig. 4b-e). The sands form tails in the lee of boulders and
446 cobbles (Fig. 4b), creating the pattern of northeast-southwest oriented lineations observed in HiRISE
447 images. Some of the boulders and cobbles are resting on the surface of Brandberg, but many protrude
448 from within the deposit (Fig. 4d, e).

449 Overall, Brandberg is a poorly sorted, unconsolidated sedimentary deposit. Three attributes indicate
450 that Brandberg is not a lithified unit (i.e., not sedimentary rock): (1) fractures and (2) veins do not cut
451 across the unit and its clasts, and (3) it is not emergent from beneath an overlying rock unit. The
452 largest boulders are angular and of several meters in size. Many of the boulders and cobbles are
453 angular, slab-shaped, and dip at steep angles relative to the surface (Fig. 4e). Supplementary Fig. 2-3
454 shows that Brandberg has a similar particle size distribution to Blackfoot of D50 of 13 mm, D84 of
455 44 mm, and D16 of 4 mm. Size analysis was performed via images acquired along the steepened
456 exposure shown in Fig. 4(e) and 5(a), where the maximum exposed clast size was 409 mm.

457 3.2.3. Evidence of Lithologic Diversity

458 The presence of boulders of differing tone in HiRISE images suggested the possibility of lithologic
459 diversity in Brandberg, years before the rover arrived (Fig. 4a). As with boulder B at Blackfoot,
460 Mastcam images of the boulders at Brandberg show that the light tones are not the result of an
461 intrinsic tonal property of the individual clasts, but instead are evident in cases in which a boulder
462 has a relatively smooth (at cm- to mm-scale), skyward-facing surface coated with eolian dust.

463 Mastcam images show that some of the boulder- and cobble-sized clasts seen along the east margin
464 of Brandberg exhibit fine lamination (sub-mm to mm-scale), relatively flat surfaces at cm-scale, and
465 are covered with a thin coating of dust (Fig. 4e). In some cases, the laminae are dipping steeply
466 relative to horizontal, indicating that they have been displaced from their original bedding orientation
467 (Fig. 4d). One of the ChemCam targets at the edge of Brandberg was Hoba (Fig. 5a, b), which from
468 the images could be part of the local bedrock. The RMI mosaic of Hoba (Fig. 5b) shows a fractured
469 rock, with fractures cutting across laminae; the rock surface is rough-textured at millimeter scales,
470 rougher than adjacent eolian sandstone surfaces. These properties are similar to those of nearby
471 outcrops of intact Murray-formation rocks. Some of the clasts in Brandberg that are interpreted to be
472 Murray-formation rocks also exhibit protrusive, cm-scale concretions (Fig. 5i), as do nearby Murray-
473 formation rocks (Fig. 5j).

474 Brandberg also has dark-gray boulders and cobbles (Fig. 4b-e). In some cases they are cross-
475 stratified and laminated at millimeter scales (Fig. 5h) and thus physically resemble rocks of the

476 Stimson formation, such as those on the nearby Emerson plateau (Fig. 1) described by Banham et al.
477 (2018). A dark-gray ChemCam target cobble, Gibeon (Fig. 5a, c) has protruding objects (grains or
478 concretions) of very coarse sand and granule size (i.e., 1–3 mm) and exhibits no distinct bedding. A
479 few of the cobble-sized stones observed at Brandberg contain pebble-sized clasts or concretions and
480 are either conglomerates, pebbly sandstones, or sandstones containing pebble-sized concretions (Fig.
481 5g). Further, some of the loose, pebble-sized clasts in the Brandberg deposit resemble concretions
482 that eroded out of Stimson formation sandstones on the nearby (~340 m to the southwest) Naukluft
483 Plateau (Fig. 5d–f).

484

485 3.3. Bimbe Image Observations

486 3.3.1. Field Site and Stratigraphic Position

487 Located due north of the Murray buttes, Bimbe was the most investigated of the three heterolithic
488 units visited by the Curiosity rover. As viewed in HiRISE images (Fig. 6), Bimbe is a boulder-
489 bearing surface with an irregular shape that covers ~16,800 m². It is intermediate in tone relative to
490 the nearby darker-toned eolian sands of the Bagnold dune field (e.g., Bridges et al., 2017) and the
491 surrounding lighter-toned, dust-coated outcroppings of the Murray formation. Most of the boulders
492 visible in HiRISE images of Bimbe are dark toned but a few, as in Brandberg and Blackfoot, exhibit
493 a light tone (Fig. 6b inset).

494 The easternmost extent of Bimbe is a ~37 x 11 m ridge that protrudes northeastward and is mantled
495 with small boulders and cobbles (Fig. 7). This ridge exhibits an eastward azimuth of ~65.5°, which is
496 within the range of the azimuths (50°–95°) exhibited by ridge forms in the nearby Murray buttes,
497 Naukluft Plateau, and Baynes Mountain areas (Fig. 6). Approximately 65–90 m southeast of Bimbe
498 are two hills mantled with dark-gray cobbles and small boulders, named Bukalo and Bailundo (Fig.
499 7); Mastcam image mosaics show that these resemble the northeast-projecting ridge on the east side
500 of Bimbe (Fig. 7).

501 With the exception of the northeastward-projecting ridge, the rest of Bimbe generally slopes down
502 toward the north and lies in a broad depression in the Murray formation which is bordered in this
503 area by Stimson formation-capped buttes and mesas on the lower northward-facing slope of Mt.
504 Sharp (Figs. 6b and 8, Supplementary Fig. 1-3). The average slope from Bimbe to a Bimbe-like
505 surface to the north (Fig. 6a) is about 4.5%. Bimbe occurs between the elevations –4417 and –
506 4426 m and exhibits 9–10 m of surface relief, more than at Blackfoot or Brandberg. A higher
507 proportion of boulders, visible in HiRISE images, occurs on the southern, higher-elevation side of
508 the unit (Figs. 6, 8). Several somewhat circular and elliptical depressions near and adjacent to Bimbe
509 exhibit dark-toned bedforms within them; by analogy to similar features throughout Gale crater,
510 these are probably meteoritic impact structures that have trapped eolian sand. One such elliptical
511 depression occurs on the southeast side of Bimbe and some of the larger boulders encountered during
512 the rover investigation of Bimbe occur there (dashed ellipse in Fig. 8).

513 The Curiosity rover was driven along the east and southeast margins of Bimbe and stopped at four
514 locations (Fig. 6b). The first site was visited on sols 1399–1400 (12–13 July 2016) and the second on
515 sols 1400 and 1401 (13–14 July 2016). The rover was parked at a stand-off position some meters
516 from the edge of Bimbe, to image the boulders and cobbles during sols 1401–1405 (15–19 July
517 2016), where ChemCam observed Murray bedrock. Then it was driven to the last investigation site
518 for study of Bimbe over sols 1405–1410 (19–24 July 2016). At the first two Bimbe investigation

519 sites (sols 1399–1400 and 1400–1401), only remote-sensing observations (ChemCam, Mastcam,
520 Navcam, Hazcam) were acquired; at the final site, MAHLI and APXS were also deployed. While a
521 large number of boulders and cobbles were observed by Mastcam at Bimbe, the descriptions given
522 here focus on the ones that were also observed by ChemCam, MAHLI, and APXS.

523 ChemCam observed two targets on Sol 1400 (Fig. 6b), Auchab and AEGIS_post_1400a (the latter
524 selected via rover autonomous targeting software; Francis et al., 2017). As the latter target was
525 observed after a rover drive, it is at the same site as the Sol 1401 ChemCam targets, Aussenkehr,
526 Canico, and Chinchimane (Fig. 6b). The final Bimbe site visited by Curiosity (sols 1405–1410)
527 displayed boulders and cobbles of various morphologies along a low (≤ 1 m) ridge trending to the
528 northwest (Fig. 9a). Several boulders were south of the ridge, sitting on Murray-formation bedrock
529 just past the southern margin of Bimbe. The boulders and cobbles nearest to the rover were examined
530 using ChemCam, Mastcam, MAHLI, and APXS (Fig. 9b). These included two boulders in the
531 robotic arm workspace, one a conglomerate with targets Tumba (MAHLI only) and Funda (APXS
532 raster and MAHLI), the other a dark-gray apparent sandstone with targets named Sonneblom (APXS,
533 MAHLI, and ChemCam) and Zambezi (MAHLI and APXS). Just behind those boulders lay a
534 partially exposed conglomeratic boulder containing ChemCam targets Seeheim, Wilhelmstal,
535 Cabamba, and Bungo. About half a meter farther on the low ridge to the right (north and east) of the
536 rover were ChemCam targets Oranjemund and Lucala (Fig. 9b). Farther to the right were several
537 conglomeratic stones, including a rounded one containing ChemCam target Balombo, along with a
538 dark-gray fine boulder named Seeis and another target selected by the rover, AEGIS_post_1406a.
539 Finally, to the left of the rover was a ChemCam target named Mariental (Fig. 9a); this small boulder
540 was not on the surface of Bimbe proper, but instead sat isolated on Murray-formation bedrock to the
541 north of the low ridge which forms the southern margin of Bimbe.

542 3.3.2. Physical Sedimentology of the Bimbe Deposit

543 The first two investigation sites (sols 1399–1400, and sols 1400 and 1401; Fig. 6b) were relatively
544 flat with the edge of the unit in contact with Murray-formation bedrock and observed to be relatively
545 abrupt. Some eolian sand and regolith occurs at the outer edge, and then, moving inward—amid a
546 regolith of granules, pebbles, and eolian sand—small cobbles, then larger cobbles and small boulders
547 occur a bit farther in from the edge. The final investigation site (sols 1405–1410; Fig. 6b) was a
548 ridge, oriented approximately west-southwest to east-northeast, littered with larger boulders and
549 cobbles. In all cases, some of the cobbles and boulders sit on the surface and others protrude from the
550 regolithic subsurface. The boulders and cobbles exhibit an array of orientations relative to internal
551 bedding structure (where present) and exhibit a range of shapes from angular to sub-rounded.
552 Patches of eolian sand form ridges in the lee of obstacles.

553 HiRISE images show Bimbe to be in contact with Murray-formation exposures all around its
554 perimeter. For the east and south side of Bimbe, imaged using the rover Mastcams, Navcams, and
555 Hazcams, the same relationship is observed from the ground—Bimbe overlies Murray-formation
556 rock; nowhere does it contact Stimson-formation rocks or other rock units. In addition, no rock unit
557 overlies Bimbe; it does not appear to be emergent from beneath a rock unit. Bimbe is not cross-cut
558 by fractures or veins or intrusive rock. Like Brandberg and Blackfoot, Bimbe is not a rock unit but is,
559 instead, an unconsolidated accumulation of poorly sorted sediment. Grain-size analysis of the Bimbe
560 unit produced a D50 of 9 mm, D84 of 33 mm and a D16 of 4 mm (Supplementary Fig. 2-3).

3.3.3. Evidence of Lithologic Diversity

As noted, Bimbe was suspected of being heterolithic because HiRISE images show that it includes light and dark-toned boulders. Like Brandberg and Blackfoot, the boulders that exhibit light tone in HiRISE images are actually dark gray and present a relatively flat, dust-coated surface toward the sky. Mastcam images and analyses made using ChemCam, APXS, and MAHLI, do, of course, show that Bimbe contains a range of lithologies. These include boulders and cobbles that are conglomerates, sandstones, and reddish stones interpretable as Murray-formation rocks (mudstones or very fine sandstones).

3.3.3.1. Sandstone Boulders and Cobbles

Intact outcrops of sandstone encountered along the Curiosity rover traverse, whether deposited in eolian, fluvial, deltaic, or near-shore lacustrine settings, have generally been dark gray in color (e.g., Grotzinger et al., 2013; Grotzinger et al., 2015; Anderson et al., 2015; Treiman et al., 2016; Edgar et al., 2017; Banham et al., 2018). Some of these sandstones exhibit clear and obvious bedding, others are more “massively” bedded at centimeter to meter scale. Some exhibit protrusive (erosion-resistant) grains of very coarse sand, granules or pebbles; others exhibit protrusive concretions that, in places, can give the rock surface a “knobby” appearance at centimeter scales. Some of the sandstones encountered by the rover also have pits in their surfaces, perhaps sites at which a coarse clast or concretion was liberated by weathering. All of these properties of the sandstones seen throughout the MSL mission in Gale crater are also found in one or another boulder or cobble at Bimbe. As a matter of communication convenience, we describe the dark-gray sandstone boulders and cobbles at Bimbe that display some form of stratification or bedding as layered, those which do not exhibit layers are described here as massive, and those with numerous mm- to cm-scale protrusions are here described as nodular. One modification to this scheme is that some dark-gray sandstones have similar appearance including apparent grain size range, and identical chemistry to the layered targets. We will show later that this class (both in layered and not apparently layered form) has been observed earlier along the traverse, and so we group these targets together here as well, calling them all “layered.”

Massive boulders and cobbles. A “massive” sandstone, for this discussion, is one that exhibits little or no evidence of layering within the cobble or boulder at the scales observable by MAHLI, RMI, and the Mastcams, Navcams, and Hazcams; this does not mean that the original outcrop from which the boulder or cobble eroded was not layered at some greater (decimeter to meter) scale. The boulder on which the targets Sonneblom and Zambezi occur provides an example (Fig. 10). It is dark gray, sand grains are observable (Fig. 10b, c), and the rock surface is pitted at millimeter to sub-millimeter scales, which appears to be a characteristic of this group. Mastcam-100 and ChemCam target, Seeis (Fig. 11a, b), is another example. Like Sonneblom, it is dark gray and pitted; dust-free surfaces can glint in sunlight and some well-rounded mm-scale grains protrude from the rock surface (e.g., 4x inset in Fig. 11b). Seeis also seems indistinctly layered. Some of these massive apparent sandstone boulders and cobbles also exhibit patches of relatively smooth, dark-gray material (Fig. 11); it is unclear whether these are intrinsic to the sediment or the remains of mineralization formed on fracture walls in the original, intact strata. One such patch was observed by ChemCam on target AEGIS 1406a (Fig. 11c, d).

Another cobble examined using Mastcam-100 and ChemCam, called Oranjemund (Fig. 12), is inferred to be a sandstone because it is dark gray and resistant to erosion; only some of its larger grains are perhaps resolvable in the RMI and Mastcam-100 images acquired are 400–700 μm in size. The majority of grains are likely smaller than this. The sunlit portion of the stone facing the

606 Mastcam-100 in Fig. 12 shows that it is laminated at the grain scale (a lamina is the smallest
607 megascopic layer that can be observed in a sedimentary rock; Campbell, 1967). Oranjemund exhibits
608 sharp corners in some places, especially near the top, and more rounded edges near the base. Some
609 glinting of the surface near the apex is evident in the Mastcam image, and the surface investigated
610 using ChemCam is scalloped or fluted. We will show in Section 3.4.1 that Oranjemund is chemically
611 related to the more obviously layered cobble, Chinchimane, described next.

612 **Layered boulders and cobbles.** Mastcam images show that some boulders and cobbles at Bimbe are
613 not only layered, they exhibit cross-bedding at scales to tens of centimeters (Fig. 13a, b). Still others
614 are finely layered, in parallel beds, at sub-millimeter scales. The ChemCam and Mastcam-100 target,
615 Chinchimane, provides an example (Fig. 14). Classified as a coarse cobble, the overall size of
616 Chinchimane is roughly 15 x 25 x 12 cm. Its top is flat and parallel to the bedding, suggesting
617 breakage along a bedding plane. Grains in Chinchimane are challenging to identify in Mastcam-100
618 and ChemCam RMI images; this can be an indicator that grains are smaller than the spatial
619 resolution of the images, or it can be an indicator that pores are filled with cement and the cement is
620 difficult to distinguish from the grains, or a bit of both. A few rounded objects visible in the RMI
621 images of Chinchimane are in the coarse to very coarse sand range, roughly 700–1100 μm in size;
622 these might be sand grains and might indicate that the rock consists largely of coarse to very coarse
623 sands. Pitting at the scale of ~ 500 μm to several mm can be also seen where the layering is indistinct;
624 the scale of these pits is consistent with the tentative identification of grains. A light-toned fracture or
625 vein cross cuts some of the layers along the right side of the Mastcam-100 image.

626 One layered sandstone cobble, explored via MAHLI from a distance of ~ 1 m, is an angular slab
627 (“angular sandstone” in Fig. 9b) oriented such that the bedding points approximately skyward (Fig.
628 15); its ~ 700 μm grain-scale-thickness bedding includes a much finer-grained, light-toned, ~ 1 cm-
629 thick recessive stratum. Nothing quite like the stone in Fig. 15 has been observed in an intact outcrop
630 during the rover’s explorations in Gale to date.

631 **Nodular sandstone boulders and cobbles.** Some of the sandstone boulders and cobbles at Bimbe
632 display surfaces of many strongly protrusive sand-sized grains, concretions, or both. Some of them
633 are light gray or white; most are darker shades of gray. Two ChemCam targets, Auchab and Canico,
634 provide good examples. At millimeter to centimeter scale, they both have rough textures with
635 protrusive objects of approximately 500–2000 μm size (Fig. 13b, c and 16a, b). Of the two, Auchab
636 contains the highest density of these objects, which appear to cover nearly 50% of its surface.

637 3.3.3.2. Conglomerate Boulders and Cobbles

638 Some of the boulders and cobbles at Bimbe are conglomerates; that is, they are boulder-sized and
639 cobble-sized fragments of conglomeratic bedrock. A conglomerate is a clastic sedimentary rock that
640 consists of $> 10\%$ clasts coarser than sand size. Conglomerates are distinguished from breccias
641 because their coarse clasts are mostly sub-rounded to rounded, whereas breccia clasts are generally
642 angular to sub-angular. The larger examples of conglomerates examined via Curiosity at Bimbe are
643 associated with the low ridge that marks the southern boundary of Bimbe. Generally, they are gray
644 and contain gray pebble clasts in a gray sandy matrix (Fig. 17). The pebble clasts have a range of
645 shapes, from angular to sub-rounded and lower to higher sphericities. Some of the boulders are
646 weakly stratified (Fig. 17a), supporting the interpretation that they are fluvial conglomerates. A few
647 boulders contain cross-cutting veins (Fig. 17b), indicative of fracturing and fluid flow at a time when
648 the conglomerates were still part of an intact rock unit or units at some depth below the Martian
649 surface. Some of these conglomerate stones lie on the surface; others protrude from the regolith. In

650 some cases, a litter of pebbles, liberated from the conglomeratic stones, lies on the ground in the
651 immediate vicinity (e.g., lower left of Fig. 17b). Attributes of four specific conglomerate boulders at
652 the sols 1405–1410 field site were examined in some detail using ChemCam (three boulders) plus
653 MAHLI and APXS (one boulder).

654 One of the conglomerate boulders at the sols 1405–1410 location was the site of four ChemCam
655 targets, Bungo, Seeheim, Wilhelmstal, and Cabamba (Fig. 18). The leftmost target, Seeheim, exhibits
656 pebble clasts that protrude somewhat more than in other areas of the boulder surface, perhaps a result
657 of greater eolian weathering. ChemCam LIBS observation points 1 and 2 at Seeheim hit a specific
658 clast, while the remaining points hit other materials—two hit individual clasts, two hit matrix
659 material (Fig. 18b). In the same boulder, the target named Cabamba is a single, angular clast that
660 contains some light-toned, angular sub-clasts or mineral grains (Fig. 18d). Wilhelmstal is a rounded
661 clast that might also have a few light-toned sub-clasts or mineral grains within it (Fig. 18e). After the
662 laser pulses removed dust from Wilhelmstal, it presented a glinting, vitreous luster. The Wilhelmstal
663 pebble also exhibits small, rounded indentations that could be vesicles. We will show in Section 3.4
664 that Cabamba and Wilhelmstal have nearly identical, homogeneous compositions. The fourth target
665 on this conglomeratic boulder, Bungo, consists entirely of sandy matrix, with grains < 500 μm in size
666 (Fig. 18c).

667 A second conglomerate boulder investigated using ChemCam had a singular target, Balombo (Fig.
668 17c). The boulder has a relatively rounded shape, overall, with mostly angular pebbles protruding
669 from its surface. At least two large sockets are present; these might once have held larger clasts. The
670 ChemCam LIBS observation points on Balombo appear to have hit sandy matrix and a few larger (<
671 2 mm) grains.

672 A fine boulder in the rover’s robotic arm workspace (sols 1405-1410), measuring ~50 cm x ~45 cm x
673 ~30 cm, was investigated using the MAHLI and APXS (Figs. 17a and 19). Like the others at Bimbe,
674 it contains mostly gray pebbles of various shapes and sizes set into a gray sandy matrix. These
675 sediments are weakly stratified. It also has recessed features that—where dust cover is minimal—are
676 white. These white objects are of sizes similar to the pebbles and granules in the boulder. MAHLI
677 and APXS were deployed to investigate one of them at a target named Funda. The white feature at
678 Funda is banded (Fig. 19b). The other target investigated in this boulder, using MAHLI and
679 Mastcam, only, is a pebble-sized sandstone fragment (Fig. 19c). This target, Tumba, provides
680 definitive evidence for recycling of sedimentary rock on Mars (Edgett et al., 2018).

681 Mariental (Fig. 20) is distinct from the other conglomeratic boulders because it occurs separate from
682 the Bimbe deposit, an outlier about ~3 m to the immediate north (Fig. 9a). Perhaps this boulder
683 rolled or slid to its present location or it was left behind by a retreating margin of the deposit. The
684 ground under Mariental is not littered with pebbles (Fig. 20a inset). As in some of the other
685 conglomerate boulders at Bimbe, the coarser clasts of Mariental are set in a dark, gray, sandy matrix
686 and some of its gray pebble clasts present a glinting, vitreous luster. In addition, and like the boulder
687 that contains the targets Tumba and Funda, Mariental includes recessed, pebble-sized white features
688 (Fig. 20b) that could be either clasts or void-filling minerals similar to Funda (Fig. 19b).

689 3.3.3.3. Murray-Formation Pebbles and Cobbles, and White Stones

690 Reddish and white stones are present but are the least common of the varieties observed in Mastcam
691 mosaics of eastern Bimbe. Fig. 16a, c shows a couple examples of the reddish stones; none were
692 investigated using the ChemCam, APXS, or MAHLI. They are inferred to be lithic fragments of
693 Murray-formation rocks. Overall, the Murray formation consists largely of mudstones and very fine

694 sand sandstones (e.g., Grotzinger et al., 2015; Rampe et al., 2017; Rivera-Hernandez et al., 2019)
695 with colors ranging from various shades of light gray to a purplish gray to brick-red. Locally, near
696 and up-slope from Bimbe, much of the Murray-formation bedrock is of the brick-red variety, like the
697 stones observed in the Bimbe deposit.

698 Angular white or very light gray pebbles are also observed in the deposit at Bimbe. Some of them are
699 angular and relatively flat (Fig. 16a, c). Experience gleaned from studies of the Stimson formation
700 showed that white “halos” of altered rock surround some fractures in the otherwise dark-gray
701 sandstone (Frydenvang et al., 2017; Yen et al., 2017; Banham et al., 2018). Some of the white or
702 very light gray pebbles and cobbles, like those in Fig. 16c, could be fragments of such altered
703 Stimson formation sandstones. Some of the smaller white pebbles could be fragments of vein
704 material. Essentially all of the white vein materials observed thus far throughout the Curiosity
705 traverse have been calcium sulfate (Nachon et al., 2014, 2017).

706

707 3.4. Bimbe Compositions

708 Compositions are presented here, starting with Bimbe, as it is the only one of the three sites that had
709 enough targets to classify them into groups which can be readily compared with other rocks
710 examined during the mission. As described in Section 3.5, targets at Blackfoot and Brandberg have
711 Murray and Stimson formation compositions.

712 ChemCam performed observations at 125 locations on sixteen Bimbe targets; APXS observed six
713 locations (3 separate targets, one as a raster) on two distinct blocks. The compositions for each
714 ChemCam observation point are given in the Supplementary Material. The mean abundances of the
715 major elements for each ChemCam target are given in Table 1. Standard deviations from the mean of
716 the ChemCam observation points within each target (rasters of 5, 9, or 10 points) are given in Table
717 2. The distance to the target generally does not appear to play a role in the standard deviations, as the
718 most distant target, Auchab, at 5.2 m, has relatively low standard deviations compared to closer
719 targets. Comparison with standard deviations taken from the single-shot spectra (n=25, dust-free)
720 within a given observation point, presented in the Supplementary Material, shows that the variations
721 between points are nearly always larger than the variations between laser shots within an individual
722 point, as would be expected for targets that are heterogeneous on a scale the size of the laser beam
723 (350-550 μm ; Maurice et al., 2012) or larger.

724 Table 3 presents abundances of several trace elements to which ChemCam is sensitive. These are
725 target averages, similar to Tables 1 and 2. In a number of cases for Rb and Sr, one or more points fell
726 below the limits of quantification. In these cases, the mean of the remaining points is given with a
727 “<” sign to indicate the reduction caused by the point with no detection. Standard deviations between
728 observation points of a given target tend to reflect trends in standard deviations of the major elements
729 for the different targets and groups of targets, indicating that, similar to the major elements, the
730 measurement precision is much better than the accuracy, and providing information on the
731 heterogeneity of the targets at the size scale of the laser beam.

732 Table 4 provides abundances and precisions for APXS observations of Bimbe targets Sonneblom,
733 Zambezi, and Funda.

734 Fig. 21 shows relationships among and between the different ChemCam Bimbe targets in terms of
735 major-element abundances. Mean abundances are plotted for all but the conglomerates; individual

736 observation points are plotted for the conglomerates. The conglomerates do not have a homogeneous
737 composition, but instead, scatter significantly. The nodular sandstones (2 targets) also scatter, but are
738 still plotted as means. Each of the other Bimbe groups (massive, vitreous-luster conglomerate clasts,
739 and layered) form loci of points that are circled. All four panels show that the massive, layered, and
740 conglomerate groups are generally distinct and do not overlap each other in overall compositions.

741 3.4.1. Layered Rocks

742 The layered group, consisting of just two targets, Chinchimane and Oranjemund, cluster tightly with
743 the exception of the SiO₂ abundance, where the two targets differ by nearly 4 wt. % (Table 1 and the
744 two yellow dots in Fig. 21). They are characterized by low Si and Al, and relatively high Ti, Mg, and
745 K. Their chemical similarity belies the fact that Chinchimane is clearly layered and Oranjemund only
746 has evidence of grain-scale lamination (Figs. 12, 14). The standard deviations between points in the
747 respective rasters of observations on these two clasts also places them together; they are among the
748 lowest of all of the ChemCam Bimbe targets (Table 2), suggesting that they are fine-grained (e.g.,
749 Rivera-Hernandez et al., 2019). In fact, their standard deviations between observation points are
750 almost within a factor of two of the standard deviations of 25 laser shots within each individual
751 observation point (Supplementary Material). These latter values speak to the homogeneity over the
752 depth of the laser pits. While the pit depths are not generally known, based on laboratory
753 experiments (Wiens et al., 2012; Maurice et al., 2016) they are generally < 150 μm for the 30 laser
754 shots used at each of the observation points reported here, suggesting that the average grain size of
755 these targets may be on the order of a few tens of microns (cf. Rivera-Hernandez et al., 2019).
756 Because of the similarity in composition of these two targets, Oranjemund is classified as “layered
757 sandstone” along with Chinchimane.

758 The mean abundances and standard deviations of all 15 ChemCam observation points on these two
759 layered targets are, for SiO₂, TiO₂, Al₂O₃, FeO_T, MgO, CaO, Na₂O, K₂O: 42.9±2.3, 1.2±0.1, 6.3±0.6,
760 20.1±0.6, 11.5±1.1, 5.2±1.2, 2.1±0.2, 1.0±0.4 wt. %.

761

762 3.4.2. Massive Rocks

763 Inspection of the compositions of the massive targets in Table 1 and Fig. 21 shows that their
764 compositions are quite similar. They have relatively high SiO₂, Na₂O, and FeO_T abundances,
765 moderate CaO, and relatively low MgO. Aluminum is surprisingly low, given the silica and alkali
766 abundances. Although low Al₂O₃ has been seen in Gale crater rocks before (e.g., Stolper et al.,
767 2013), the Al₂O₃/(CaO+Na₂O+K₂O) ratios are even lower in the Bimbe massive targets, as will be
768 discussed in Section 3.6.4. Table 3 shows that the Bimbe massive targets are enriched in Sr (387 to
769 673 ppm mean abundances) and Li (24-34 ppm) relative to the other Bimbe targets. In particular, the
770 lowest Sr abundance of the massive targets (Sonneblom_CCAM, at 387 ppm) is more than double
771 the next highest Sr value (Chinchimane, at 173 ppm; Table 3) among the Bimbe targets. Simple
772 statistical evaluation of the compositions and deviations of the massive targets, from Tables 1 and 2,
773 indicate that they belong together as a compositional group. Specifically, standard deviations of the
774 major-element abundances of the different targets, from Table 1, are significantly less than the means
775 of the standard deviations between observation points within each target, from Table 2, indicating the
776 compositional spread is greater within each target than it is between the different targets for the
777 massive targets.

778 The mean abundances of all 42 ChemCam observation points on massive targets are, for SiO₂, TiO₂,
779 Al₂O₃, FeO_T, MgO, CaO, Na₂O, K₂O: 54.3±6.3, 1.1±0.5, 8.2±3.4, 17.1±3.2, 2.5±1.0, 4.7±3.2,
780 4.6±0.9, 1.1±0.6 wt. %.

781 The Sonneblom and Zambezi APXS targets (Table 4) were on different areas of the same block.
782 They are compositionally similar to one another. Slight differences in composition can be attributed
783 to the varying dust coverage for the two different targets. The Sonneblom target was on the top,
784 dusty surface of the rock, and the Zambezi target was on a darker gray, cleaner, inclined surface (Fig.
785 10a). The increased dust on the Sonneblom surface results in somewhat higher FeO, MgO, CaO,
786 SO₃, Cl, Ni, Zn, and Br concentrations than for the cleaner Zambezi target. Zambezi has relatively
787 high SiO₂, Na₂O, and K₂O concentrations. Al₂O₃, MgO, CaO, SO₃, and Ni contents are relatively
788 low. Comparison of ChemCam compositions with that of APXS (Table 4) for Sonneblom (Fig. 10)--
789 the one target that was analyzed by both instruments--shows similar compositions. All of the major
790 elements observed by APXS are within one standard deviation of the ChemCam compositions except
791 for MgO, Na₂O, and K₂O. The MgO abundance observed by APXS is significantly higher than that
792 of ChemCam, and Na₂O is lower, possibly due to dust. APXS's Zambezi observation appears more
793 dust-free, and its Mg and Na abundances are close to those of ChemCam. An explanation for the
794 substantially higher K₂O observed by APXS at both locations of this block is unknown.

795 3.4.3. Conglomerates

796 Conglomerates show significant compositional scatter in Fig. 21 and Tables 1-3, as expected for a
797 group of cemented clasts from diverse sources, and consistent with previous conglomerates observed
798 by ChemCam LIBS (Williams et al., 2013; Mangold et al., 2016). As mentioned above, two sub-
799 clasts with vitreous lusters were sampled by ChemCam as individual targets within the
800 conglomerates; these are Wilhelmstal and Cabamba. The compositions of these two targets (e.g., Fig.
801 18d, e) are each quite homogeneous (Table 2), and the two targets have similar compositions (Table
802 1 and Fig. 21) for all elements except Mg, where the mean MgO abundances range from 4.9 to 7.2
803 wt. %. For the other elements, the differences between these two targets are generally smaller than
804 the standard deviations within individual targets (Table 2), indicating significant homogeneity among
805 the two. (Note, however, white grains in Fig. 18d, e that may not have been sampled by ChemCam).
806 The source of this apparent vitreous-luster, homogeneous material is not known, but it could be
807 produced by impact melting or partial melting of some of the conglomerate source material, resulting
808 in a relatively homogeneous glass with a composition that is near the mean composition of the more
809 heterogeneous conglomerate.

810 A third target, AEGIS_post_1400a (Fig. 14a, and Supplementary Material), appears to be
811 compositionally similar to the vitreous-luster conglomerate clasts: Its composition is almost identical
812 to that of Wilhelmstal, and also to that of Cabamba with the exception of MgO. This is in spite of
813 having a quite different texture: The AEGIS target is not a conglomerate or part of a conglomerate; it
814 is rough at the sub-millimeter scale and covered by indistinct 5-10 mm diameter lumps (Fig. 11c, d).
815 Some of the protrusions are angular while others are rounded. We will show in Section 3.6.1 that its
816 composition is that of the Stimson formation.

817 Among the ChemCam conglomerate targets, Bungo (Fig. 18c) shows the lowest heterogeneity
818 between points (Table 2), besides the vitreous-luster ones. It also has the highest FeO_T and lowest Al
819 and alkalis (Table 1). The RMI image (Fig. 18c) shows no observable clasts in the targeted region.
820 So a possibility is that Bungo's composition represents matrix material. Bungo's composition is
821 somewhat different from the vitreous-luster conglomerate clasts in that it has lower Al and alkalis

822 and higher Mg, although the standard deviations of Bungo and the vitreous-luster conglomerate
823 clasts overlap (Tables 1-2).

824 Table 2 shows that, except for Bungo and the vitreous-luster conglomerate clasts, the standard
825 deviations within each individual conglomerate target are large, at least for Si, Al, Fe, Ca, and the
826 alkalis. This might be expected, as the individual clasts within the conglomerates appear dissimilar.
827 Thus the compositional variation agrees with the visual inspection, suggesting that these
828 conglomerates contain clasts from a range of different host rocks. Seeheim (shown in Fig. 18b) in
829 particular has high standard deviations (Table 2) due to several observation points apparently hitting
830 nearly pure feldspars, with alkali totals in the 6-9 wt. % range (Supplemental Material). As noted
831 above, nearly every point hit a different clast within the conglomerate.

832 The mean abundances of all 44 ChemCam observation points on conglomerates are, for SiO₂, TiO₂,
833 Al₂O₃, FeO_T, MgO, CaO, Na₂O, K₂O: 45.9±5.3, 1.0±0.1, 11.1±2.6, 18.4±3.2, 6.4±2.0, 6.4±2.4,
834 3.3±1.0, 0.5±0.5 wt. %.

835 The compositions of individual ChemCam observation points of the conglomerates revealed other
836 details of the chemistry, including a fluorine-rich point. This is described briefly in the
837 Supplementary Material section 5.

838 Embedded in a conglomerate, the banded clast Funda and the surrounding matrix and clasts (Fig.
839 19a, b) were analyzed only by APXS. Funda raster-spot 3 had a significant proportion of the APXS
840 field of view filled with the white clast, and the chemical data (Table 4) suggest that it consists of
841 calcium sulfate. Funda could be either a mineral fill in a former void, or it could be a calcium sulfate
842 clast liberated from a previous rock and deposited with the sands and pebbles observed in the
843 boulder. The remaining APXS raster spots do not have appreciable calcium sulfate, but reveal
844 appreciable MgO, CaO and Na₂O contents and relatively low K₂O concentrations.

845 3.4.4. Nodular Sandstones

846 Targets Auchab and Canico are classified as nodular or coarse sandstone based on their textures
847 (Figs. 13, 16). These two targets were found at different locations, both separated from the main
848 group of Bimbe targets (Fig. 6b), and Auchab having been observed at a relatively long distance of
849 5.2 m. The two appear to differ in their FeO_T and K₂O abundances (Table 1), with Auchab being
850 higher in the latter and Canico higher in FeO_T. However, the standard deviations of the points (Table
851 2) are relatively high, so that the Fe difference is not significant in terms of the overall rock
852 composition. ChemCam's K₂O abundances have been observed to be higher for targets at distances >
853 3.5 m; Auchab is in the >95th percentile in terms of target distance (Maurice et al., 2016), so the K₂O
854 difference is not likely significant.

855 To investigate briefly the chemical make-up of the nodules, we look at the compositions of the
856 individual points (Supplementary Material). From the Canico data, Fe is anti-correlated with Si, Al,
857 Ca, and Na; it is uncorrelated with Mg, and Fe is positively correlated with Ti ($R^2 = 0.73$).
858 Qualitatively it is also positively correlated with Mn, although the Mn results are not elaborated
859 further in this paper. Auchab, at more than twice the distance from ChemCam, generally shows the
860 same trends, but with greater scatter. The images (Figs. 13, 16) show that Auchab has a far higher
861 density of coarse nodules. The generally higher Fe abundance of Auchab (Table 1) might suggest
862 that the nodules are high in Fe and Ti, although it is difficult to make any stronger inferences from
863 this limited data set.

864 The mean abundances of all 10 ChemCam observation points on these two nodular sandstone targets
865 are, for SiO₂, TiO₂, Al₂O₃, FeO_T, MgO, CaO, Na₂O, K₂O: 42.9±4.4, 0.9±0.1, 10.7±3.2, 24.1±4.9,
866 6.1±2.1, 5.1±1.1, 3.3±1.0, 1.3±0.7 wt. %.

867 Mariental's sedimentology (Fig. 20) was noted to be different from other conglomerates targeted by
868 ChemCam, and its chemistry differs somewhat as well. Mariental's CaO abundance is higher than
869 any of the conglomerates and massive float rocks. Mariental's silica abundance is in between that of
870 the conglomerates and the massive targets. Its composition is more iron-poor than the conglomerates
871 (Table 1), and it lies within the relatively tight FeO_T range of the massive floats. Its MgO is
872 relatively low compared to the conglomerates, but definitely higher than the massive floats.
873 Mariental is also distinguished by the highest Al₂O₃ of any of the Bimbe clasts analyzed by
874 ChemCam. From these differences we might conclude that Mariental differs in origin from the more
875 bedded conglomerates at this Bimbe location.

876

877 3.5. Blackfoot and Brandberg Compositions

878 Compositional data from Blackfoot and Brandberg are sparse. Of the few targets observed by
879 ChemCam, most either clearly belong to the Murray or Stimson formations or else they were at
880 relatively long distances ~4.5 meters which, as discussed above, is near the limit of where the
881 calibration can be trusted. At the edge of Brandberg, targets Roter Kamm and Hoba (Fig. 5b) are
882 identical in composition to Murray bedrock (Supplementary Material), although Hoba lies within the
883 Brandberg unit. Target Gibeon (Fig. 5c) was shot at longer distance and because the autofocus was
884 made along a receding edge of the rock, the observation points were mostly out of focus. This dark-
885 gray float rock appears to have dark nodules protruding on its right side. Observation point 3 hit a
886 dark patch and shows a strongly enriched FeO_T content. This observation might classify this rock
887 with the Bimbe nodular sandstones, although more details on the composition are lacking.

888 At Blackfoot, the ChemCam targets at reasonable observing distances included Sunburst, Jefferson,
889 and Lincoln (Tables 1, 2, 3; Fig. 2a, 3a, b, e), observed on sols 1100 and 1102. Of these, Sunburst
890 corresponds to a relatively rare group of Stimson formation targets referred to as Cluster 1 by
891 Bedford et al. (2020). It has high MgO, like the Bimbe and Bradbury layered targets, but its K₂O is
892 much lower, averaging 0.2 wt. % compared to 1 wt. % for the other layered targets. Additionally,
893 Sunburst shows no detectable Rb, and its Sr is nominally less than two thirds of the Sr abundances of
894 Chinchimane and Oranjemund (Table 3).

895 Jefferson (shown in Supplementary Material) is the only ChemCam-sampled example of the
896 enigmatic flat-topped boulders (such as the ones that appear light-toned from orbit, e.g., Fig. 2c). Its
897 composition bears some similarities to Sunburst, both having relatively low SiO₂ (Table 1).
898 However, considering all of the layered clasts, both at Bimbe and (possibly) Sunburst at Blackfoot,
899 Jefferson is an outlier in most of the major elements. It has higher Al₂O₃ and Na₂O, and lower MgO
900 and K₂O, though as noted above Sunburst has even lower K₂O (Table 1). Additionally, Table 2
901 shows that Jefferson has greater variance among its ten observation points. This is especially true for
902 Al₂O₃ and MgO, where the standard deviations are several times higher than those of the layered
903 sandstone targets. The higher standard deviations suggest that Jefferson has a larger grain size than
904 the other layered sandstone targets.

905 Lincoln's (shown in Supplementary Material) composition is somewhat similar to Jefferson's but the
906 differences are in a direction away from those of the layered targets. It has a slightly more felsic
907 composition (higher Si, Al, and alkalis, and lower Mg; Table 1).

908 The target Madison (Fig. 3e) was observed at a distance of 4.5 m; four of the five points were on Ca-
909 sulfate material adhering to the side of the rock. The one point that appeared to hit the relatively dark
910 gray rock itself has a felsic composition with 55 wt. % SiO₂, 17 wt. % Al₂O₃, 4.6 wt. % Na₂O, and
911 2.2 wt. % K₂O, along with moderate FeO_T. This would place it near the Bimbe massive-rock
912 composition except the Al₂O₃ and K₂O are both way too high for the Bimbe Massive group.
913 Additionally, Madison's Sr abundance is near zero, below the RMS error of 85 ppm, far below the
914 mean Sr abundance for the Bimbe massive targets (Table 3), suggesting more strongly that Madison
915 is different from the Bimbe massive targets. Another target, Swan (shown in Supplementary
916 Material) was observed by ChemCam on the Blackfoot unit, but its composition is identical to that of
917 Stimson bedrock. The one APXS target within the Blackfoot deposit, Badlands, has an average
918 Mars-like composition, similar to many Stimson formation APXS targets, but with elevated K₂O and
919 Na₂O.

920 We conclude that a number of Brandberg and Blackfoot ChemCam targets have compositions
921 synonymous with Murray and Stimson formation rocks, while several targets, including Jefferson,
922 Lincoln, and Madison, and the APXS target Badlands, do not clearly match any other compositions.

923

924 3.6. Compositional Comparisons to Other Gale Clasts

925 The Bimbe sediments appear to be overlying the eroded surface cutting across strata of the Murray
926 formation, and they are within a couple hundred meters of Stimson formation outcrops. Fig. 21
927 shows that none of the targets observed using ChemCam are close in composition to that of the
928 Murray formation; the same is true for the APXS targets (although, as noted in Section 3.3.3.3, based
929 on appearances in the images, there are cobbles and pebbles at Bimbe which are likely derived from
930 the Murray formation). The Murray targets taken for comparison in Fig. 21 are from Hartmanns
931 Valley, located near the Bimbe unit (Supplementary Material, Section 3). Murray compositions
932 varied somewhat across the ~350 m of vertical elevation between the lowest and the highest portions
933 of the Murray formation investigated to date. A significant change was the reduction in CaO as the
934 rover ascended higher in the Murray formation (e.g., Mangold et al., 2019). However, CaO is not
935 critical to distinguishing between groups of Bimbe targets or establishing a connection to Murray
936 materials. Overall, comparisons with other targets observed during the mission suggest some specific
937 similarities for the conglomerates and the layered targets, which we discuss in turn below.

938 3.6.1. Conglomerates

939 Here we compare the Bimbe conglomerates to those observed earlier in the mission. We limit this
940 discussion to ChemCam observations. Mangold et al. (2016) compiled the compositions from 197
941 observation points on conglomerates encountered early in the mission on Bradbury rise prior to Sol
942 540; these were called "Darwin type" in their paper. The same work characterized a number of
943 conglomerates from between sols 540 and 670 in the vicinity of the Kimberley waypoint (Fig. 1).
944 These have distinctly different compositions, being alkali-rich with Na₂O/K₂O < 2.0. The mean
945 value (not shown) of all 40 Bimbe conglomerate and nodular sandstone observation points is
946 nominally lower in Al₂O₃, Na₂O, and K₂O (11.3, 3.3, and 0.7 wt. %, respectively) and substantially
947 higher in MgO (6.3 wt. %) relative to both Bradbury and Kimberley conglomerates (Fig. 21).

948 Further, the Bimbe conglomerate compositions do not appear to lie along any kind of mixing trend
949 that would relate them to the other two types of conglomerates. This is especially apparent with the
950 alkali elements (Fig. 21 b), where a trend through Kimberley and extending through Bradbury
951 conglomerates with lower K₂O would require higher Na₂O for Bimbe, but Bimbe conglomerates
952 instead have substantially lower Na₂O. One might consider, very generally speaking, that Bimbe
953 conglomerates are basaltic, close in composition to a Mars crust average (see details in Mangold et
954 al., 2016), and on a trend between soil composition toward the mafic end, and Bradbury
955 conglomerates toward the felsic end.

956 Geographically, the Bimbe unit is closer in distance to Kimberley than to the Bradbury
957 conglomerates encountered near the beginning of the mission. The Bimbe conglomerate
958 compositions are in some respects closer to the average composition of Kimberley conglomerates for
959 most elements, including SiO₂ (45.2 wt. %), Al₂O₃, MgO, and Na₂O. However, K₂O and, to some
960 extent FeO_T, spoil this potential relationship. At Kimberley, observations of sediment targets showed
961 high K₂O abundances (Le Deit et al., 2016; Thompson et al., 2016), as high as 5.7 wt. % (Le Deit et
962 al., 2016) with individual observation points showing even higher values, while the CheMin team
963 reported a high proportion of the mineral sanidine (28% of crystalline material), which is inferred to
964 be the carrier of the potassium (Treiman et al., 2016).

965 Overall, Bimbe conglomerates match far better with Stimson formation composition than any other
966 possibility. Fig. 21 shows the Stimson formation targets observed by ChemCam using density
967 contours based on > 300 ChemCam observation points in the Stimson formation (Supplementary
968 Material). The ensemble of Stimson compositions could be described as slightly bimodal, with trends
969 in the direction of more felsic or mafic compositions. The mafic end is anchored to some degree by
970 the composition of modern-day soil (Fig. 21). This generalization does not fit entirely, as Stimson
971 contours trend toward somewhat higher Fe and Mg than soil, even if the description fits for Si, Al,
972 Na, and K. For some of the plots in Fig. 21, the Stimson contours and the conglomerate scatter
973 pattern appear to match well (for example, CaO vs. MgO in panel c, and Na₂O vs. K₂O in panel b),
974 while some of the conglomerate points are low for Al₂O₃ and SiO₂ (panels a and d, respectively). By
975 comparison, the targets classified as vitreous conglomerate clasts plot close to the densest part of the
976 Stimson contour pattern in almost every case.

977 An equivalence test was run to compare the Bimbe conglomerates and Stimson compositions, as
978 described in the Supplementary Material. While the match appears relatively close in some panels of
979 Fig. 21 and in boxplots in the Supplementary Material, the test passes for generally mafic elements
980 (Ti, Fe, Mg, Ca) plus K, but fails for alkali felsic elements (Si, Al, Na). With this result we cannot
981 say that the two groups are clearly equivalent, but they could have the same sources, for example, if
982 the conglomerates picked up a small amount of additional felsic material.

983 3.6.2. Nodular Sandstone

984 Regarding nodular targets Auchab and Canico (Figs. 13, 16), some areas of the Stimson formation
985 are dense with concretions (e.g., Banham et al., 2018). The first concretion-rich sandstone of Stimson
986 composition was encountered at Upheaval Dome, roughly 100 meters north of Pahrump Hills (Fig.
987 1) in an outcrop that also contained some conglomerates (Williams et al., 2018). Overall, the Stimson
988 concretions do not show much deviation from bulk rock composition but for FeO_T there are a
989 number of extreme outliers to high FeO_T concentrations, particularly in the Naukluft locality (see the
990 boxplot in the Supplementary Material; Bedford, 2019; Bedford et al., 2020). These concretions may
991 relate to preferential cementation of the sandstone. If this is true, the sandstone in the Stimson

992 formation could be predominately cemented by iron oxides that formed from olivine diagenesis
993 when Stimson was buried (Yen et al., 2017; Hausrath et al., 2018). Thus if Bimbe's nodular
994 sandstones are derived from Stimson then it would be possible that they could have Fe-rich
995 concretions based on what has been analyzed and interpreted for the concretions at Emerson and
996 Naukluft plateaus (Fig. 1). If these features do not distort any sedimentary structures (like
997 laminations) then they are more likely to be concretions, which would support this hypothesis.

998 3.6.3. Layered Rocks

999 Another apparent match occurs with the Bimbe layered sandstone group (Chinchimane and
1000 Oranjemund). Mangold et al. (2015) noted that a number of float rocks observed near the edge of
1001 Bradbury Rise (Fig. 22a, b)--both before the rover entered Yellowknife Bay and after it exited--form
1002 a compositionally and morphologically distinct group. The best known of these Bradbury layered
1003 rocks is Bathurst Inlet (Figs. 1, 22a), which was observed by Mastcam, MAHLI, APXS, and
1004 ChemCam on Sol 55 (e.g., Schmidt et al., 2014; Mangold et al., 2015). Other Bradbury layered
1005 sandstones of this class and in this area were chemically analyzed only by ChemCam (Mangold et
1006 al., 2015). The re-calibrated abundances of all 109 reported ChemCam observation points on these
1007 float rocks are given in the supplementary material of Clegg et al. (2017). The mean compositions
1008 and standard deviations are plotted in Fig. 21. The match is relatively good in that the mean
1009 compositions of the two Bimbe layered targets are generally within the standard deviations even if
1010 they are not coincident with the mean Bradbury composition. The largest exceptions are
1011 Chinchimane's SiO₂ and Al₂O₃ abundances, both of which are low by a little more than the standard
1012 deviation of the Bradbury Layered group (Fig. 21).

1013 Fig. 23 shows ChemCam relative reflectance spectra of representative members of the Bimbe layered
1014 and nodular rock classes compared to members of the Bradbury layered rocks. Both exhibit flat to
1015 negative spectral slopes in the near-infrared. The Bimbe rocks Chinchimane and Auchab have peak
1016 reflectance positions near 600 nm, whereas all the Bradbury rocks exhibit longer wavelength peak
1017 reflectances (650-675 nm). This may indicate that the Bradbury layered rocks include lower-calcium
1018 pyroxenes and/or less olivine than the Bimbe rocks.

1019 The equivalence test was also run on these two layered groups (Supplementary Material). The groups
1020 fail the equivalence test for a number of elements (Ti, Al, Fe, Ca, and K), so while their
1021 compositions appear similar in Fig. 21 and in boxplots (Supplementary Material Section 3), and they
1022 are unique in their Mg abundances, we definitely cannot say they are equivalent. However, caution
1023 should be exercised with conclusions of this equivalence test due to the small number of Bimbe
1024 points (10), which is well below the recommended number of samples per group for this test.

1025 At least one other ChemCam target along the traverse appears to have a close chemical relationship
1026 to the Bradbury and Bimbe layered compositions. It is Pyramid Hills (Sol 692; Fig. 22f), with SiO₂ =
1027 42.0, TiO₂ = 1.1, Al₂O₃ = 5.6, FeO_T = 19.4, MgO = 10.8, CaO = 5.0, Na₂O = 2.1, K₂O = 1.0 wt. %
1028 (Fig. 21). The standard deviations between points are also small, like the Bimbe layered targets
1029 (Table 2), and its morphology appears to fit this class as well. The Pyramid Hills rock face was in
1030 shadow, so its passive spectrum cannot be compared. A couple of other ChemCam targets in the area
1031 near Pyramid Hills (Fig. 1) may also be related. The significance of this match is discussed in
1032 Section 4.1.1.

3.6.4. Massive Rocks

The dark-toned massive float rocks of the Bimbe unit look most like some of the dark rocks observed at a topographic high named Twin Cairns Island (Sol 343; Fig. 1) approximately 0.5 km from Yellowknife Bay (e.g., Wiens et al., 2017). ChemCam targets there consisted of Black Trout, Bull Arm, and Mallard Lake (all observed on Sol 349; Fig. 1, 22c, and Supplementary Material). Float rocks there and at Bimbe also bear a resemblance to the wind-eroded fine boulder named Jake_M (Figs. 1, 22d), observed by Mastcam, ChemCam, APXS, and MAHLI in the first 100 sols of the mission (Stolper et al., 2013). Jake_M's composition falls within the range of the three targets from the Twin Cairns Island topographic high. The mean composition and standard deviation of the 33 ChemCam observation points on these Bradbury rise float rocks, including Jake_M, is plotted in each of the panels of Fig. 21 and labeled "Bradbury Massive". It is apparent that the standard deviations are large for this group of targets, a feature that was already noted for Jake_M in Stolper et al. (2013); it was found to be quite heterogeneous even at the scale of the APXS footprint. Comparison of the Bimbe massive and vitreous conglomerate targets with the Bradbury massive composition shows that the Bradbury compositions appear to overlap the massive group in several respects, but the two are quite distinct in Al abundance, where the nominal Bradbury Al_2O_3 is ~17 wt. %, while all of the Bimbe massive targets are below 10 wt. %. Additionally, Bradbury massive targets are much lower in trace elements Li, Rb, and Sr. For example, the mean Sr abundance of the 33 points on the Bradbury massive targets is <200 ppm compared to a mean Sr abundance of 479 ppm in the Bimbe massive targets. Thus, the Bimbe massive targets, as seen by ChemCam, do not have the same compositions as, or similar compositions to, most of the massive targets on Bradbury rise. These two groups fail the equivalence test for all major elements but Mg (Supplementary Material Section 4).

The APXS analyses of the Sonneblom/Zambezi boulder do, however, indicate a compositional similarity between this rock and an alkaline float rock, Oscar, analyzed by APXS on Bradbury Rise (Sol 516; Fig. 22e). Curiosity encountered a concentration of erosion-resistant, dark-toned float rocks on Bradbury rise between sols 503 and 526, and APXS analyzed nine of these, all of which are alkaline in composition. Other alkaline float rocks interrogated by APXS on Bradbury rise include the targets Jake_M (Fig. 22e) and Monkey Yard (Fig. 1). All the alkaline float rocks analyzed by APXS exhibit similar elemental trends: elevated Na_2O , SiO_2 and K_2O , and depleted MgO , Cr_2O_3 , MnO , FeO_T and Ni relative to average Mars. However, Oscar and Zambezi have higher SiO_2 and FeO_T , and significantly lower Al_2O_3 and CaO concentrations than the other alkaline float rocks. They are also somewhat depleted in Na_2O , MgO , Cr_2O_3 and Zn relative to the other alkaline float rocks.

3.6.5. Blackfoot and Brandberg

Of the Blackfoot and Brandberg targets, Lincoln (shown in Supplementary Material) appears to be a reasonable match to Stimson formation compositions. For the single observation point on Madison, its composition lies relatively close to the Bradbury massive targets for several elements (Table 1), but the Bradbury massive targets have much higher CaO , and at least one Bradbury massive target contained Ca-rich pyroxene (supplementary material of Stolper et al., 2013). The one Brandberg ChemCam target, Hoba, looks like Murray formation in terms of composition and petrography; its composition fits well for the Murray formation except for somewhat high K, which is due to the observation distance (see comment in Section 3.4.4).

APXS observed one Blackfoot target, Badlands, on Sol 1102 (Fig. 3f). Its composition is given in Table 4, and is overall relatively similar to Stimson formation rocks except for higher K and Na

1078 abundances. As such, it is considered to be of the Bell Island class, with somewhat lower K₂O than
1079 Bathurst Inlet (Fig. 1), a layered float clast observed by APXS at Bradbury Rise (Schmidt et al.,
1080 2014).

1081

1082 4. DISCUSSION

1083 4.1. Compositional Relationships to Other Gale Rocks and Outcrops: Possible Implications

1084 4.1.1. Bimbe Layered Rock Similarity to Bradbury Layered Rocks

1085 The compositional similarity between the layered Bimbe targets and the layered Bradbury targets
1086 (Schmidt et al., 2014; Mangold et al., 2015) was noted above. Here we note their textural similarity.
1087 Only one Bimbe ChemCam target, Chinchimane, exhibits clear layering, while another target,
1088 Oranjemund, is compositionally very similar but only displays grain-scale laminations. Inspection of
1089 the rocks in Bradbury rise shows that the compositionally similar targets there exhibit both layering
1090 and no apparent layering. This is seen most clearly in Fig. 22a, where clasts at the lower right of the
1091 image are obviously layered but clasts from the same unit at the upper left, including APXS,
1092 MAHLI, and ChemCam target Bathurst Inlet (Fig. 1), are not obviously layered. This is consistent
1093 with the layered and non-layered Bimbe clasts with similar composition being related to each other;
1094 their morphological variations may suggest various levels of cementation. Additionally, Fig. 22b
1095 shows a Bradbury layered clast that is cross bedded.

1096 The Bradbury clasts in Fig. 22a (Bathurst Inlet and surrounding clasts), while not connected as a
1097 single outcrop, appear to form a distinct unit relative to the surrounding gravelly surface material.
1098 The same feature appears to occur at the location of Pyramid Hills (Fig. 22f), where the ground
1099 appears to be covered with similar clasts. ChemCam observed two other targets--Johnnie and South
1100 Park2--that may belong to the same family (see their compositions and images in the Supplementary
1101 Materials). In this location and at Bathurst Inlet near Yellowknife Bay the rocks appear to be broken
1102 fragments of an intact rock unit.

1103 The layered clasts in Bimbe (Sol 1401), Pyramid Hills (Sol 692), and Bathurst Inlet (Sol 55; Fig. 1)
1104 are not time-equivalent, given the significant difference in elevation (~100 m). Assuming that they
1105 are related, one possibility is that the rocks at Bimbe were sourced from a stratum or strata that
1106 was/were younger and located at a higher elevation than Bradbury rise, but have since eroded away
1107 completely. This stratum or strata that sourced the Bimbe rocks may have shared a similar
1108 provenance and depositional setting and process as the Bradbury layered targets.

1109 Another possibility is that the layered rocks in Bimbe were deposited from the same source and at
1110 the same time as the Bradbury layered material. Considering the bedded nature of the material
1111 surrounding Bathurst Inlet on Bradbury rise (Fig. 1, 22a), this would require an unconformable unit
1112 that draped across the elevation difference between Bimbe and this portion of Bradbury rise,
1113 somewhat like the Stimson formation drapes over the Murray formation (Banham et al., 2018).
1114 Indeed these rocks could have been strata that were slightly younger than and overlaid the Stimson
1115 formation. Several factors lend credence to this idea. The first is that, based on ChemCam
1116 observations, the composition of bedded sandstones on Bradbury Rise, for example, at the Darwin
1117 and Cooperstown waypoints (Fig. 1), is nearly the same as those of the Stimson formation (Bedford,
1118 2019; Bedford et al., 2020), suggesting that the Stimson formation may have extended farther from
1119 Mt. Sharp than the observable portion of the Murray formation (see Williams et al., 2018). This has
1120 implications for the timing of the deposition of rocks exposed on Bradbury Rise that is not discussed

1121 here. Secondly, the fact that the Stimson formation is already found to drape unconformably over the
1122 Murray formation lends some credence to the idea of additional stratigraphically higher draping rock
1123 units. In this scenario, the draping formation that produced the Bradbury and Bimbe layered clasts
1124 would have almost completely eroded away, leaving only the rocks at Bathurst Inlet, some scattered
1125 layered clasts nearby (other layered float rocks in Mangold et al., 2015), the rocks at Pyramid Hills,
1126 and scattered layered clasts in another area having conditions that permitted long preservation,
1127 namely in the Bimbe unit.

1128 4.1.2. Bimbe Massive Sandstones and Relationships to Other Clasts along the 1129 Traverse

1130 As described above, the Bimbe massive sandstones are not the same composition as most of their
1131 float-rock counterparts on Bradbury rise. The massive targets have been enigmatic ever since they
1132 were first reported (e.g., Stolper et al., 2013; Schmidt et al., 2014). Their compositions are consistent
1133 with a low degree of chemical alteration, but their textures are not igneous, appearing sedimentary
1134 instead. Massive Bimbe float rocks display some faint layering as well as apparent spherical grains
1135 (lower left portion of Seeis, Fig. 11b). Similar to Jake_M on Bradbury rise (Fig. 22d), Seeis appears
1136 heavily wind scoured (Fig. 11), and the other Bimbe massive targets also show significant wind
1137 abrasion, suggesting that these clasts are very well cemented, if sedimentary in origin.

1138 Besides Bradbury rise and the heterolithic units, there is one other location along the traverse, named
1139 Bressay (Fig. 1; studied on sols 2013-2023), where massive float rocks of similar appearance were
1140 studied. While it is beyond the scope of this work to describe Bressay, it is important to note that the
1141 portion it and its clasts that were explored by Curiosity are very different from the three heterolithic
1142 units described here. The areal extent of the Bressay deposit explored by Curiosity is far smaller,
1143 with most of the clasts within just one meter of each other and a few other float rocks scattered a few
1144 meters away, although a larger extent to Bressay was imaged (Williams et al., 2020). The Bressay
1145 clasts investigated by Curiosity, all of which are smaller than boulders, include conglomerates,
1146 massive sandstones, and compositionally unique ones, including at least one apparent igneous clast
1147 (Bridges et al., 2019). The composition of the massive clasts do not match those in Bimbe, but
1148 instead appear to be close to those at Bradbury Rise. The compositions of the other clasts also do not
1149 match those in Bimbe. In summary, the Bressay clasts that were investigated appear unrelated to
1150 those of Bimbe, and based on size and appearance, are also unrelated to those of Brandberg and
1151 Blackfoot.

1152 4.1.3. Conglomerates with Compositions Similar to Stimson, and Implications

1153 The compositional similarity of the Bimbe conglomerates to the range of Stimson compositions (Fig.
1154 21) is significant. As noted earlier, vitreous-luster clasts (sampled by targets Wilhelmstal and
1155 Cabamba) in conglomerates are fine-grained (as observed by ChemCam standard deviations of
1156 points), and compositionally they are located near the center of the locus of Stimson compositions.
1157 Other ChemCam observation points on conglomerates have larger ranges of compositions, but
1158 generally still fall within the Stimson contours, although the two groups fail the equivalence test for
1159 Si, Al, and Na. The ChemCam observations of the Stimson formation exhibit a range of
1160 compositions. As described by Bedford (2019) and Bedford et al. (2020) there are clear felsic to
1161 mafic trends among compositions observed in the Stimson formation. These are consistent with
1162 Curiosity observations of Bagnold dunes, where grain segregation is apparent (e.g., Cousin et al.,
1163 2017b; Ehlmann et al., 2017; Johnson et al., 2017; O'Connell-Cooper et al., 2017). Stimson

1164 formation is an eolian sandstone (Banham et al., 2018), and so the preservation of compositional
1165 variations reminiscent of grain segregation in contemporary dunes is not surprising.

1166 The similarity in composition between Bimbe conglomerates and Stimson-formation rocks could
1167 imply either that their material comes from a similar or common source, or that the Bimbe
1168 conglomerate clasts are actually broken-up pieces of Stimson-formation sandstones, perhaps with
1169 some felsic clasts added. These two possibilities have quite different implications. A potential
1170 objection to the first possibility is that we do not see any obvious (significant) very local precursor
1171 material for the Bagnold dunes that exist currently (e.g., Ehlmann et al., 2017). If the same is true for
1172 the Stimson formation in spite of the different directions of their sources (Banham et al., 2018;
1173 Bedford, 2019; Bedford et al., 2020), then the observation of angular Stimson-composition pebbles
1174 in the conglomerates might be inconsistent with the lack of a local source. But if the clasts are
1175 broken-up Stimson sandstones, it would imply that the conglomerates were formed in fluvial action
1176 that came much later in time, after the Stimson-precursor dunes were buried and compacted,
1177 lithified, and then exhumed. That possibility, while seeming unlikely, cannot currently be completely
1178 discounted based on our limited data set.

1179 The most likely possibility seems to be that there was in fact fluvial activity that was nearly
1180 contemporaneous with (e.g., either shortly before or after) the deposition of the Stimson eolian
1181 material and that this fluvial activity deposited conglomerates containing pebbles sourced from the
1182 same or similar material to that of the Stimson eolian material. That is consistent with some
1183 outcropping of conglomerates seen earlier, relatively near Stimson material (Williams et al. 2018).
1184 At some later point in time, some conglomerate material was broken up and transported to the
1185 heterolithic units, where it lies as described in this study. The next two sections (4.2 and 4.3) will
1186 discuss this latter step—how the material was transported to the heterolithic units and was apparently
1187 preserved.

1188 4.2 Comparisons of the Three Units: Similarities and Differences

1189 Here we consider all three heterolithic units, and their possible origins. But before going into models
1190 of deposition, we briefly summarize features of the three units, starting with their similarities: 1) the
1191 deposits form thin, isolated but coherent patches; 2) they are composed of unconsolidated pebbles,
1192 cobbles and boulders with varying degrees of roundness; 3) the patches include particles derived
1193 from the Stimson and Murray formations, and from other sources; 4) the deposits unconformably
1194 overlie Murray and (at least in one case) Stimson formation bedrock; 5) the deposits occur on an
1195 eroded landscape, below adjacent local ridges and surrounding buttes, mesas, and plateaus capped by
1196 Stimson formation rocks, and are not immediately adjacent to talus slopes from these local
1197 topographic highs, 6) there are similar boulder-rich patches in the region along the lower slopes of
1198 Mt. Sharp in HiRISE images (Fig. 6a), and 7) those patches are distributed in a band along the lower
1199 elevations of Mt. Sharp on slopes of about 5%.

1200 Differences among the three units are highlighted in Table 5. Blackfoot is the only one of the three
1201 units that physically superposes outcrops of the Stimson formation. The lithologic diversity of
1202 Blackfoot and Bimbe includes conglomeratic boulders and cobbles. Whether conglomerates occur at
1203 Brandberg is uncertain; if they are present, they are small (cobble-sized) and rare. The conglomerates
1204 at Blackfoot and Bimbe may have different lithologies as compared with each other; those at
1205 Blackfoot are small, in a greater state of disintegration, and appear to have better-rounded pebbles
1206 within them. Some of the boulder- and cobble-sized stones at Brandberg are interpretable as Murray-

1207 formation mudstone lithic fragments; some of the cobble-sized stones at Bimbe are also interpreted
1208 as Murray-formation mudstones (though none that were analyzed for chemistry). In both cases, the
1209 mudstone fragments are similar in color and sedimentary texture to the nearby and adjacent intact
1210 Murray-formation outcrops. Blackfoot has no mudstone lithic fragments. Sandstones at all three units
1211 are dark gray and exhibit “massive,” “layered,” and “nodular” morphologies. Only at Blackfoot and
1212 Bimbe are light-gray and white sandstones observed (Figs. 3g, 15b, 16c)—possibly derived from
1213 fracture-associated “halo” areas in the Stimson formation. Only at Brandberg are concretions
1214 liberated from sandstones observed (Fig. 5d); these resemble the concretion forms observed via MSL
1215 cameras on the east side of the Naukluft Plateau (Figs. 5e, f).

1216 A few more differences are as follows: Brandberg exhibits a circular shape and conforms to an
1217 arcuate ridge eroded into the adjacent Murray-formation mudstone (Fig. 4f). Some of the sandstone
1218 boulders and cobbles at Brandberg are slab-shaped, embedded in the deposit like lawn darts, and
1219 dipping steeply toward the center of the unit. Brandberg and Blackfoot are not cratered within their
1220 structures; the south edge of Bimbe is superposed by one, or possibly two, impact crater(s) (Fig. 8).
1221 The outline of Bimbe is irregular and its northeastern-most portion is a ridge. In summary, there are
1222 significant differences among the three heterolithic units visited by Curiosity.

1223 4.3 Origin of the Heterolithic Units

1224 To explore the origin of the heterolithic units, we describe five different process sequences (models)
1225 that could have led to these distinct deposits. We use illustrations (Fig. 24) showing common
1226 elements: Each panel shows three time steps: an initial condition, delivery of the heterolithic
1227 sediment, and subsequent landscape erosion leaving isolated patches of heterolithic units. In every
1228 case, eolian abrasion causes erosion and deflation at variable rates around these units. In each
1229 illustration, the gray, stippled bedrock layer represents the Stimson formation which overlies the
1230 Murray formation (white with lines representing bedding) across an erosional unconformity. The
1231 subsequent heterolithic unit is indicated in orange. For the first two illustrations (Fig. 24a, b),
1232 dissection of the Stimson and Murray formations occurs simultaneously with the generation of local
1233 heterolithic units. The travel distance of sediments is short, on the scale of the preserved sediment
1234 pile, e.g., on the order of 50 m. In the subsequent three models (Fig. 24c-e), the initial condition is
1235 shown as a partially dissected landscape across lower Mt. Sharp that undergoes a pulse of burial
1236 followed by subsequent erosion which leaves isolated heterolithic units. In these three cases some
1237 sediment may be arriving from > 10 km in the upslope direction, with an elevation drop > 1 km. The
1238 partially dissected initial condition localizes sediment deposition on eroded Murray and Stimson
1239 formation surfaces and exposes these rocks (and the no-longer-present conglomerate bedrock) to
1240 entrainment and incorporation into deposits that become the heterolithic unit.

1241 4.3.1 Model 1: Crater Impact and Fill (Fig. 24a)

1242 Impacts large enough to penetrate through the Stimson formation into the Murray formation at an
1243 earlier point in time (i.e., at a time when there was greater or complete coverage of the Murray
1244 formation by the Stimson formation) could have resulted in local accumulations of residual pebble,
1245 cobble, and boulder deposits. In this case broken rock of the Stimson and Murray formations would
1246 have collected on the floor from ejecta fall-back and subsequent erosional retreat of the crater walls.
1247 Wind erosion could then force retreat and elimination of crater walls and would eventually leave a
1248 coarse lag of material, covering the crater floor, that is more resistant to wind abrasion than the
1249 Murray bedrock. This model could explain the circularity of Brandberg, the arcuate ridge just

1250 outside of the unit (Fig. 4f), and the angular, steeply-dipping “lawn dart” rocks within the unit (Fig.
1251 4d). The nearby clast observed by ChemCam (Hoba; Fig. 5a, b) has a Murray-formation composition
1252 and sedimentary texture, consistent with an expectation of local material falling into a crater. Gibeon
1253 (Fig. 5a, c) may be a remnant clast from the Stimson formation, and the clast in Fig. 5d is definitely
1254 similar to concretions that formed in the Stimson at the nearby Naukluft plateau (Fig. 5e, f). Other
1255 types of clasts may exist in Brandberg (e.g., conglomerates in Fig. 5g), depending on what overlying
1256 layers, above the Stimson formation, may have been present when the crater was formed. An impact
1257 crater of this size in the vicinity of dunes will fill with fine sediment, which may help preserve clasts
1258 from erosion for some period.

1259 An impact origin is more difficult to fit with the overall shapes of Blackfoot and Bimbe, which are
1260 elliptical and irregular, respectively. Blackfoot could have been formed from an oblique impact, but
1261 if so, it does not retain the types of more telltale features seen at Brandberg, especially the
1262 surrounding ridge. Future exploration by the rover of craters excavated in Greenheugh Pediment
1263 (Stimson formation; Fig. 1) may shed light on the ability of craters to explain the heterolithic units.

1264 4.3.2 Model 2: Local Valley Incision (Fig. 24b)

1265 This scenario bifurcates into two pathways, but both begin with valley incision through an erosion-
1266 resistant capping unit (Fig. 24b, first two time steps). The valley widens as scarps retreat. Such
1267 retreat could have occurred when the environment was wet enough to involve cap-rock undermining
1268 by seepage and removal of debris by streams. However, no landforms are present in the current
1269 landscape that would require a role for water in the retreat of these scarps (the same point applies to
1270 Model 1, above).

1271 Progressive scarp retreat in a setting in which there is an erosion-resistant capping unit, like the
1272 Stimson formation, leads to formation of—in order of decreasing planimetric size—plateaus, mesas,
1273 and buttes (e.g., Duszyński et al., 2019). Such landscapes on Earth are usually connected to
1274 tectonism plus stream incision followed by scarp formation and retreat through a combination of
1275 weathering, creep, landslides, overland flow, and groundwater seepage (e.g. Twidale and Milnes,
1276 1983; Howard and Selby, 1994). On Earth, boulders shed from the capstone of retreating cliffs
1277 typically do not extend far from the base of the slope (e.g. Glade et al., 2017). Shedding of material
1278 from, or disintegration of, the Murray buttes and precursors in the vicinity of the heterolithic units
1279 could potentially result in both Murray and Stimson clasts in the heterolithic units. The scarp in Fig.
1280 24b is at least on the order of the height of the Murray buttes, e.g., 7-17 m. The local slopes from the
1281 Murray Buttes to the heterolithic units are not steep (Fig. 6b and supplementary material).

1282 **Shedding of boulders and cobbles from retreating mesa and butte scarps.** One way by which
1283 scarp retreat could create a deposit like Bimbe, Brandberg, or Blackfoot is by the accumulation of
1284 boulders and cobbles shed from the slopes as they fail. In particular, this would lead to an abundance
1285 of the most erosion-resistant rocks, such as the Stimson formation capping unit. If conglomeratic
1286 bodies of rock were present just above, below, or within the otherwise sandstone capping rock unit,
1287 they too, would be incorporated in the accumulation. The problem is that much of the space between
1288 Murray buttes or between the other scarps which expose the Stimson formation in the area is devoid
1289 of such boulders and cobbles. They mainly accumulate on and at the base of the scarp slope. As the
1290 scarps retreat, the destruction of boulders and cobbles apparently keeps pace with that retreat.
1291 Therefore, if this model is to explain the existence of a heterolithic unit such as Bimbe, it would
1292 require the accumulation of boulders and cobbles to be particularly thick, such that while destruction

1293 of boulders and cobbles might keep pace with scarp retreat, originally thicker accumulations of
1294 boulders at these sites has not yet been fully removed. Perhaps in the early stage of development,
1295 blocks accumulated across the valley floor and limited fetch (wind exposure) plus a rough valley
1296 floor reduced wind strength and thus abrasion, but once the mesa retreat was sufficiently wide,
1297 boulders that reached the base of the mesa were eliminated by wind abrasion. This concept could
1298 explain why boulders and cobbles are restricted to the specific heterolithic units where they are
1299 found. The coarse patches of the heterolithic sediment are not connected to the adjacent mesas.

1300 **Decay and death of buttes.** Another pathway to leave behind an accumulation of boulders and
1301 cobbles is through the decay and near-destruction of buttes. In this case, the boulders and cobbles
1302 would have been just barely displaced from their original positions as the capping rock was
1303 undermined and broke apart. The progression toward complete destruction of buttes is illustrated by
1304 Parzoch and Migon (2015) and Migoń et al. (2018). In this case, we would expect the boulders and
1305 cobbles of a given heterolithic unit to be superimposed on a small, remnant hill of Murray formation
1306 bedrock. The ridge at the northeast end of Bimbe, plus the two boulder- and cobble-mantled hills
1307 named Bukalo and Bailundo (Fig. 7) provide examples that such decayed buttes likely do occur in
1308 the landscape around Bimbe. However, the bulk of the area beneath Bimbe is not a low hill that
1309 could be interpreted as a decayed mesa or butte or collection of these (see topographic contours in
1310 Fig. 6).

1311 4.3.3 Model 3: Landscape Burial by Mass Transport of Debris Followed by Extensive 1312 Erosion (Fig. 24c)

1313 Model 3 starts with a partially dissected lower Mt. Sharp landscape representing an area at least 10
1314 km in length. Some features, specifically the heterolithic units, are not drawn to scale. A mass flow,
1315 either a massive landslide, rock glacier or glacier descends from Mt. Sharp and spreads across the
1316 lower slopes, scouring and depositing debris on previously-exposed Murray and Stimson formation
1317 surfaces. Subsequent wind erosion erases the trace of the scar and leaves isolated patches, most
1318 likely preserved for some time in depressions (craters, canyons, fractures). This model could account
1319 for Murray and Stimson clasts in the heterolithic units, as well as other varieties of clasts sourced
1320 from material father up Mt. Sharp. Various authors have proposed that the distinct lobate features on
1321 the middle slopes of Mt. Sharp, 20 km to the east of the Bimbe deposits, record landslides or
1322 glacial/periglacial features formed at a relatively late stage after Mt. Sharp had its present form (e.g.
1323 Anderson and Bell, 2010; Le Deit, et al., 2013; Fairen et al., 2014; García et al., 2016).

1324 A weakness of this model is the lack of evidence of either an upslope landslide scar or an
1325 accumulation zone for the supply to an advancing glacier in the ablation zone. Rocks along the
1326 rover's traverse also lack glacial polish. However, the progressive erosional retreat of Mt. Sharp
1327 could have eliminated such evidence. Sediment sorting shown in Supplementary Fig. 2-4 suggests
1328 that the sediment deposit is not an unsorted matrix-supported mass typical of mass flow deposits, but
1329 is instead similar to fluvial sorting, although the infrequent large boulders call for exceptional
1330 transport ability.

1331 Periglacial (Anderson and Bell, 2010; Le Deit, et al., 2013) and glacial (Fairen, et al., 2014)
1332 processes have been proposed as possibly active in Gale in the past. Glacial moraines are
1333 characterized by poor sorting. The presence of conglomerates at Bimbe and Blackfoot could be
1334 explained from fluvial channels occurring beneath a glacier; the conglomerates would have later
1335 been transported to their current location. Another related possibility is that these units were

1336 deposited in a perennially ice-covered lake (PICL) that formed in Gale crater (not shown in the
1337 Model drawing). On Earth, sediments of varying compositions and sizes can accumulate on the ice
1338 cover of PICLs (e.g., Rivera-Hernandez et al., 2018). For PICLs without liquid water columns (due
1339 to drainage, evaporation or sublimation of the liquid water), laterally discontinuous patches of
1340 sediment (i.e., sediment mounds) form as let-down till from the sublimation of the lake ice (Hendy et
1341 al., 2000; Hall et al., 2006). The sediment mounds consist of very poorly sorted mud to boulder sized
1342 grains. Sediment accumulated on the ice cover of PICLs can be substantial, for example Lake Miers
1343 in Antarctica has sediment piles up to several meters high, ten meters in width, and a couple tens of
1344 meters long (e.g., Bradley and Palmer, 1967). For PICLs abutting calving glaciers, let-down till can
1345 also occur as arcuate debris bands that extend across the former lake floor (Hendy et al., 2000; Hall
1346 et al., 2006). PICLs abutting calving glaciers and with liquid water columns, can also have ice-rafted
1347 poorly sorted sediments accumulate along the lake edge (which is ice-free during the summer) as a
1348 result of the ice cover being pushed towards the lake edge when glacial ice is incorporated into the
1349 lake ice (Hendy et al., 2000; Hall et al., 2006). Geomorphic evidence associated with PICLs abutting
1350 calving glaciers (Hendy et al., 2000; Hall et al., 2006) has not been observed in the vicinity of the
1351 heterolithic deposits either upslope or at the depositional sites.

1352 4.3.4 Model 4: Landscape Burial by Laterally Extensive Fluvial or Debris Flow Fan 1353 Deposits, Followed by Extensive Erosion (Fig. 24d)

1354 This model proposes fluvial (water dominated) or debris flow (mobilized by mud supporting matrix)
1355 transport in which successive flows descend from Mt. Sharp and spread deposits across a broad area,
1356 burying the partially eroded landscape. The heavier black lines are meant to suggest successive
1357 channel pathways common to fan construction. Similar to Model 3 (mass transport), the deposited
1358 material is mostly lost to wind abrasion over time, leaving patches of sediment, most likely preserved
1359 in the original valleys where thicker deposits would have accumulated. Also similar to Model 3, this
1360 model would result in Stimson and Murray clasts as well as other material sourced farther up Mt.
1361 Sharp.

1362 Transport of clasts in stream beds within Gale crater is now widely accepted to have occurred in the
1363 Bradbury rise region. Large amounts of igneous cobbles and pebbles of sizes up to ~ 10 cm were
1364 transported from the crater rim via Peace Vallis (Fig. 1 inset) and other channels (Sautter et al., 2014,
1365 2015, Cousin et al., 2017a). HiRISE observations have also been made of fans deposits overlying the
1366 “washboard unit” (Siccar Point group) in other parts of Gale crater (Milliken et al., 2014). Grain size
1367 analyses reported for the three heterolithic units and shown in Supplementary Fig. 2-4 are similar to
1368 gravel-bed rivers on Earth. Median grain sizes range from 9 to 16 mm. The heterolithic-unit grain
1369 size distributions are influenced by abrasion and weathering breakdown of large particles, partial
1370 burial by sand, and possible lag concentration due to wind erosion. The gravel and boulders are
1371 subangular (Powers visual scale), although ventifact shaping of the surface particles is common and
1372 obscures the original shapes of many of the larger boulders. The limited exposure on the edge of the
1373 deposits do not show matrix-supported clasts (as typifies debris flow deposits).

1374 The prominent boulders that stand out in the heterolithic units are 30 to 40 times larger than the
1375 median size of the units, and thus would probably not be mobile in flows moving the finer gravel
1376 making up most of the deposits. Two explanations are possible for this admixture of very coarse
1377 rocks with finer gravel. The flows could have originated more than 5 km away on the slopes of Mt.
1378 Sharp and swept into previously partially-dissected landscape where talus from retreating mesas
1379 could be locally incorporated in the flows. Boulders may be entrained and then carried a short

1380 distance into the passing flows. Alternatively, the flows may have incorporated sufficient fines to
1381 have densified and transformed into debris flows, which could readily carry such boulders on gentle
1382 slopes in thin flows (e.g. Whipple and Dunne, 1992).

1383 The laterally extensive occurrences of other apparent heterolithic deposits seen from orbit (e.g., one
1384 in Fig. 6a), if indeed these are genetically related to the three heterolithic units studied here, support a
1385 laterally extensive burial of the foot of Mt. Sharp. The description and study of these other units
1386 observed from orbit are beyond the scope of this paper. As mentioned for Model 3, no observations
1387 were made of deposits on the Stimson-capped mesas that would suggest such massive burial.

1388 4.3.5 Model 5: Localized Fluvial or Debris Flow Transport Down Dissected Plains (Fig. 1389 24e)

1390 The primary difference between this model and Model 4 is the proposed extent and thickness of the
1391 depositional field. In this model, localized avenues of runoff and sediment transport extend down a
1392 dissected lower Mt. Sharp landscape. Transport could be fluvial or debris-flow dominated or a
1393 mixture. In this case, the deposits would be initially relatively thin, and confined in valleys. Post-
1394 burial valley-wall retreat and valley-floor dissection by wind abrasion led to the localized, elevated
1395 patches of sediment. Preservation of these coarse deposits may be attributable to exceptionally low
1396 wind abrasion rates (the landscape was already mostly dissected to its current state by earlier longer-
1397 duration eolian abrasion) and the relative strength of the stones in the deposits compared to the
1398 underlying Murray formation.

1399 4.3.6 Discussion

1400 The topographic setting of the Blackfoot, Brandberg, and Bimbe suggests a localized transport and
1401 deposition origin for the deposits. The Bimbe deposit lies in a ~300 m wide, nearly flat-floored
1402 sloping valley (Supplementary Fig. 1-3). Further to the north is a deposit that from HiRISE images
1403 is very similar in appearance (“Bimbe-like surface” in Fig. 6a; Supplementary Fig. 1-3). Over a
1404 ~500 m length, starting up slope of Bimbe and ending with the northern deposit, the valley slope is
1405 about 5% (Supplementary Fig. 1-3). Fluvial gravels, confined in channel banks in river canyons, are
1406 typically coarser than 16 mm on such slopes (e.g. Dietrich et al., 2017), but on fans, these median
1407 grain sizes do occur on such steep slopes (Stock et al., 2007). The current widths of the deposits are
1408 much greater than any likely individual channel. One possible interpretation is that a succession of
1409 flows traveled downslope to this area, spread, shallowed and deposited the sediment, as a fan-like
1410 deposit bordered by mesa walls. A similar argument can be made for Blackfoot, which forms a
1411 diagonal ridge connecting a row of southwest-northeast directed ridges of bedrock bordering its
1412 southern and northern edge (Supplementary Fig. 1-1). It is an erosional remnant with scoured
1413 depressions ~4 m deep to the west and east. It rests on Murray-formation rocks to the south and rises
1414 onto Stimson formation rocks at its southern edge. The Brandberg deposit is the same elevation as
1415 Blackfoot (Supplementary Fig. 1-2). A transport path would have followed a partially etched surface
1416 into the Murray, bordered by Stimson formation capped ridges, some of which were not deeply
1417 incised.

1418 The three investigated deposits lie downslope from Gediz Vallis, associated ridge deposits, and
1419 Greenheugh pediment (Fig. 1; e.g., Bryk et al., 2019). The stratigraphy and apparent coarse texture
1420 of the Gediz Vallis ridge deposit suggest it may be the remnant of a fan of fluvial or debris flow
1421 origin. It is possible that the deposits once extended further downslope and that distal flows may

1422 have travelled the ~ 3 km from here downslope to the Bimbe-Blackfoot locations either during fan
1423 construction or during subsequent erosion. It was at one time a ready supply of sediment, and could
1424 also be a source for lithologic heterogeneity of the sediment during its erosion. This scenario
1425 requires that at least a portion of the Gediz Vallis sedimentation postdated lithification of the
1426 Stimson formation. The flow would have occurred before the existence of the shallow valley (Glen
1427 Torridon; Fig. 1) separating Greenheugh pediment and VRR. The relatively short travel distance to
1428 Bimbe would likely cause only limited rounding of sediment (Szabo et al. 2015) during their
1429 transport and deposition as collections of float rocks.

1430 More than one model may have given rise to the three heterolithic units. For example, the round
1431 shape of and arcuate ridge around Brandberg (Fig. 4f) seem to be indicators of an impact crater but
1432 Blackfoot and Bimbe seem to require other factors. The fact that Bimbe and its non-visited
1433 companion to the north (Fig. 6a) lie in a broad valley (Supplementary Fig. 1-3) may be a clue, but
1434 Brandberg and Blackfoot do not share that characteristic.

1435 The bare, unconsolidated appearance of the sediment in these units, showing clear signs of wind
1436 abrasion, raises question of whether these thin deposits were, for a period of time, buried by
1437 sufficiently thick deposits of sand (like that in the Bagnold dunes) that exposure to wind erosion was
1438 greatly reduced, as active erosion proceeded to cut widened valleys and local troughs into the
1439 underlying Murray formation. Alternatively, the wind erosion rates may be exceptionally slow on the
1440 relatively hard stones and be diminished due to the roughened surface produced by diverse grain
1441 sizes. In either case, the current three patches are generally elevated relative to some of their
1442 immediate surroundings, indicating greater resistance to erosion than the underlying Murray.

1443 5. CONCLUSIONS

1444 Exploration of the three heterolithic units has revealed a number of unique details. Significantly, the
1445 presence of conglomerates with compositions that are very close to that of the Stimson formation
1446 implies that some wet epoch must have existed after the Murray formation was eroded to nearly its
1447 present surface, and during or after the time period that the eolian material was deposited to form the
1448 Stimson formation. This must have been significantly later than the lacustrine activity associated
1449 with the Murray formation, thus representing a “later wet period” in Gale crater (see Palucis et al.,
1450 2016). The conglomerates would have been formed from fluvial activity that was relatively close in
1451 time to the deposition of the Stimson eolian strata. (However, note that these eolian strata are notable
1452 for their lack of evidence of wet conditions; Banham et al., 2018). At some later time the
1453 conglomerate outcrops would have been broken up and transported to where they are now found in
1454 the heterolithic units.

1455 The chemical similarity of float rocks explored early in the mission, classified as Bradbury layered
1456 (Mangold et al., 2015) to two stones of similar appearance at Bimbe, and at least one located midway
1457 between these locations, raises the possibility of the previous presence of overlying strata, above the
1458 Stimson formation and extending northward across Bradbury rise. These rocks are notably elevated
1459 in Mg and K. These strata, if they existed, would likely have been part of the Siccar point group, as is
1460 the Stimson formation (which also shows some elevation of Mg and K, but not to the higher values
1461 observed in these disparate samples from Bathurst Inlet to Bimbe).

1462 The dark, gray massive boulders and clasts of Bimbe analyzed by ChemCam are not the same
1463 compositions as a number of similar-appearing boulders and smaller rocks at Bradbury Rise.

1464 However, the alkaline float rock, Oscar, analyzed on Sol 516 by APXS and ChemCam, is essentially
1465 identical in composition to these Bimbe targets.

1466 In terms of the origins of the heterolithic units, we explore five different models that attempt to
1467 explain various attributes of the three units explored by Curiosity. Brandberg shows evidence for
1468 starting as an impact crater, while the other two units lack such evidence, suggesting that they
1469 formed by different means. Particle size analysis suggests a possible fluvial origin for the deposits,
1470 but the large boulders suggests a role played by debris flows. A common thread seems to be
1471 preservation of the sandstone clasts, cobbles, and boulders by the deposition of soils in the proposed
1472 depressions that may have characterized these units at an earlier point in time.

1473 On the observational side, large blocks with relatively flat skyward faces can result in higher
1474 apparent albedos from orbit than blocks of the same composition and morphology that are more
1475 rounded and not skyward facing. Care must be taken in interpreting the albedos of blocks observed
1476 from orbit.

1477

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1485

1486 **6. REFERENCES**

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Table 1. Mean relative abundances in wt. % of major elements for ChemCam targets in the Bimbe and Blackfoot units.

Mis en forme : Début de section : Nouvelle page

Bimbe Targets	Sequence	# points	dist. (m)	Group	SiO₂	TiO₂	Al₂O₃	FeO_T	MgO	CaO	Na₂O	K₂O	SUM
Aussenkehr	01401	10	2.61	Massive	51.5	1.06	8.2	17.5	1.9	5.1	4.3	1.1	90.7
AEGIS_post_1406a	15900	9	2.88	Massive	56.9	1.00	8.6	17.9	2.6	3.1	4.8	1.1	95.9
Lucala	01407	5	2.62	Massive	55.4	1.41	8.8	15.8	2.3	3.4	4.9	1.3	93.4
Sonneblom_CCAM	04407	9	2.25	Massive	54.4	0.90	7.0	17.3	3.0	5.2	4.6	0.8	93.3
Seeis	04409	9	2.39	Massive	54.2	1.08	8.7	16.2	2.5	5.9	4.6	1.1	94.4
Bungo	03407	10	2.54	Conglomerate	44.2	0.92	9.8	19.5	7.2	6.7	2.7	0.2	91.3
Balombo	05407	10	2.83	Conglomerate	43.9	0.92	10.3	18.2	7.1	7.5	3.0	0.7	91.6
Seeheim	01409	5	2.52	Conglomerate	51.2	0.89	13.2	13.7	4.5	6.1	4.4	1.1	94.9
Wilhelmstal	02409	9	2.53	Conglom. Vitreous	45.5	0.95	11.0	19.2	7.2	5.8	3.4	0.4	93.4
Cabamba	02407	10	2.47	Conglom. Vitreous	47.2	1.04	12.2	19.2	4.9	5.7	3.5	0.6	94.2
AEGIS_post_1400a	15900	9	2.59	Knobby SS (Stimson)	45.3	0.86	11.4	19.1	7.7	5.7	3.1	0.5	93.8
Auchab	01400	5	5.20	Nodular SS	43.5	0.95	11.4	26.4	7.2	5.0	3.2	1.8	99.5
Canico	02401	5	2.52	Nodular SS	42.3	0.95	10.0	21.9	4.9	5.3	3.3	0.7	89.4
Chinchimane	03401	5	2.28	Layered	40.4	1.17	6.1	20.2	11.7	5.2	1.9	1.1	87.9
Oranjemund	03409	10	2.95	Massive / Layered	44.1	1.17	6.5	20.1	11.3	5.2	2.1	0.9	91.3
Mariental	05409	5	4.17	Other	48.7	1.05	15.5	17.6	5.2	8.2	3.7	0.4	100.4
Blackfoot Targets													
Sunburst	02100	10	2.36	Stimson Cluster #1	42.4	0.92	8.2	19.4	12.5	4.7	1.6	0.2	90.0
Jefferson	02102	10	2.94	Other	44.0	1.30	10.2	20.3	9.5	4.4	2.5	0.4	92.5
Lincoln	04102	5	2.96	Other	46.2	1.07	11.7	20.5	7.8	4.5	2.8	0.7	95.3

Dist. = distance; SS = sandstone; see text for definition of other terms

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1745

1746 Table 2. Standard deviations between observation point compositions for major elements in wt. % for ChemCam targets in the Bimbe
 1747 and Blackfoot units.

Bimbe Targets	Group	SiO₂	TiO₂	Al₂O₃	FeO_T	MgO	CaO	Na₂O	K₂O	SUM
Aussenkehr	Massive	4.5	0.50	2.8	1.9	0.7	3.4	1.0	0.5	5.3
AEGIS_post_1406a	Massive	7.3	0.28	3.9	3.1	0.8	1.8	1.2	0.5	6.5
Lucala	Massive	5.5	0.70	4.8	1.6	0.7	2.8	0.9	0.7	6.4
Sonneblom_CCAM	Massive	6.9	0.26	2.6	3.7	1.3	3.1	0.5	0.4	4.3
Seeis	Massive	6.6	0.56	3.9	4.5	1.0	4.3	0.7	0.8	4.7
Bungo	Conglomerate	2.1	0.09	2.6	1.1	1.3	1.0	0.4	0.1	3.1
Balombo	Conglomerate	6.8	0.13	2.6	2.5	2.5	4.3	1.2	0.3	5.9
Seeheim	Conglomerate	9.7	0.09	3.0	7.3	2.2	2.7	1.7	1.1	3.6
Wilhelmstal	Conglom. Vitreous	1.7	0.06	1.0	0.7	0.9	0.6	0.4	0.1	2.1
Cabamba	Conglom. Vitreous	3.7	0.07	2.6	1.6	1.4	1.1	0.6	0.3	3.4
AEGIS_post_1400a	Knobby SS (Stimson)	1.6	0.09	2.8	1.0	2.3	0.8	0.5	0.1	3.0
Auchab	Nodular SS	1.9	0.08	2.3	3.2	1.9	0.8	0.6	0.6	2.5
Canico	Nodular SS	6.2	0.15	4.1	5.6	1.8	1.5	1.4	0.1	5.3
Chinchimane	Layered	1.1	0.10	0.2	0.4	0.9	1.0	0.2	0.2	1.0
Oranjemund	Massive/Layered	1.7	0.12	0.6	0.6	1.2	1.3	0.3	0.4	1.5
Mariental	Other	4.9	0.39	2.6	5.1	1.3	4.1	0.9	0.3	3.0
Blackfoot Targets										
Sunburst	Stimson Cluster #1	1.5	0.17	0.8	0.7	0.8	1.3	0.2	0.1	1.9
Jefferson	Other	2.2	0.30	3.2	1.0	2.7	1.0	0.5	0.1	3.3
Lincoln	Other	1.9	0.37	2.7	1.1	3.3	0.8	0.5	0.3	2.6

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1749

1750 Table 3. Selected trace-element abundances for ChemCam targets in the Bimbe and Blackfoot units. Abundances are in parts per
 1751 million.

Bimbe Targets	Group	Li	Rb	Sr
Aussenkehr	Massive	32.1	48.8	487
AEGIS_post_1406a	Massive	33.9	67.2	458
Lucala	Massive	23.6	74.5	673
Sonneblom_CCAM	Massive	27.9	<57.9	387
Seeis	Massive	27.8	69.2	473
Bungo	Conglomerate	10.3	<26.0	<98
Balombo	Conglomerate	14.1	<56.3	<133
Seeheim	Conglomerate	8.6	91.8	<167
Wilhelmstal	Conglom. Vitreous	10.7	<26.0	<103
Cabamba	Conglom. Vitreous	10.1	<42.0	<120
AEGIS_post_1400a	Knobby SS (Stimson)	20.1	61.4	<129
Auchab	Nodular SS	11.6	<39.5	<96
Canico	Nodular SS	8.9	<34.6	<168
Chinchimane	Layered	17.4	38.7	173
Oranjemund	Massive/Layered	11.8	52.2	152
Mariental	Other	21.3	<26.9	<115
Blackfoot Targets*				
Sunburst	Stimson Cluster #1	14.6	31.0	<118
Jefferson	Other	10.1	28.7	<147
Lincoln	Other	14.9	--	<96

1752

1753 *Rb abundance for Lincoln was not computed; for Sunburst and Jefferson the results are each based on a single point.

1754

1755 Table 4. APXS compositions for targets at Bimbe and Blackfoot.

Element	Sonneblom	Stat.	Zambezi	Stat.	Funda1	Stat.	Funda2	Stat.	Funda3	Stat.	Funda4	Stat.	Badlands	Stat.
Na ₂ O	3.92	0.14	4.52	0.2	3.2	0	3.14	0.14	3	0.14	3.21	0.14	3.25	0.14
MgO	4.55	0.17	2.64	0.08	7.27	0.17	7.72	0.17	7.09	0.17	7.26	0.17	8.42	0.25
Al ₂ O ₃	9.22	0.19	9.23	0.19	10.42	0.29	10.38	0.29	9.35	0.19	9.5	0.29	8.86	0.19
SiO ₂	54.08	0.64	59.25	0.64	47.22	0.54	46.18	0.54	42.34	0.54	47.99	0.54	43.57	0.54
P ₂ O ₅	0.71	0.05	0.57	0.05	1.18	0.07	1.09	0.07	1.03	0.07	1.23	0.07	0.74	0.05
SO ₃	4.3	0.05	2.87	0.05	3.22	0.12	3.23	0.12	9.5	0.22	4.22	0.12	5.08	0.07
Cl	1.02	0.02	0.71	0.02	1.11	0.05	1.31	0.05	1.3	0.06	1.33	0.05	1.52	0.02
K ₂ O	2.61	0.08	3.17	0.1	0.61	0.04	0.49	0.02	0.51	0.04	0.62	0.04	0.93	0.04
CaO	3.83	0.04	2.96	0.04	6.55	0.01	7.04	0.01	9.18	0.13	6.83	0.1	5.86	0.07
TiO ₂	0.86	0.03	0.82	0.03	1.22	0.05	1.05	0.05	0.9	0.05	0.97	0.05	0.89	0.03
Cr ₂ O ₃	0.08	0.01	0.03	0.01	0.28	0.03	0.26	0.03	0.26	0.03	0.25	0.03	0.39	0.01
MnO	0.22	0.01	0.21	0.01	0.35	0.03	0.39	0.03	0.29	0.03	0.33	0.03	0.40	0.01
FeO	14.37	0.2	12.69	0.13	17.22	0.2	17.56	0.2	15.12	0.2	16.14	0.2	19.87	0.26
Ni	0.012	0.001	0.0056	0.001	0.0239	0.0035	0.0227	0.0035	0.0294	0.004	0.0209	0.003	0.0485	0.003
Zn	0.0184	0.001	0.0169	0.001	0.0605	0.0035	0.0431	0.003	0.0334	0.0025	0.0437	0.0025	0.0449	0.002
Br	0.0208	0.001	0.0033	0.0005	0.024	0.0015	0.0245	0.0015	0.0274	0.0015	0.0209	0.0015	0.0277	0.001

1756 Stat. = statistical uncertainty (precision). Units are weight percent.

1757

1758 Table 5. Differing characteristics of the three heterolithic units in this study.

	Blackfoot	Brandberg	Bimbe
Rover studied on sols	1099-1104	1158-1160	1399-1410
Elevation	-4434 to -4432 m	-4435 to -4432 m	-4417 to -4426 m
Approximate size	1730 m ²	1600 m ²	16800 m ²
Shape	Semi-elliptical	Nearly circular	Irregular
Arcuate ridge at perimeter	No	Yes	No
Steeply-dipping sediments	No	Yes	No
Contains a several-meter ridge?	No	No	Yes
Superposes Stimson formation?	Yes	No	No
Stimson-like concretions ?	No	Yes	Perhaps, in Auchab and Canico
Contains mudstone lithic fragments (possible Murray) ?	No?	Yes	Yes
Light gray-white sandstones ?	Yes	No	Yes
Contains conglomerates?	Yes, small, disaggregated	Possibly	Yes

1759

1760 FIGURES

1761

1762 Fig. 1. The Curiosity rover field site occurs on the lower northwest slope of the 5-km-high Aeolis
1763 Mons (Mt. Sharp), a mountain of predominantly stratified sediments in Gale crater. Gale is a
1764 ~154 km diameter impact structure. The white trace indicates the rover traverse from landing
1765 until September 2019. The inset shows the location of the field site within Gale crater. The three
1766 heterolithic units studied by the rover are indicated by gray-filled circles. Waypoints are
1767 indicated by black circles. Targets mentioned in the text that are outside of the heterolithic units
1768 are indicated by triangles. Other features mentioned in the text are also indicated.

1769 Fig. 2. (a) The Curiosity rover and the Blackfoot heterolithic unit (within blue dashed outline) as
1770 imaged by HiRISE on 04 September 2015. Yellow trace indicates rover traverse, from north
1771 toward southwest. Locations of boulders A and B and the sites of two rover stops on Blackfoot
1772 are indicated. Locations of ChemCam targets Sunburst, Swan, Lincoln, Jefferson, Madison, and
1773 the APXS/MAHLI target Badlands, are indicated in green. (b) Boulder A is dark-toned when
1774 viewed from above; the rock is a dark gray sandstone and it has a surface that is rough at a
1775 centimeter scale. (c) Boulder B is light-toned when viewed from above (e.g. HiRISE images);
1776 the rock is a dark-gray sandstone; bedding is apparent; the skyward-facing surface is smooth at a
1777 centimeter scale and coated with eolian dust. (d) Blackfoot as seen from the north on Sol 1094
1778 when the rover was parked at the position shown in (a). Boulders A and B and the locations of
1779 (e), (f), and (g) are indicated. (e) The north and east margins of the Blackfoot heterolithic unit
1780 overlie dark-gray, cross-bedded eolian Stimson formation sandstones. (f) North edge of
1781 Blackfoot reveals the deposit in cross-section; here, it consists of a jumble of angular cobbles and
1782 pebbles; cobbles display a variety of orientations relative to their internal sedimentary structures
1783 (bedding). Dark-toned eolian sand has filled some of the gaps between stones. (g) Many of the
1784 open fractures which cut through Stimson formation sandstones exhibit a light-toned, fracture-
1785 parallel, altered zone (a “halo;” see Frydenvang et al., 2017 and Yen et al., 2017). Here a fracture
1786 and associated halo follow the red trace and are abruptly truncated where covered by the
1787 Blackfoot heterolithic unit; this indicates that the fracture and fluids responsible for the “halo”
1788 alteration did not penetrate the Blackfoot deposit; i.e., one of the indicators that the deposit is not
1789 a lithic unit. (h) At its west-southwest end, the Blackfoot unit directly overlies mudstones of the
1790 Murray formation. (i) The cobbles and boulders of Blackfoot display a range of orientations,
1791 relative to their internal structure (bedding). Some of them protrude from the surface, others rest
1792 on the surface.

1793 Fig. 3. (a) Typical Blackfoot surface, with scattered cobbles, small boulders, pebbles, and sand of
1794 various orientations (relative to internal sedimentary structure, such as bedding), colors, and
1795 lithologies. Two key examples are highlighted: A cross-stratified sandstone boulder (ChemCam
1796 target named Sunburst) and a conglomeratic cobble. (b) Dark-gray sandstone target named
1797 Sunburst. White and light-gray sand grains are readily distinguished because of their contrast
1798 relative to the majority of grains, which are dark gray. (c) Example of a light-gray conglomeratic
1799 cobble, protruding from the surface. The orange-brown material on part of this stone is eolian
1800 dust. (d) Pebbles in an otherwise light-gray sandy matrix in a conglomeratic stone protruding

1801 from the surface at Blackfoot. (e) ChemCam target Madison; inset shows the image location on
1802 the rock face. The large, light-toned feature consists of the remains of a fracture wall vein
1803 composed of calcium sulfate. More importantly, the image shows light-toned sand grains, which
1804 contrast with the bulk of dark-toned sand grains (much more difficult to see) in this rock.
1805 Madison is a dark-gray sandstone. (f) APXS/MAHLI target, Badlands. This stone, too, is a dark-
1806 gray sandstone. Unlike Madison and Sunburst, Badlands has no light-toned sand grains; they are
1807 all dark gray. The sizes of two larger grains are indicated; most grains are smaller and difficult to
1808 distinguish from each other and their intergranular cement. Brownish-orange patches are
1809 depressions (some of them, perhaps, may be sockets from which sand grains have been removed)
1810 containing eolian dust. (g) Two examples of the light-toned sandstone or pebbly conglomerate
1811 fragments which occur at Blackfoot.

1812 Fig. 4. (a) Brandberg and the Curiosity rover as viewed by HiRISE on Sol 1159. Yellow trace
1813 indicates the rover traverse; drive direction was from northeast to southwest. ChemCam targets
1814 are indicated by name. (b) Eastern Brandberg. In this scene, Brandberg is downhill from the
1815 rover; the near side of Brandberg forms a shallow depression. Rover tracks provide scale. Eolian
1816 bedforms explain the faint lineated texture observable in HiRISE images. (c) Brandberg as
1817 viewed from the northeast. (d) Examples of steeply dipping cobble-sized angular clasts in
1818 Brandberg. (e) Examples of clast variety in northeastern Brandberg. The largest boulder-sized
1819 clasts dip toward the center of the circular landform. Boulders with relatively flat, skyward-
1820 facing surfaces are coated with dust and thus appear light-toned when seen from above in
1821 HiRISE images. The ChemCam target, Gibeon, is indicated. (f) Red/cyan stereo pair anaglyph
1822 produced from two HiRISE images; the dashed yellow arc indicates a ridge that might be an
1823 indicator that Brandberg occurs within the eroded remains of an impact structure.

1824 Fig. 5. (a) Sol 1160 view of the variety of boulders, cobbles, and pebbles which compose the
1825 Brandberg deposit. Yellow outlines indicate locations of panels b, c, d, g, h, and i. (b) Dust-
1826 coated, fractured Murray-formation lithic clast target named Hoba. (c) Dark-gray sandstone
1827 cobble target named Gibeon. The inset shows enlargement of a single grain or concretion,
1828 representative of the larger grains (or typical concretion size) in this rock, ~2 mm. (d) Sandstone
1829 with concretions. (e) Example sandstone with concretions (target named Maiberg) liberated from
1830 Stimson formation bedrock on the east side of Naukluft Plateau, imaged on Sol 1277; shown
1831 here for comparison. (f) Sedimentary structure and texture details of Maiberg. (g) Examples of
1832 candidate, rare conglomeratic stones at Brandberg. (h) Example of angular, cobble-sized
1833 fragment of cross-bedded sandstone. (i) Example lithic fragment of Murray-formation bedrock
1834 incorporated into the Brandberg deposit; white arrows indicate erosion-resistant concretions;
1835 compare with (j): Example of intact Murray-formation bedrock south of Brandberg which
1836 contains similar concretions (white arrows).

1837 Fig. 6. (a) Local context of Bimbe on the lower slopes of Mt. Sharp, between the Murray buttes
1838 to the south, Naukluft Plateau and some of the Bagnold dunes to the east, and Baynes Mountain
1839 to the north. The white trace is the Curiosity rover traverse; the drive direction was from
1840 northeast (upper right) toward the south (bottom left of center). Blue box indicates the location of
1841 (b): Bimbe with ChemCam, APXS, and MAHLI targets indicated in yellow. Green dots indicate

1842 ChemCam targets, red dots indicate APXS targets, and black dots indicate rover parking spots.
1843 The inset, a 3x expanded view of the area inside the white circle next to target Auchab, shows an
1844 example of light- and dark-toned boulders as observed from the orbiting HiRISE camera. The
1845 white trace is the Curiosity rover traverse; the drive direction was from the northeast (upper
1846 right) toward the south (bottom center). The elevation contours are derived from HiRISE stereo-
1847 pair products calibrated to Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA),
1848 topography by Parker and Calef (2016).

1849 Fig. 7. A ridge on the northeast side of Bimbe, which trends northeast-southwest (azimuth
1850 $\sim 65.5^\circ$), is mantled with cobbles and small boulders in Mastcam images (inset). The ridge
1851 resembles nearby boulder- and cobble-mantled hills named Bukalo and Bailundo (insets). These
1852 are likely examples of buttes that have weathered to the point that they are hills with remnants of
1853 the capping rock taking the form of small boulders and cobbles (cf. Migoñ et al., 2018).

1854 Fig. 8. Stereo pair anaglyph of Bimbe (large, dark-toned patch) and its vicinity. Most of the
1855 boulders observed at Bimbe occur on the elevated portions of the south margin of Bimbe. The
1856 feature within the dashed yellow ellipse, indicated with a “?”, might be the eroded remains of an
1857 impact structure. Definitive impact craters are labeled with “c” and probable impact structures
1858 are labeled with “i”. Dark-toned eolian sand, expressed as bedforms, has collected in the impact
1859 structure depressions. Features labeled “MB” are a couple of the Murray buttes.

1860 Fig. 9. (a) Work site for sols 1405–1410, viewed from the east. Names of targets investigated
1861 using ChemCam, Mastcam, APXS, and MAHLI are indicated. The dashed yellow trace
1862 approximately indicates the crest of a low ridge line that defines the southern margins of Bimbe.
1863 (b) Navcam view of the work site. ChemCam, APXS, and MAHLI targets are indicated (except
1864 Mariental, which is to the left of this scene. The stone labeled “angular sandstone,” imaged by
1865 MAHLI on Sol 1407, is also shown in Fig. 15 and was not a named target. For scale, the width of
1866 the rover wheel (right of lower center) is 40 cm.

1867 Fig. 10. (a) Boulder containing targets Sonneblom (ChemCam, APXS, MAHLI) and Zambezi
1868 (APXS, MAHLI). The boulder is a dark-gray, pitted sandstone; the locations of the MAHLI
1869 views in (b) and (c) are indicated. (b and c) Close-up views of the surface; the yellow arrows
1870 point to several individual grains.

1871 Fig. 11. (a) Context for two ChemCam targets, Seeis and Aegis_1406a, on two separate stones at
1872 Bimbe. (b) Seeis target; yellow outline indicates location of ChemCam RMI coverage, 4x inset
1873 indicates examples of the largest (mm-scale) grains. (c) AEGIS_1406a target; yellow outline
1874 indicates the location of the ChemCam RMI coverage shown to the right. (d) Close-up view,
1875 with red crosshairs indicating LIBS observation points on AEGIS_1406a.

1876 Fig. 12. (a) Dark-gray sandstone cobble target named Oranjemund. White box indicates location
1877 of expanded view in (b); yellow outline indicates ChemCam RMI coverage in (c). (b) View
1878 showing grain-scale bedding, which runs diagonally from upper left to lower right. (c) Close-up
1879 view of Oranjemund; inset shows 3x expanded view with measurements on features that could
1880 be among the larger sand grains in the rock (i.e., most of the grains are smaller than $\sim 400 \mu\text{m}$).
1881 Oranjemund is compositionally identical to layered target Chinchimane (Fig. 14).

1882 Fig. 13. (a) Local context for ChemCam target Auchab; yellow outline indicates location of
1883 panel (b); closer view of knobby gray target Auchab; yellow outline indicates ChemCam RMI
1884 coverage in (c). Note the nearby angular, cross-bedded sandstone clast. Both stones are
1885 surrounded by windblown sand and overlie reddish Murray-formation bedrock. (c) ChemCam
1886 RMI mosaic showing the nodular texture of Auchab.

1887 Fig. 14 (a) Local context for layered gray sandstone cobble target Chinchimane. Note the
1888 differences in cobble orientation relative to their bedding structure, as well as the diversity of
1889 cobble colors, response to sunlight, and sedimentary structure and texture. (b) Mastcam-100
1890 view. Bedding is approximately parallel and thin (sand grain scale thickness). A fracture filled
1891 with a white material (vein) cuts across bedding. The yellow outline indicates the location of the
1892 ChemCam RMI coverage shown in (c), where a few individual sand grains can be identified in a
1893 well cemented and well sorted sandstone.

1894 Fig. 15. Angular sandstone cobble with fine-grained interbeds. (a) Location (white arrow) of the
1895 cobble relative to the larger boulders in the rover workspace during sols 1405–1410. (b) Highest
1896 spatial resolution view of the cobble. Coarser grains are $\sim 700\ \mu\text{m}$; the skyward rock face cuts
1897 steeply across the original bedding. A recessed interval of $\sim 1\ \text{cm}$ thickness consists of grains too
1898 small to resolve.

1899 Fig. 16. (a) Example showing diversity of cobble and boulder orientations, sedimentary
1900 structures, and colors at Bimbe. The white circles indicate examples of white stones shown in
1901 (c); the yellow circles indicate examples of “red” stones in (c). (b) Knobby sandstone target,
1902 Canico. (c) Examples of “red” (left) and white (center and right) cobbles which are minor
1903 constituents of the Bimbe deposit; locations and relative sizes are shown in (a). The red stone at
1904 the lower left in (c) has a white vein cutting across bedding within the stone.

1905 Fig. 17. (a) Conglomeratic boulder containing MAHLI targets Tumba and Funda; the latter was
1906 also an APXS target. (b) Conglomeratic boulder, $\sim 60\ \text{cm}$ wide, that includes veins that cut across
1907 the sandy matrix (inset). (c) Conglomeratic boulder that includes the ChemCam target Balombo
1908 (yellow outline indicates RMI image coverage).

1909 Fig. 18. (a) Conglomeratic boulder investigated via four ChemCam targets. (b-e) Respective
1910 RMI views and LIBS target areas of Seeheim, Bungo, Cabamba, and Wilhelmstal. Note the
1911 vitreous luster of Wilhelmstal, and similarity to Cabamba.

1912 Fig. 19. (a) Conglomeratic boulder that includes the APXS/MAHLI target, Funda, and the
1913 MAHLI target, Tumba. White arrows indicate recessed white objects similar to Funda; blue
1914 arrows indicate light-gray and white protrusive pebble clasts. (b) Close-up view of white,
1915 recessed, banded object (clast or void fill) comprising the target Funda. (c) Pebble clast target
1916 named Tumba. (d) Close-up view of a portion of the Tumba pebble clast, showing that it is a
1917 sandstone; arrows point to a few example grains.

1918 Fig. 20. (a) Conglomeratic boulder with ChemCam target, Mariental. Inset shows the entire
1919 boulder. (b) Close-up view of Mariental and the locations of ChemCam LIBS observations.
1920 Recessive white features are interpreted to be similar to Funda (Fig. 19).

1921 Fig. 21. Major-element abundances, in wt. %, of ChemCam targets at Bimbe. Larger symbols
1922 indicate averages of individual targets for Aussenkehr, Lucala, Seeis, Sonneblom,
1923 AEGIS_post_1406a (“Massive,” red dots); Wilhelmstal, Cabamba (“Vitreous Conglomerate,
1924 blue diamonds, also includes AEGIS_post_1400a); Chinchimane, Oranjemund (“Bimbe
1925 Layered,” yellow dots), Auchab and Canico (“Nodular SS,” brown dots). Smaller symbols
1926 represent individual observation points for the conglomerates (“Conglomerate Pts”), which have
1927 more diverse compositions. Circles indicate groupings of Bimbe layered (yellow), massive (red),
1928 and vitreous conglomerate (blue) targets. Standard deviations between individual LIBS
1929 observation points within a target are given in Table 2. Upper limits on precision for individual
1930 point observations are shown in each panel, taken from 480 Sheepbed measurements (Mangold
1931 et al., 2015). Also shown are the mean compositions, and standard deviations of the means, of
1932 other types of targets observed nearby and earlier along the traverse. These include Murray, Mars
1933 soil, two groups of conglomerates, ChemCam target Pyramid Hills, and a group of massive
1934 targets from Bradbury rise. Stimson formation compositions are shown as contours where each
1935 contour represents equal weighting in terms of density of samples (see text and Supplementary
1936 Material).

1937 Fig. 22. Rocks observed on Bradbury rise that match Bimbe float rocks in terms of morphology
1938 and composition in some cases, and only in morphology in other cases. (a) Bathurst_Inlet,
1939 observed Sol 55, and (b) Nullataktok (Sol 336), found in the same area, have similar
1940 compositions and morphologies to the Bimbe layered clasts. Bradbury massive targets (c) Bull
1941 Arm and (d) Jake_M do not match the compositions of the Bimbe massive targets, although they
1942 bear morphological resemblances. (e) Oscar (observed Sol 516) does match the Bimbe massive
1943 target compositions. (f) Pyramid Hills (observed north of Hidden Valley on Sol 692) is a close
1944 match to the Bimbe layered compositions, as well as to the Bradbury layered targets, e.g., (a) and
1945 (b). Locations of these targets are shown on Fig. 1.

1946 Fig. 23. ChemCam relative reflectance spectra of representative samples of the Bimbe layered
1947 and nodular rocks, along with sample spectra from the Bradbury layered rocks. The Bimbe
1948 rocks show either flat near-infrared spectra or downturns that begin near 600 nm, whereas the
1949 Bradbury rocks have peak reflectance wavelengths near 650-675 nm.

1950 Fig. 24. Possible scenarios for formation of the heterolithic units. Each panel shows three time
1951 steps. The grey stippled top layer is the Stimson formation, the white bedded unit is the Murray,
1952 and the orange records the heterolithic unit. (a) Impact penetrates through the Stimson formation
1953 into the Murray formation, creating a crater whose walls erosionally retreat through time. (b)
1954 Incision into a resistant Stimson cap rock (either by wind or water) that creates buttes and sheds
1955 Stimson and Murray blocks into a narrow valley. Further erosional retreat leaves isolated
1956 patches. Alternately, buttes decay in place to create the heterolithic units. Sediments are
1957 protected from weathering in the original location of the incision, or boulders shed from the
1958 mesas are collected in certain areas that are not subject to erosion. (c) Mass transport of debris,
1959 either dry or by glacial processes, followed by extensive erosion that obscures the original source
1960 region. (d) Large-scale fluvial or debris flow fan deposits followed by erosion. (e) Localized
1961 fluvial or debris flow followed by erosion.

1962

1963 **Tasks:**

1964 1. Send to co-authors for comments

1965 2. Submit by 5/25.

1827 FIGURES

1828

1829 Fig. 1. The Curiosity rover field site occurs on the lower northwest slope of the 5-km-high Aeolis
1830 Mons (Mt. Sharp), a mountain of predominantly stratified sediments in Gale crater. Gale is a
1831 ~154 km diameter impact structure. The white trace indicates the rover traverse from landing
1832 until September 2019. The inset shows the location of the field site within Gale crater. The three
1833 heterolithic units studied by the rover are indicated by gray-filled circles. Waypoints are
1834 indicated by black circles. Targets mentioned in the text that are outside of the heterolithic units
1835 are indicated by triangles. Other features mentioned in the text are also indicated.

1836 Fig. 2. (a) The Curiosity rover and the Blackfoot heterolithic unit (within blue dashed outline) as
1837 imaged by HiRISE on 04 September 2015. Yellow trace indicates rover traverse, from north
1838 toward southwest. Locations of boulders A and B and the sites of two rover stops on Blackfoot
1839 are indicated. Locations of ChemCam targets Sunburst, Swan, Lincoln, Jefferson, Madison, and
1840 the APXS/MAHLI target Badlands, are indicated in green. (b) Boulder A is dark-toned when
1841 viewed from above; the rock is a dark gray sandstone and it has a surface that is rough at a
1842 centimeter scale. (c) Boulder B is light-toned when viewed from above (e.g. HiRISE images);
1843 the rock is a dark-gray sandstone; bedding is apparent; the skyward-facing surface is smooth at a
1844 centimeter scale and coated with eolian dust. (d) Blackfoot as seen from the north on Sol 1094
1845 when the rover was parked at the position shown in (a). Boulders A and B and the locations of
1846 (e), (f), and (g) are indicated. (e) The north and east margins of the Blackfoot heterolithic unit
1847 overlie dark-gray, cross-bedded eolian Stimson formation sandstones. (f) North edge of
1848 Blackfoot reveals the deposit in cross-section; here, it consists of a jumble of angular cobbles and
1849 pebbles; cobbles display a variety of orientations relative to their internal sedimentary structures
1850 (bedding). Dark-toned eolian sand has filled some of the gaps between stones. (g) Many of the
1851 open fractures which cut through Stimson formation sandstones exhibit a light-toned, fracture-
1852 parallel, altered zone (a “halo;” see Frydenvang et al., 2017 and Yen et al., 2017). Here a fracture
1853 and associated halo follow the red trace and are abruptly truncated where covered by the
1854 Blackfoot heterolithic unit; this indicates that the fracture and fluids responsible for the “halo”
1855 alteration did not penetrate the Blackfoot deposit; i.e., one of the indicators that the deposit is not
1856 a lithic unit. (h) At its west-southwest end, the Blackfoot unit directly overlies mudstones of the
1857 Murray formation. (i) The cobbles and boulders of Blackfoot display a range of orientations,
1858 relative to their internal structure (bedding). Some of them protrude from the surface, others rest
1859 on the surface.

1860 Fig. 3. (a) Typical Blackfoot surface, with scattered cobbles, small boulders, pebbles, and sand of
1861 various orientations (relative to internal sedimentary structure, such as bedding), colors, and
1862 lithologies. Two key examples are highlighted: A cross-stratified sandstone boulder (ChemCam
1863 target named Sunburst) and a conglomeratic cobble. (b) Dark-gray sandstone target named
1864 Sunburst. White and light-gray sand grains are readily distinguished because of their contrast
1865 relative to the majority of grains, which are dark gray. (c) Example of a light-gray conglomeratic
1866 cobble, protruding from the surface. The orange-brown material on part of this stone is eolian
1867 dust. (d) Pebbles in an otherwise light-gray sandy matrix in a conglomeratic stone protruding

1868 from the surface at Blackfoot. (e) ChemCam target Madison; inset shows the image location on
1869 the rock face. The large, light-toned feature consists of the remains of a fracture wall vein
1870 composed of calcium sulfate. More importantly, the image shows light-toned sand grains, which
1871 contrast with the bulk of dark-toned sand grains (much more difficult to see) in this rock.
1872 Madison is a dark-gray sandstone. (f) APXS/MAHLI target, Badlands. This stone, too, is a dark-
1873 gray sandstone. Unlike Madison and Sunburst, Badlands has no light-toned sand grains; they are
1874 all dark gray. The sizes of two larger grains are indicated; most grains are smaller and difficult to
1875 distinguish from each other and their intergranular cement. Brownish-orange patches are
1876 depressions (some of them, perhaps, may be sockets from which sand grains have been removed)
1877 containing eolian dust. (g) Two examples of the light-toned sandstone or pebbly conglomerate
1878 fragments which occur at Blackfoot.

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1880 indicates the rover traverse; drive direction was from northeast to southwest. ChemCam targets
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1883 bedforms explain the faint lineated texture observable in HiRISE images. (c) Brandberg as
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1887 facing surfaces are coated with dust and thus appear light-toned when seen from above in
1888 HiRISE images. The ChemCam target, Gibeon, is indicated. (f) Red/cyan stereo pair anaglyph
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1994 more diverse compositions. Circles indicate groupings of Bimbe layered (yellow), massive (red),
1995 and vitreous conglomerate (blue) targets. Standard deviations between individual LIBS
1996 observation points within a target are given in Table 2. Upper limits on precision for individual
1997 point observations are shown in each panel, taken from 480 Sheepbed measurements (Mangold
1998 et al., 2015). Also shown are the mean compositions, and standard deviations of the means, of
1999 other types of targets observed nearby and earlier along the traverse. These include Murray, Mars
2000 soil, two groups of conglomerates, ChemCam target Pyramid Hills, and a group of massive
2001 targets from Bradbury rise. Stimson formation compositions are shown as contours where each
2002 contour represents equal weighting in terms of density of samples (see text and Supplementary
2003 Material).

2004 Fig. 22. Rocks observed on Bradbury rise that match Bimbe float rocks in terms of morphology
2005 and composition in some cases, and only in morphology in other cases. (a) Bathurst_Inlet,
2006 observed Sol 55, and (b) Nullataktok (Sol 336), found in the same area, have similar
2007 compositions and morphologies to the Bimbe layered clasts. Bradbury massive targets (c) Bull
2008 Arm and (d) Jake_M do not match the compositions of the Bimbe massive targets, although they
2009 bear morphological resemblances. (e) Oscar (observed Sol 516) does match the Bimbe massive
2010 target compositions. (f) Pyramid Hills (observed north of Hidden Valley on Sol 692) is a close
2011 match to the Bimbe layered compositions, as well as to the Bradbury layered targets, e.g., (a) and
2012 (b). Locations of these targets are shown on Fig. 1.

2013 Fig. 23. ChemCam relative reflectance spectra of representative samples of the Bimbe layered
2014 and nodular rocks, along with sample spectra from the Bradbury layered rocks. The Bimbe
2015 rocks show either flat near-infrared spectra or downturns that begin near 600 nm, whereas the
2016 Bradbury rocks have peak reflectance wavelengths near 650-675 nm.

2017 Fig. 24. Possible scenarios for formation of the heterolithic units. Each panel shows three time
2018 steps. The grey stippled top layer is the Stimson formation, the white bedded unit is the Murray,
2019 and the orange records the heterolithic unit. (a) Impact penetrates through the Stimson formation
2020 into the Murray formation, creating a crater whose walls erosionally retreat through time. (b)
2021 Incision into a resistant Stimson cap rock (either by wind or water) that creates buttes and sheds
2022 Stimson and Murray blocks into a narrow valley. Further erosional retreat leaves isolated
2023 patches. Alternately, buttes decay in place to create the heterolithic units. Sediments are
2024 protected from weathering in the original location of the incision, or boulders shed from the
2025 mesas are collected in certain areas that are not subject to erosion. (c) Mass transport of debris,
2026 either dry or by glacial processes, followed by extensive erosion that obscures the original source
2027 region. (d) Large-scale fluvial or debris flow fan deposits followed by erosion. (e) Localized
2028 fluvial or debris flow followed by erosion.

2029

2030 **Tasks:**

2031 1. Send to co-authors for comments

2032 2. Submit by 5/25.

Fig. 1

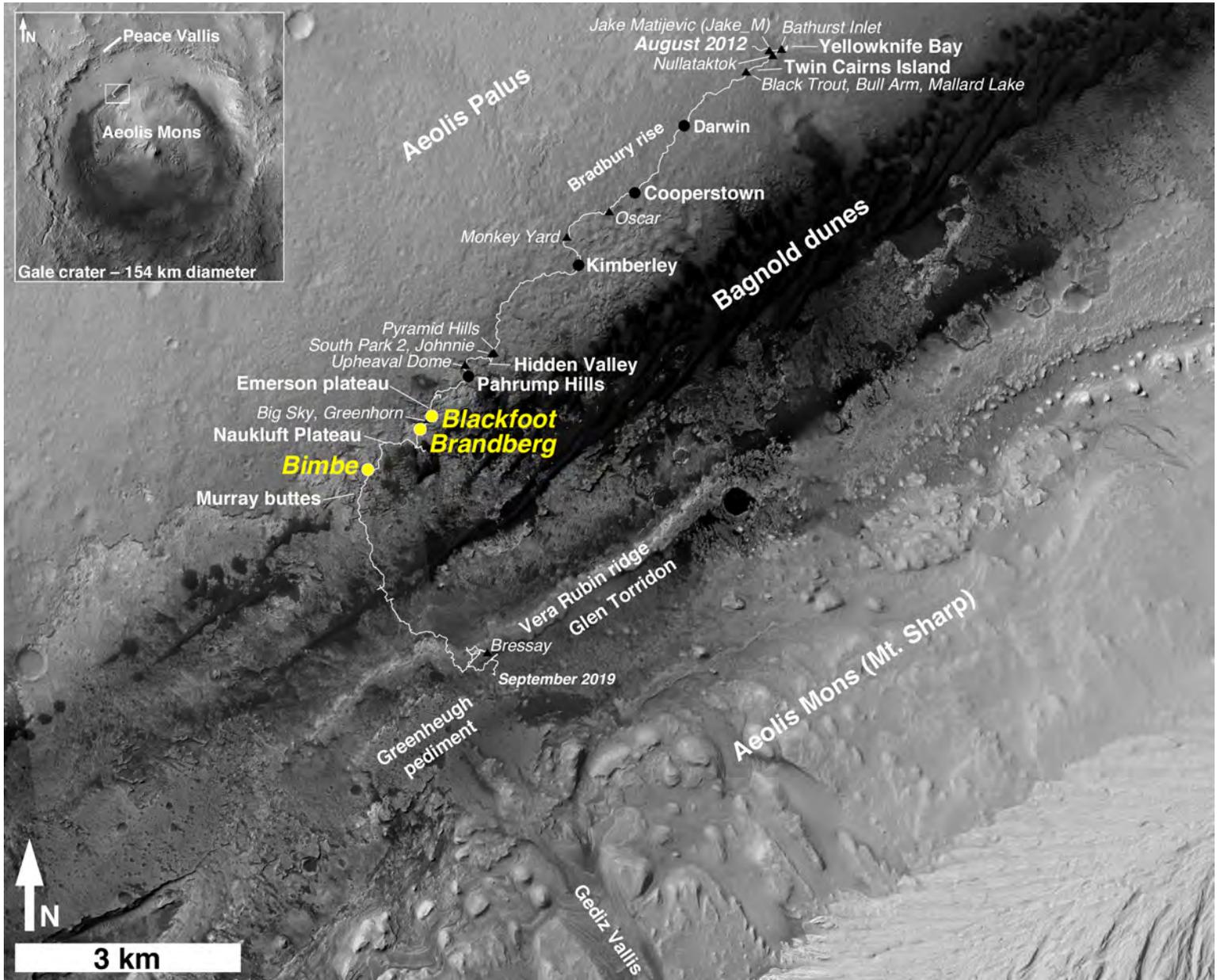


Fig. 1. The Curiosity rover field site occurs on the lower northwest slope of the 5-km-high Aeolis Mons (Mt. Sharp), a mountain of predominantly stratified sediments in Gale crater. Gale is a ~154 km diameter impact structure. The white trace indicates the rover traverse from landing until September 2019. The inset shows the location of the field site within Gale crater. The three heterolithic units studied by the rover are indicated by gray-filled circles. Waypoints are indicated by black circles. Targets mentioned in the text that are outside of the heterolithic units are indicated by triangles. Other features mentioned in the text are also indicated.

FIG 2

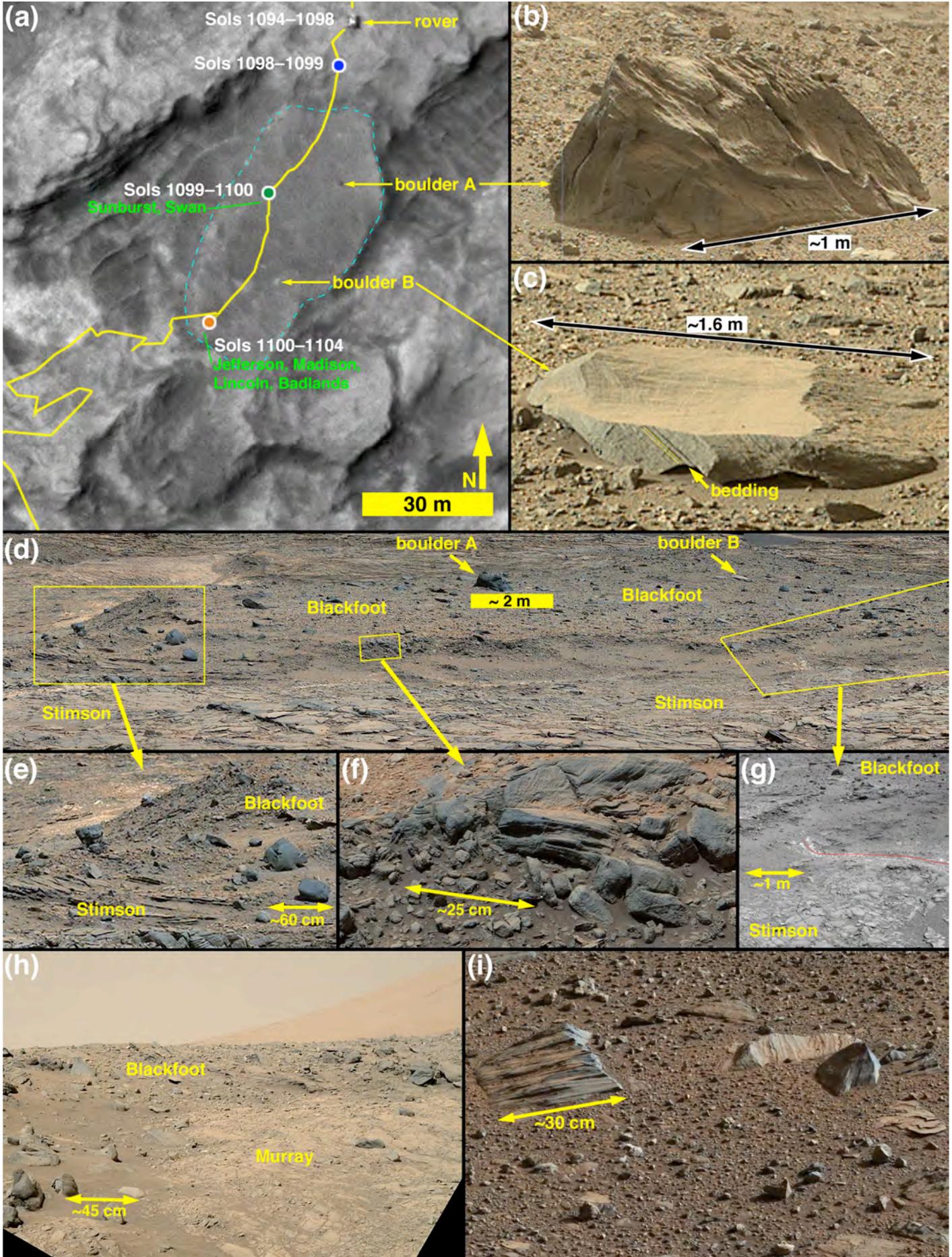


Fig. 2. (a) The Curiosity rover and the Blackfoot heterolithic unit (within blue dashed outline) as imaged by HiRISE on 04 September 2015. Yellow trace indicates rover traverse, from north toward southwest. Locations of boulders A and B and the sites of two rover stops on Blackfoot are indicated. Locations of ChemCam targets Sunburst, Swan, Lincoln, Jefferson, Madison, and the APXS/MAHLI target Badlands, are indicated in green. (b) Boulder A is dark-toned when viewed from above; the rock is a dark gray sandstone and it has a surface that is rough at a centimeter scale. (c) Boulder B is light-toned when viewed from above (e.g. HiRISE images); the rock is a dark-gray sandstone; bedding is apparent; the skyward-facing surface is smooth at a centimeter scale and coated with eolian dust. (d) Blackfoot as seen from the north on Sol 1094 when the rover was parked at the position shown in (a). Boulders A and B and the locations of (e), (f), and (g) are indicated. (e) The north and east margins of the Blackfoot heterolithic unit overlie dark-gray, cross-bedded eolian Stimson formation sandstones. (f) North edge of Blackfoot reveals the deposit in cross-section; here, it consists of a jumble of angular cobbles and pebbles; cobbles display a variety of orientations relative to their internal sedimentary structures (bedding). Dark-toned eolian sand has filled some of the gaps between stones. (g) Many of the open fractures which cut through Stimson formation sandstones exhibit a light-toned, fracture-parallel, altered zone (a “halo;” see Frydenvang et al., 2017 and Yen et al., 2017). Here a fracture and associated halo follow the red trace and are abruptly truncated where covered by the Blackfoot heterolithic unit; this indicates that the fracture and fluids responsible for the “halo” alteration did not penetrate the Blackfoot deposit; i.e., one of the indicators that the deposit is not a lithic unit. (h) At its west-southwest end, the Blackfoot unit directly overlies mudstones of the Murray formation. (i) The cobbles and boulders of Blackfoot display a range of orientations, relative to their internal structure (bedding). Some of them protrude from the surface, others rest on the surface.

FIG 3

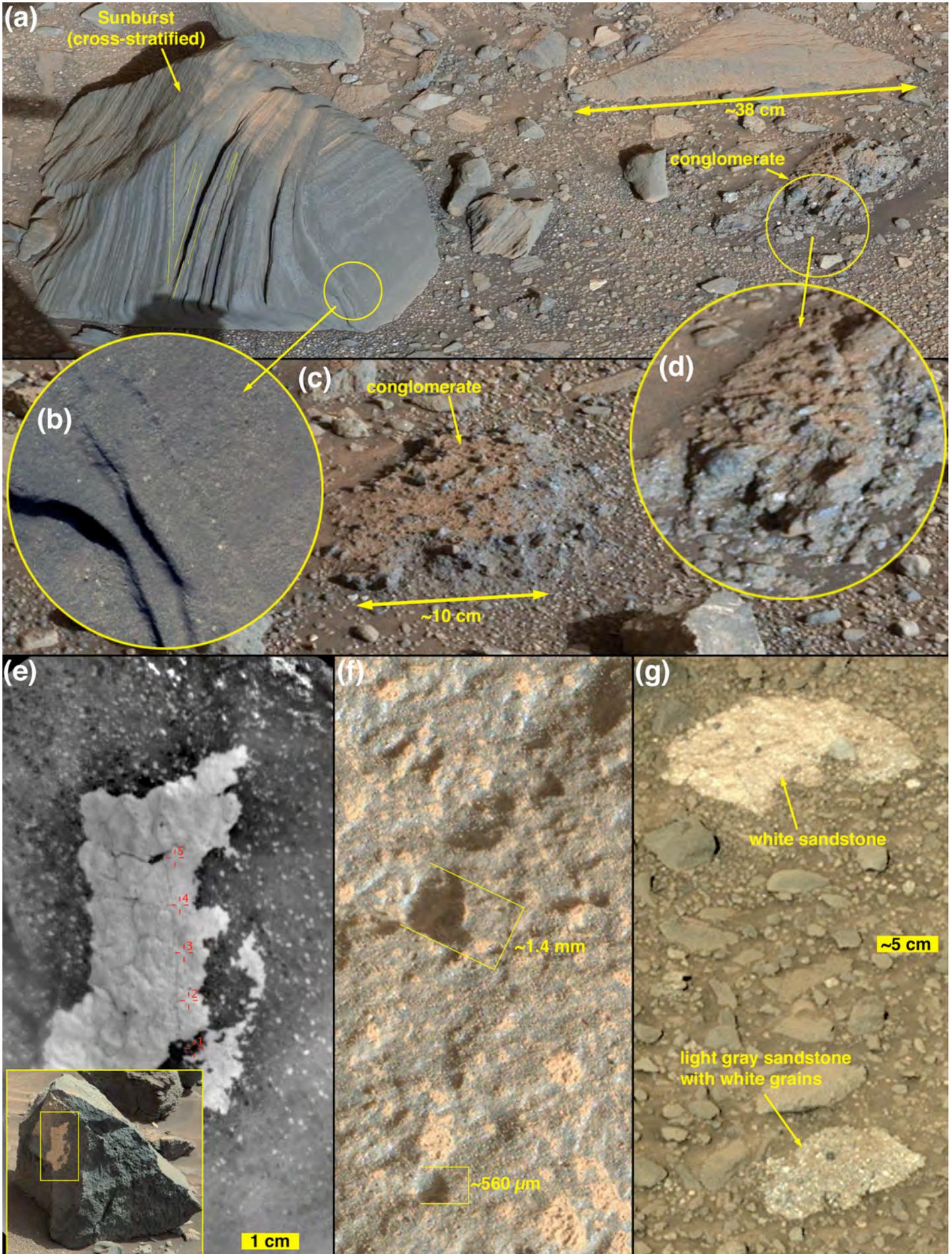


Fig. 3. (a) Typical Blackfoot surface, with scattered cobbles, small boulders, pebbles, and sand of various orientations (relative to internal sedimentary structure, such as bedding), colors, and lithologies. Two key examples are highlighted: A cross-stratified sandstone boulder (ChemCam target named Sunburst) and a conglomeratic cobble. (b) Dark-gray sandstone target named Sunburst. White and light-gray sand grains are readily distinguished because of their contrast relative to the majority of grains, which are dark gray. (c) Example of a light-gray conglomeratic cobble, protruding from the surface. The orange-brown material on part of this stone is eolian dust. (d) Pebbles in an otherwise light gray sandy matrix in a conglomeratic stone protruding from the surface at Blackfoot. (e) ChemCam target Madison; inset shows the image location on the rock face. The large, light-toned feature consists of the remains of a fracture wall vein composed of calcium sulfate. More importantly, the image shows light-toned sand grains, which contrast with the bulk of dark-toned sand grains (much more difficult to see) in this rock. Madison is a dark-gray sandstone. (f) APXS/MAHLI target, Badlands. This stone, too, is a dark-gray sandstone. Unlike Madison and Sunburst, Badlands has no light-toned sand grains; they are all dark gray. The sizes of two larger grains are indicated; most grains are smaller and difficult to distinguish from each other and their intergranular cement. Brownish-orange patches are depressions (some of them, perhaps, may be sockets from which sand grains have been removed) containing eolian dust. (g) Two examples of the light-toned sandstone or pebbly conglomerate fragments which occur at Blackfoot.

FIG 4

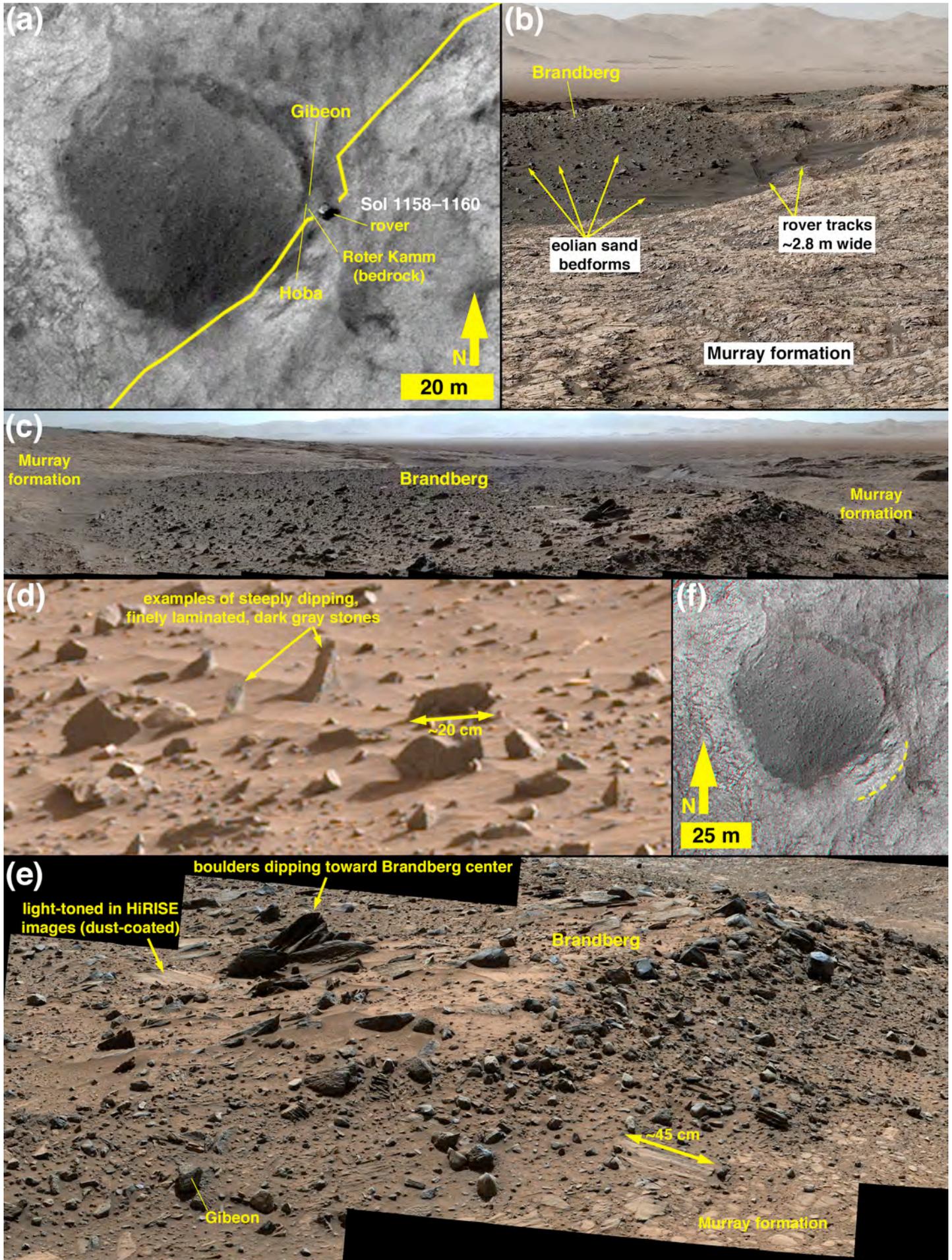


Fig. 4. (a) Brandberg and the Curiosity rover as viewed by HiRISE on Sol 1159. Yellow trace indicates the rover traverse; drive direction was from northeast to southwest. ChemCam targets are indicated by name. (b) Eastern Brandberg. In this scene, Brandberg is downhill from the rover; the near side of Brandberg forms a shallow depression. Rover tracks provide scale. Eolian bedforms explain the faint lineated texture observable in HiRISE images. (c) Brandberg as viewed from the northeast. (d) Examples of steeply dipping cobble-sized angular clasts in Brandberg. (e) Examples of clast variety in northeastern Brandberg. The largest boulder-sized clasts dip toward the center of the circular landform. Boulders with relatively flat, skyward-facing surfaces are coated with dust and thus appear light-toned when seen from above in HiRISE images. The ChemCam target, Gibeon, is indicated. (f) Red/cyan stereo pair anaglyph produced from two HiRISE images; the dashed yellow arc indicates a ridge that might be an indicator that Brandberg occurs within the eroded remains of an impact structure.

FIG 5

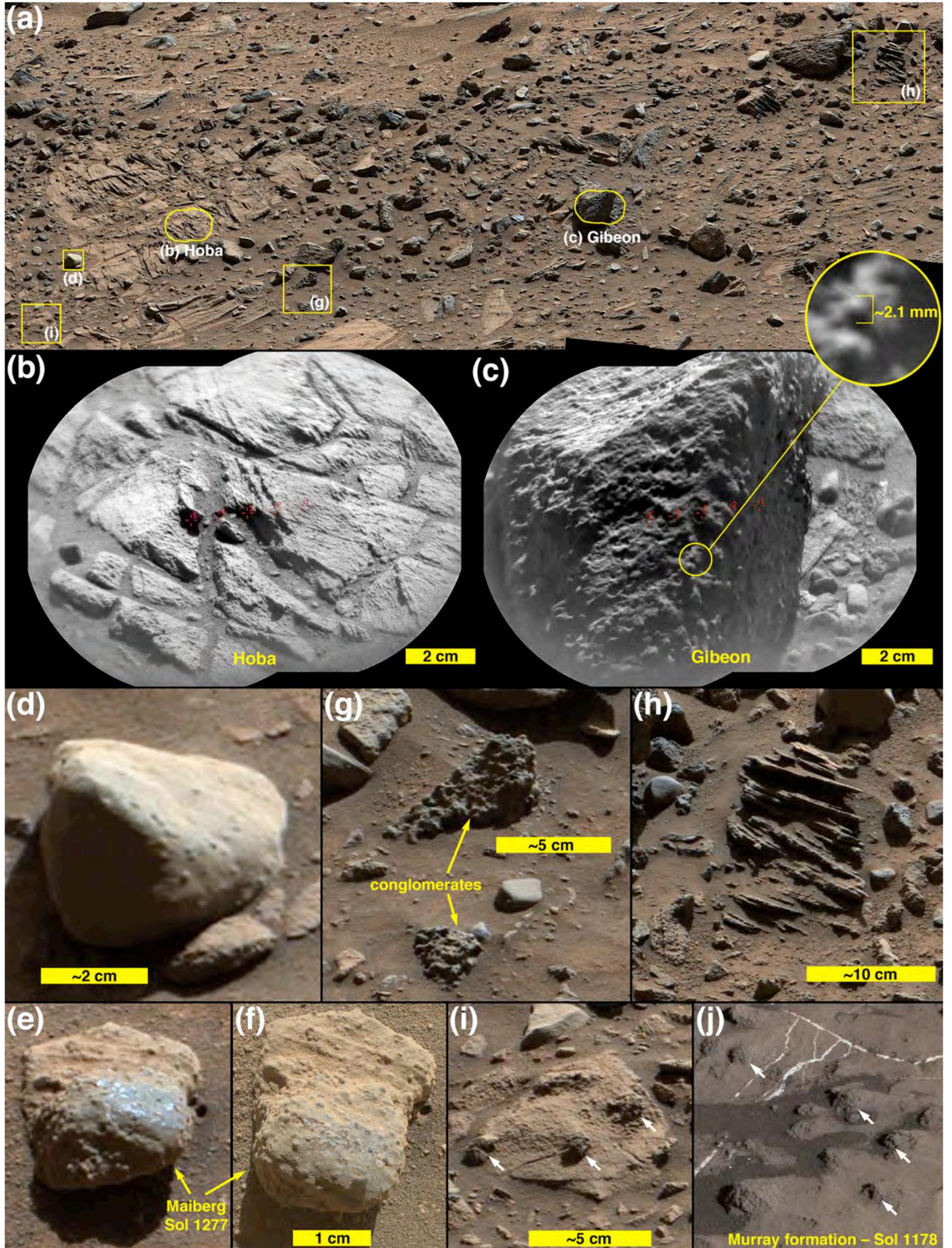


Fig. 5. (a) Sol 1160 view of the variety of boulders, cobbles, and pebbles which compose the Brandberg deposit. Yellow outlines indicate locations of panels b, c, d, g, h, and i. (b) Dust-coated, fractured Murray-formation lithic clast target named Hoba. (c) Dark-gray sandstone cobble target named Gibeon. The inset shows enlargement of a single grain or concretion, representative of the larger grains (or typical concretion size) in this rock, ~2 mm. (d) Sandstone with concretions. (e) Example sandstone with concretions (target named Maiberg) liberated from Stimson formation bedrock on the east side of Naukluft Plateau, imaged on Sol 1277; shown here for comparison. (f) Sedimentary structure and texture details of Maiberg. (g) Examples of candidate, rare conglomeratic stones at Brandberg. (h) Example of angular, cobble-sized fragment of cross-bedded sandstone. (i) Example lithic fragment of Murray-formation bedrock incorporated into the Brandberg deposit; white arrows indicate erosion-resistant concretions; compare with (j): Example of intact Murray-formation bedrock south of Brandberg which contains similar concretions (white arrows).

FIG 6a

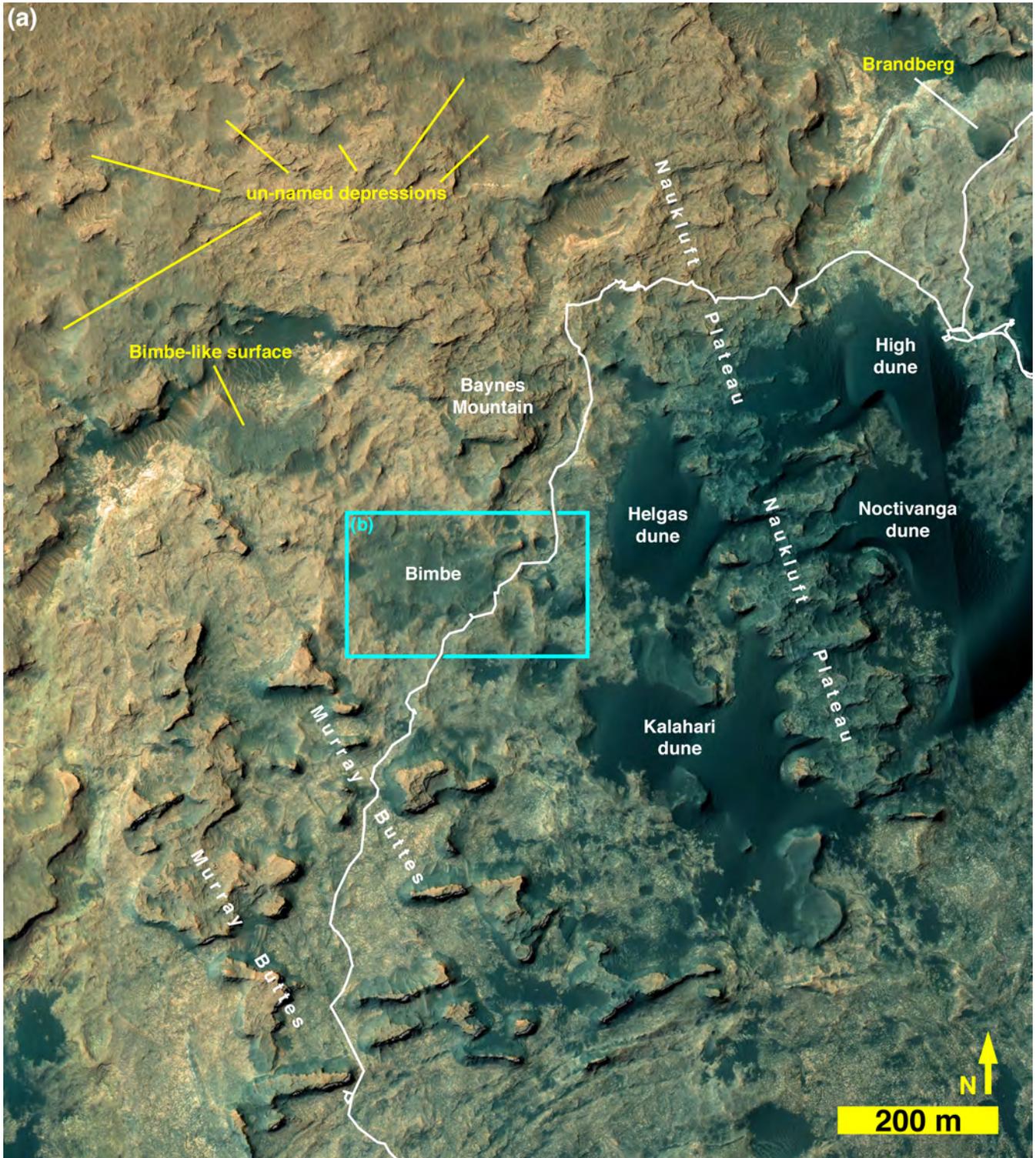


FIG 6b

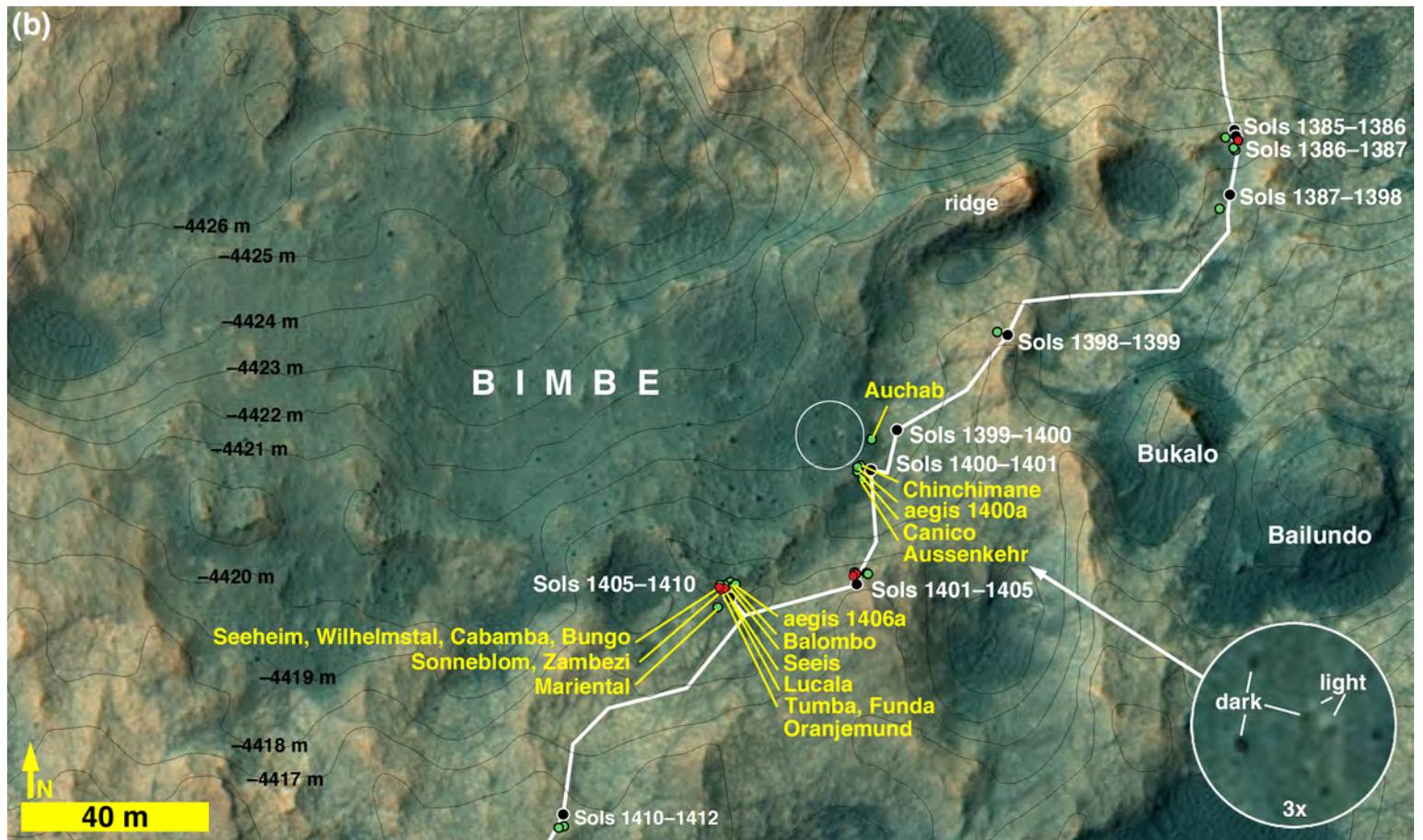


Fig. 6. (a) Local context of Bimbe on the lower slopes of Mt. Sharp, between the Murray buttes to the south, Naukluft Plateau and some of the Bagnold dunes to the east, and Baynes Mountain to the north. The white trace is the Curiosity rover traverse; the drive direction was from northeast (upper right) toward the south (bottom left of center). Blue box indicates the location of (b): Bimbe with ChemCam, APXS, and MAHLI targets indicated in yellow. Green dots indicate ChemCam targets, red dots indicate APXS targets, and black dots indicate rover parking spots. The inset, a 3x expanded view of the area inside the white circle next to target Auchab, shows an example of light- and dark-toned boulders as observed from the orbiting HiRISE camera. The white trace is the Curiosity rover traverse; the drive direction was from the northeast (upper right) toward the south (bottom center). The elevation contours are derived from HiRISE stereo pair products calibrated to Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA), topography by Parker and Calef (2016).

FIG 7

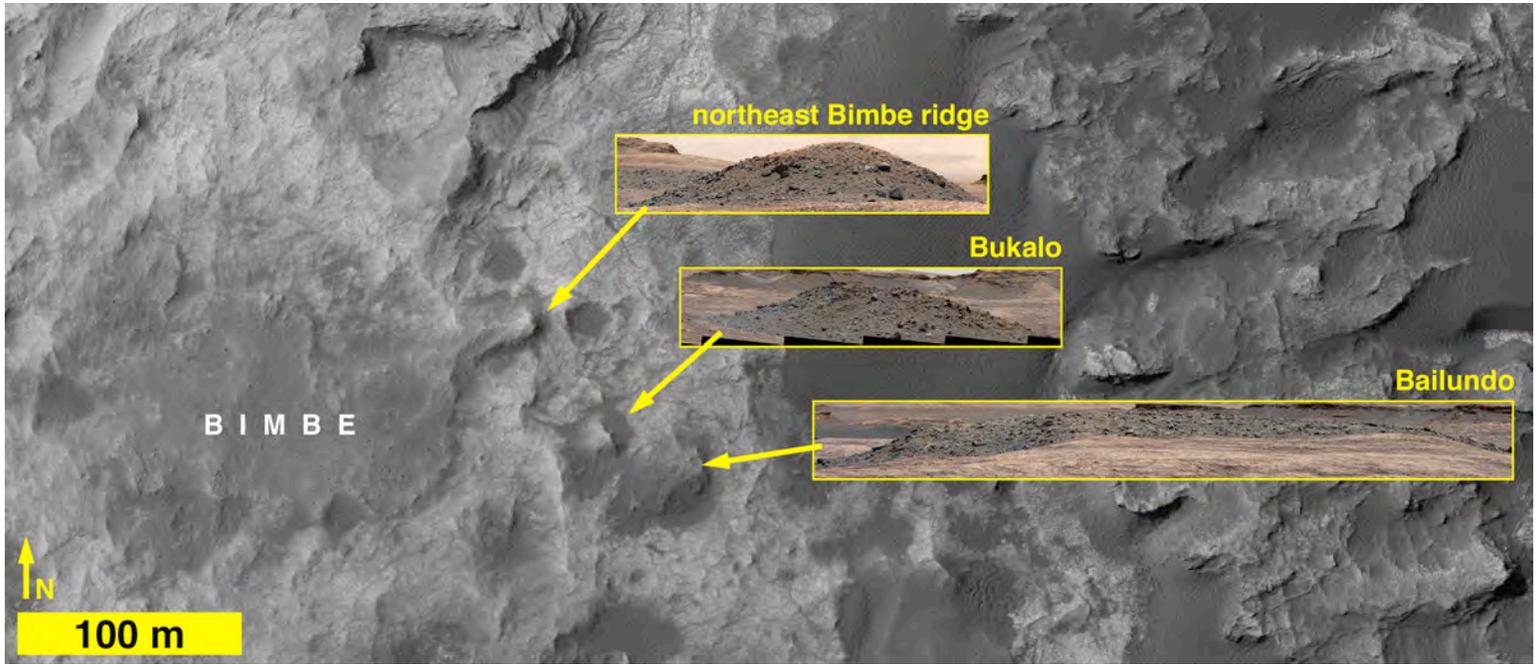


Fig. 7. A ridge on the northeast side of Bimbe, which trends northeast-southwest (azimuth $\sim 65.5^\circ$), is mantled with cobbles and small boulders in Mastcam images (inset). The ridge resembles nearby boulder- and cobble-mantled hills named Bukalo and Bailundo (insets). These are likely examples of buttes that have weathered to the point that they are hills with remnants of the capping rock taking the form of small boulders and cobbles (cf. Migoń et al., 2018).

FIG 8

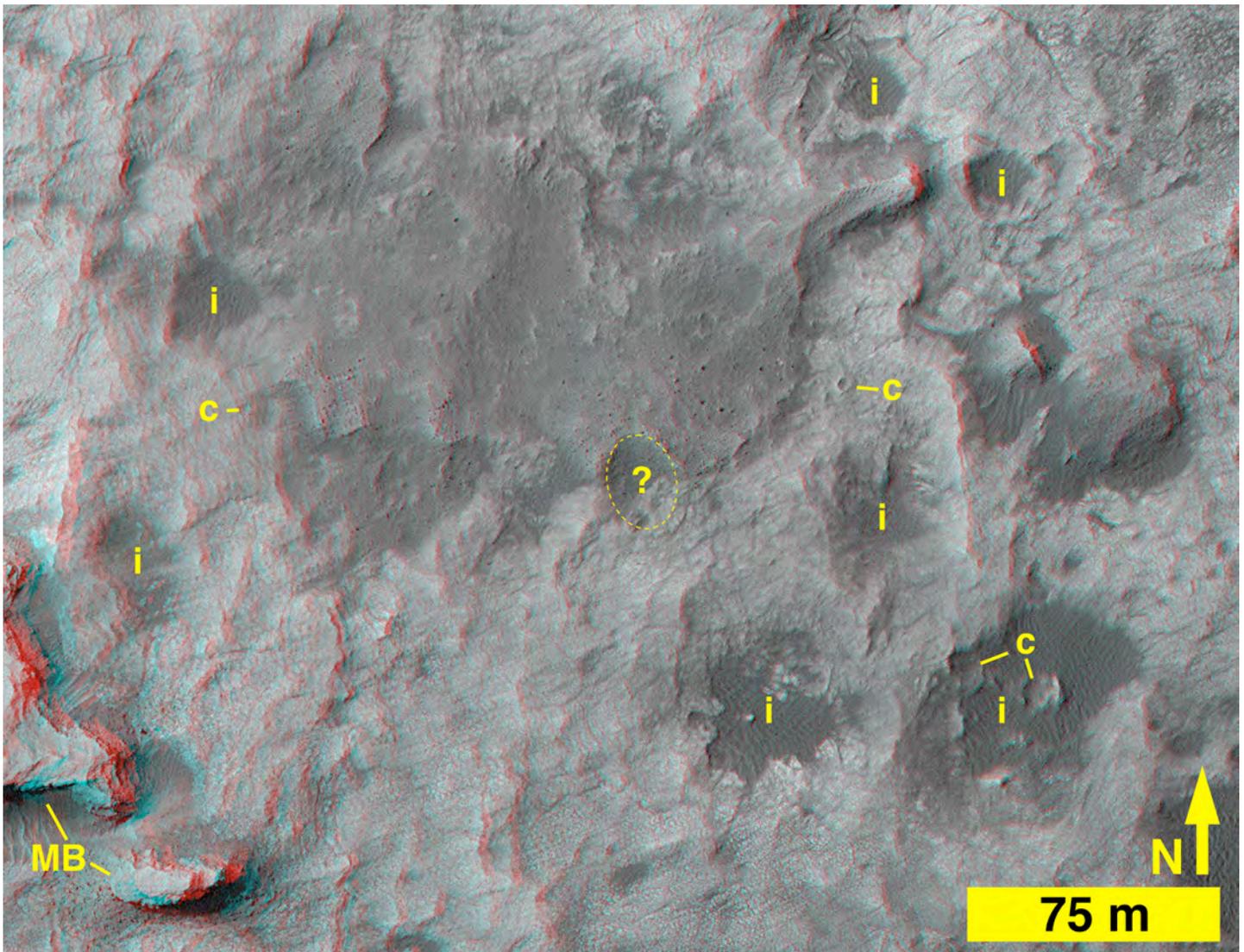


Fig. 8. Stereo pair anaglyph of Bimbe (large, dark-toned patch) and its vicinity. Most of the boulders observed at Bimbe occur on the elevated portions of the south margin of Bimbe. The feature within the dashed yellow ellipse, indicated with a “?”, might be the eroded remains of an impact structure. Definitive impact craters are labeled with “c” and probable impact structures are labeled with “i”. Dark-toned eolian sand, expressed as bedforms, has collected in the impact structure depressions. Features labeled “MB” are a couple of the Murray buttes.

FIG 9a



FIG 9b

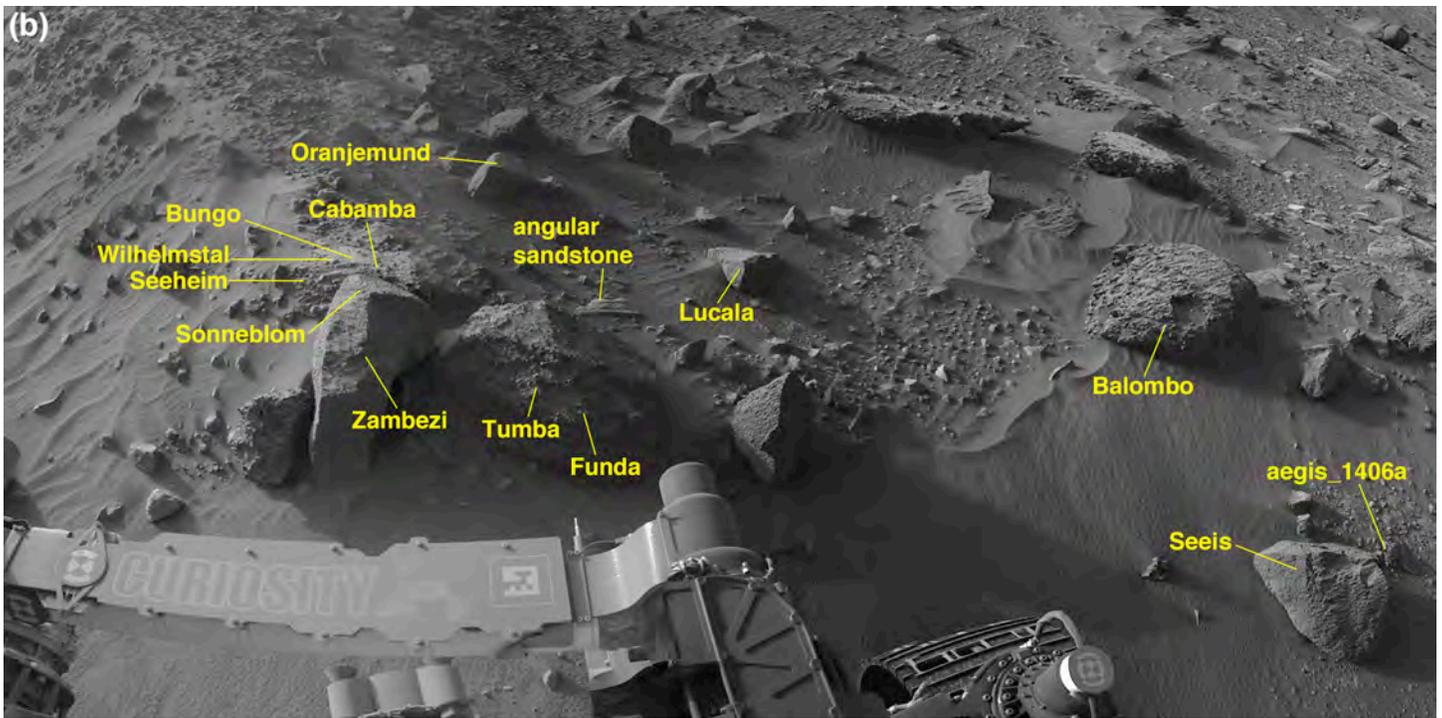


Fig. 9. (a) Work site for sols 1405–1410, viewed from the east. Names of targets investigated using ChemCam, Mastcam, APXS, and MAHLI are indicated. The dashed yellow trace approximately indicates the crest of a low ridge line that defines the southern margins of Bimbe. (b) Navcam view of the work site. ChemCam, APXS, and MAHLI targets are indicated (except Mariental, which is to the left of this scene). The stone labeled “angular sandstone,” imaged by MAHLI on Sol 1407, is also shown in Fig. 15 and was not a named target. For scale, the width of the rover wheel (right of lower center) is 40 cm.

FIG 10

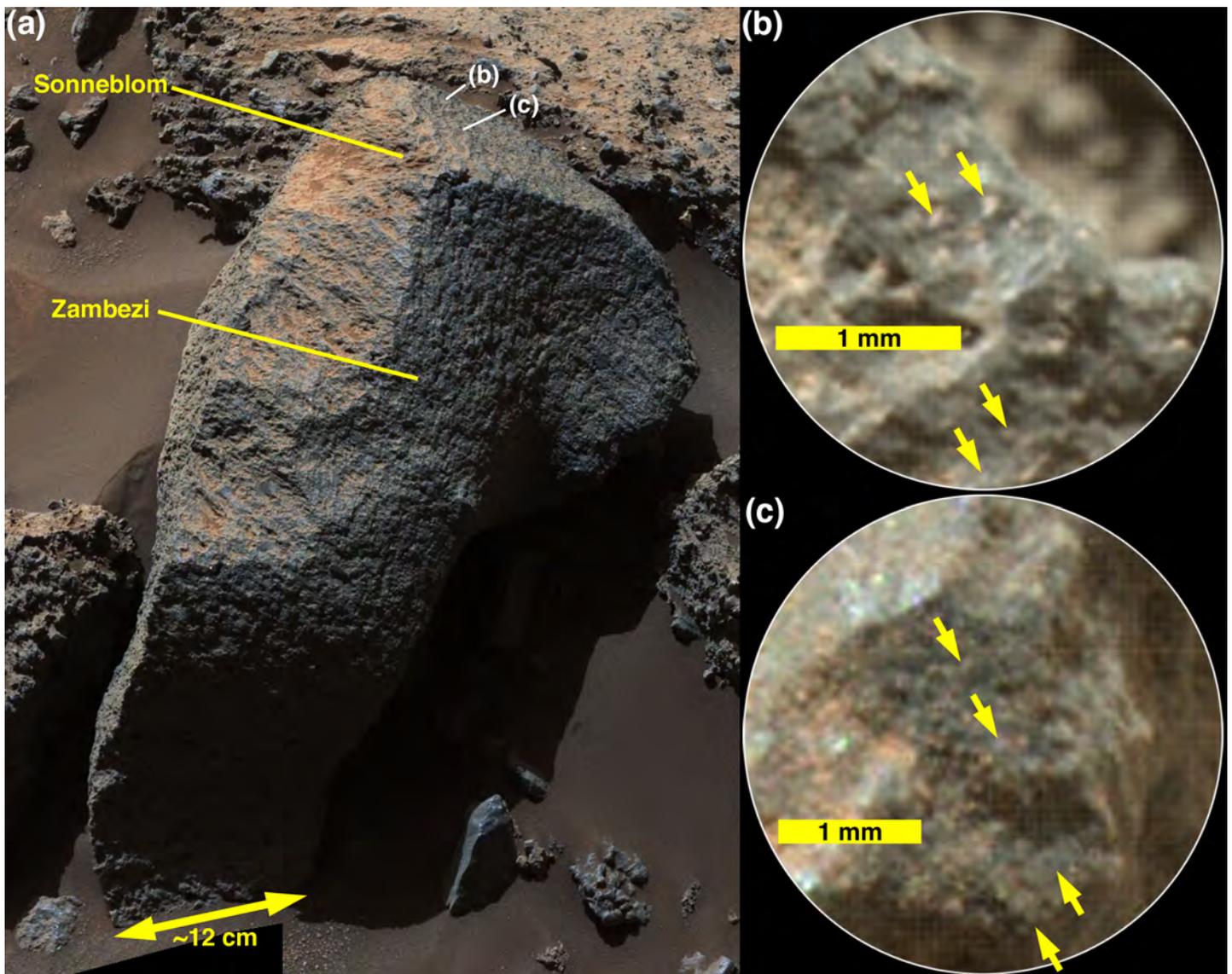


Fig. 10. (a) Boulder containing targets Sonneblom (ChemCam, APXS, MAHLI) and Zambezi (APXS, MAHLI). The boulder is a dark-gray, pitted sandstone; the locations of the MAHLI views in (b) and (c) are indicated. (b and c) Close-up views of the surface; the yellow arrows point to several individual grains.

FIG 11

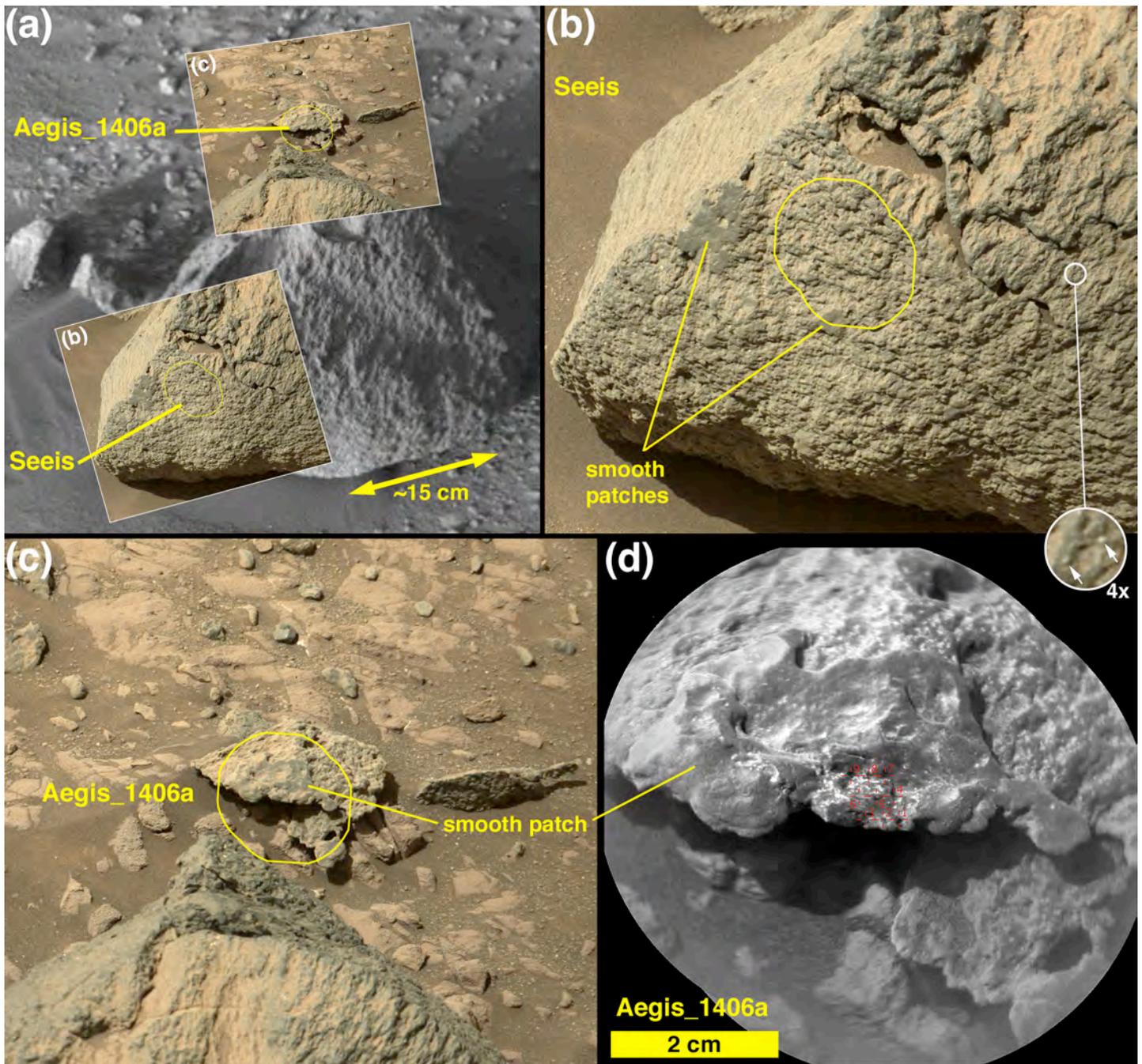


Fig. 11. (a) Context for two ChemCam targets, Seeis and Aegis_1406a, on two separate stones at Bimbe. (b) Seeis target; yellow outline indicates location of ChemCam RMI coverage, 4x inset indicates examples of the largest (mm-scale) grains. (c) AEGIS_1406a target; yellow outline indicates the location of the ChemCam RMI coverage shown to the right. (d) Close-up view, with red crosshairs indicating LIBS observation points on AEGIS_1406a.

FIG 12

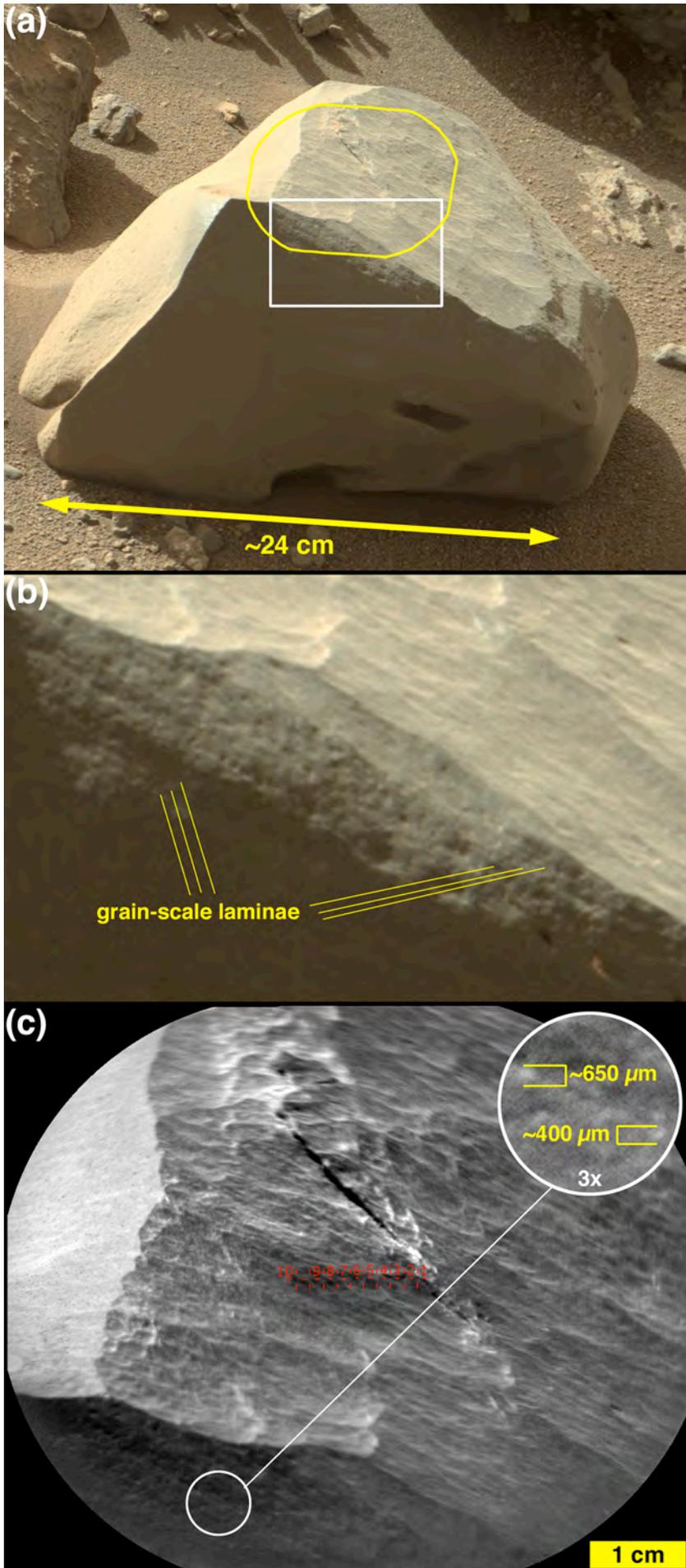


Fig. 12. (a) Dark-gray sandstone cobble target named Oranjemund. White box indicates location of expanded view in (b); yellow outline indicates ChemCam RMI coverage in (c). (b) View showing grain-scale bedding, which runs diagonally from upper left to lower right. (c) Close-up view of Oranjemund; inset shows 3x expanded view with measurements on features that could be among the larger sand grains in the rock (i.e., most of the grains are smaller than ~400 μm). Oranjemund is compositionally identical to layered target Chinchimane (Fig. 14).

FIG 13

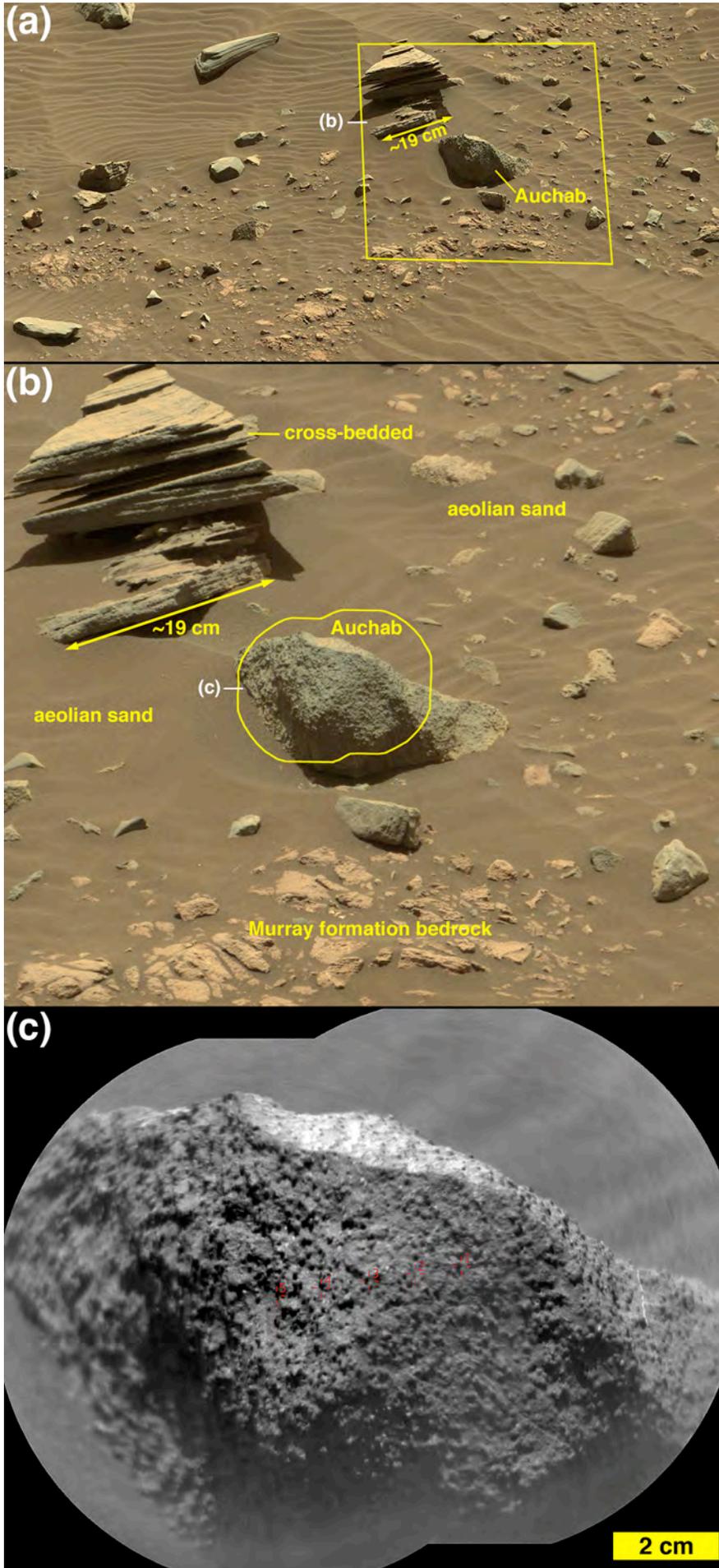


Fig. 13. (a) Local context for ChemCam target Auchab; yellow outline indicates location of panel (b); closer view of knobby gray target Auchab; yellow outline indicates ChemCam RMI coverage in (c). Note the nearby angular, cross-bedded sandstone clast. Both stones are surrounded by windblown sand and overlie reddish Murray-formation bedrock. (c) ChemCam RMI mosaic showing the nodular texture of Auchab.

FIG 14

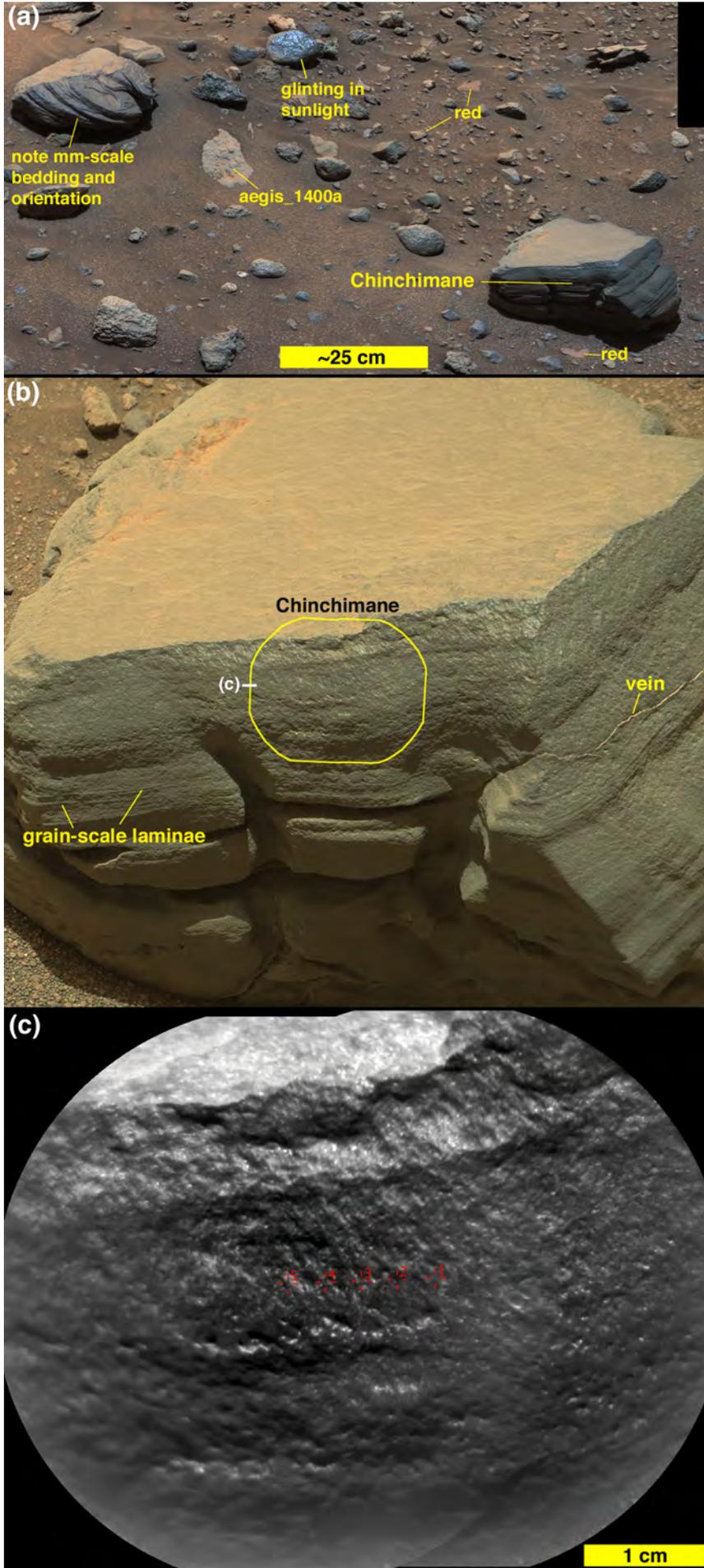


Fig. 14 (a) Local context for layered gray sandstone cobble target Chinchimane. Note the differences in cobble orientation relative to their bedding structure, as well as the diversity of cobble colors, response to sunlight, and sedimentary structure and texture. (b) Mastcam-100 view. Bedding is approximately parallel and thin (sand grain scale thickness). A fracture filled with a white material (vein) cuts across bedding. The yellow outline indicates the location of the ChemCam RMI coverage shown in (c), where a few individual sand grains can be identified in a well cemented and well sorted sandstone.

FIG 15

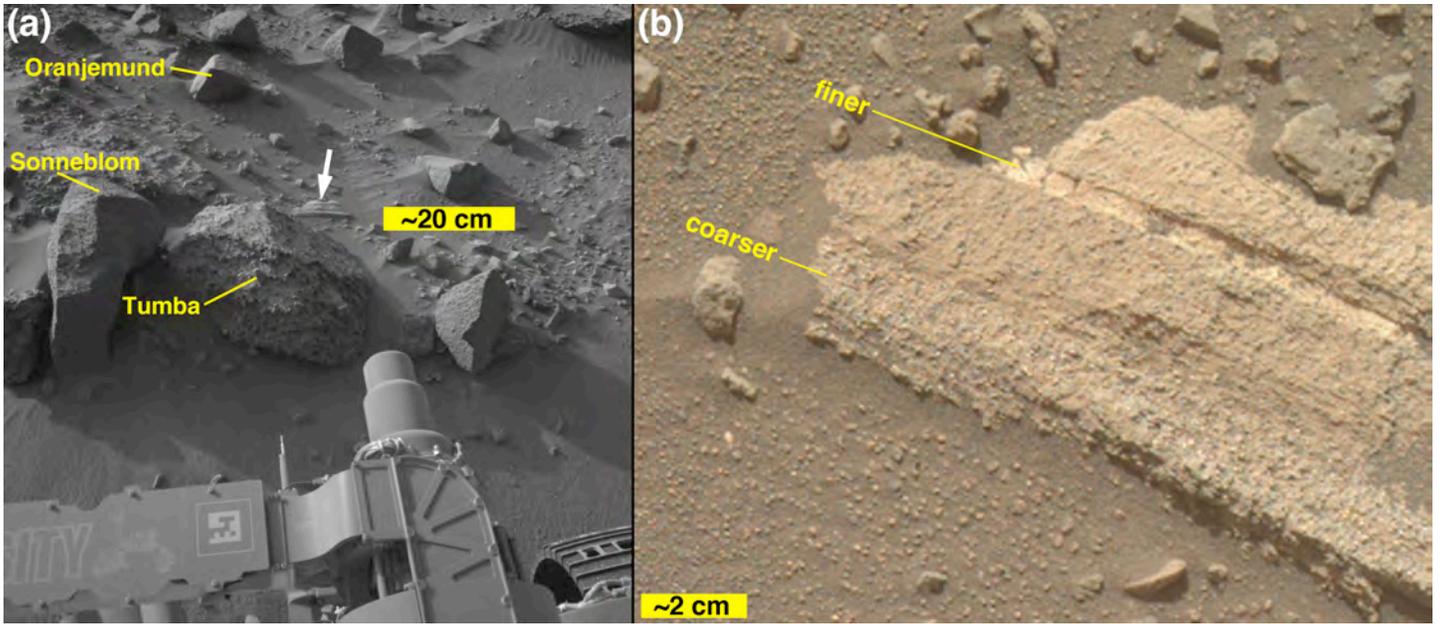


Fig. 15. Angular sandstone cobble with fine-grained interbeds. (a) Location (white arrow) of the cobble relative to the larger boulders in the rover workspace during sols 1405–1410. (b) Highest spatial resolution view of the cobble. Coarser grains are $\sim 700 \mu\text{m}$; the skyward rock face cuts steeply across the original bedding. A recessed interval of $\sim 1 \text{ cm}$ thickness consists of grains too small to resolve.

FIG 16

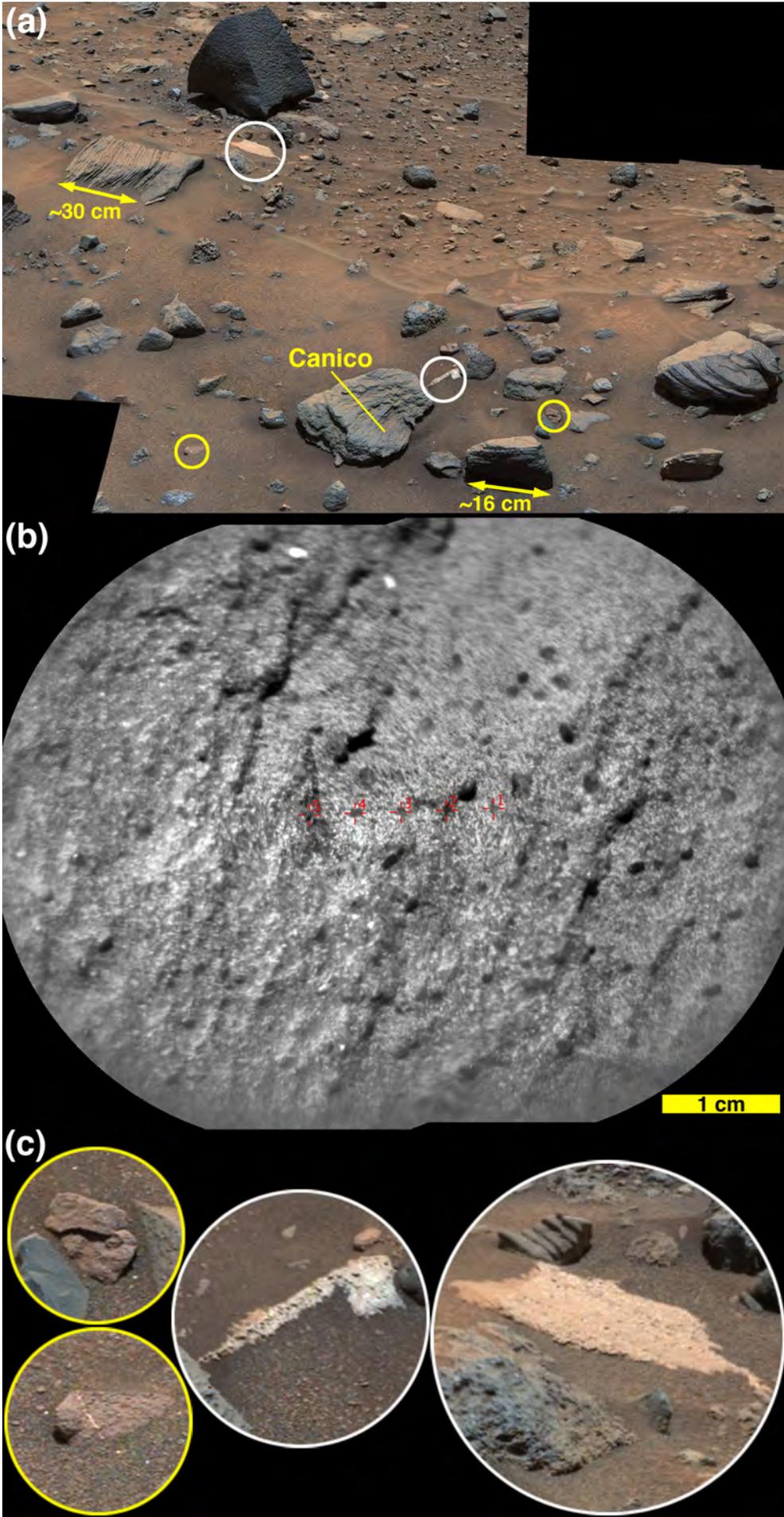


Fig. 16. (a) Example showing diversity of cobble and boulder orientations, sedimentary structures, and colors at Bimbe. The white circles indicate examples of white stones shown in (c); the yellow circles indicate examples of “red” stones in (c). (b) Knobby sandstone target, Canico. (c) Examples of “red” (left) and white (center and right) cobbles which are minor constituents of the Bimbe deposit; locations and relative sizes are shown in (a). The red stone at the lower left in (c) has a white vein cutting across bedding within the stone.

FIG 17

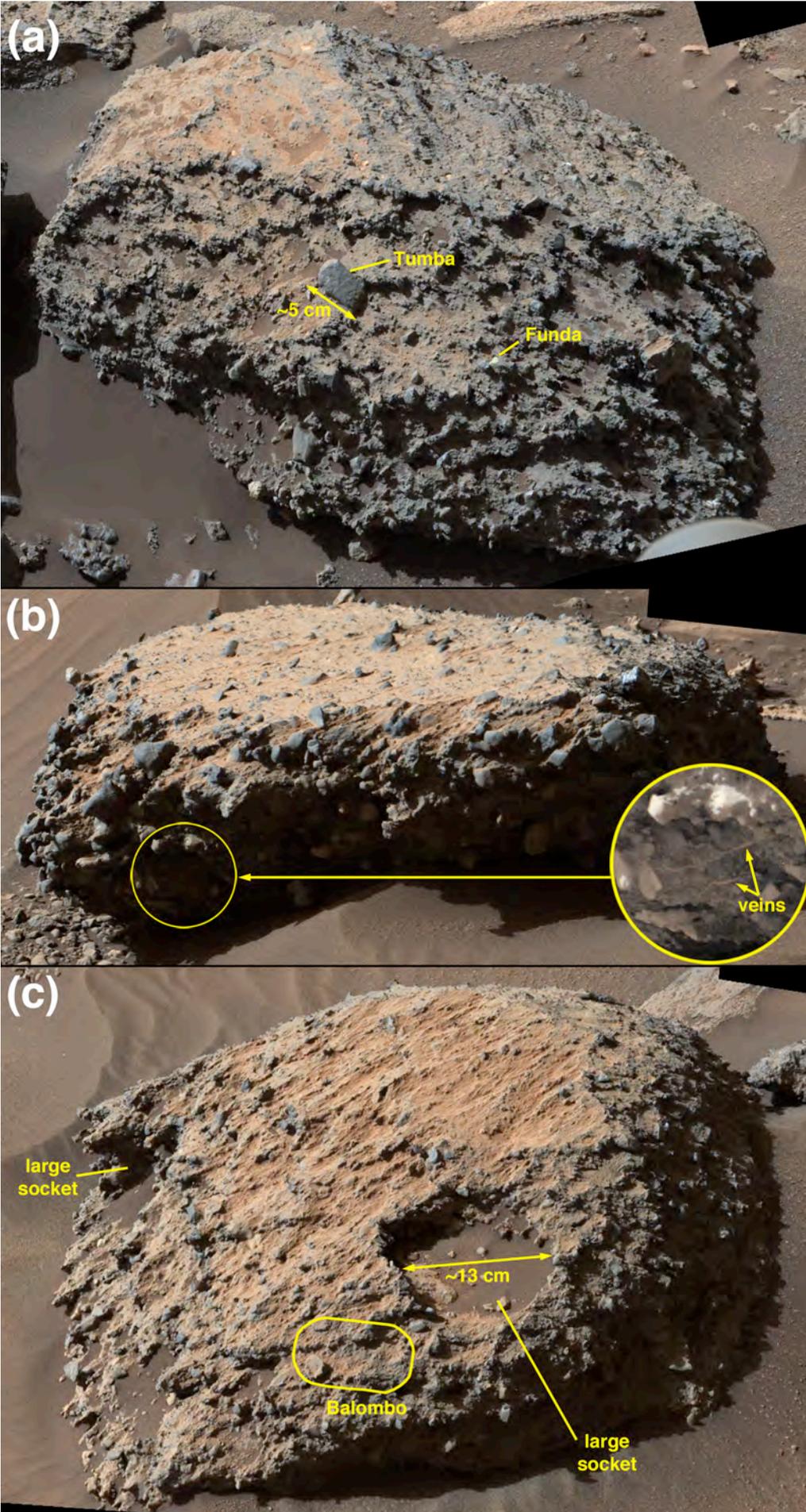


Fig. 17. (a) Conglomeratic boulder containing MAHLI targets Tumba and Funda; the latter was also an APXS target. (b) Conglomeratic boulder, ~60 cm wide, that includes veins that cut across the sandy matrix (inset). (c) Conglomeratic boulder that includes the ChemCam target Balombo (yellow outline indicates RMI image coverage).

FIG 18

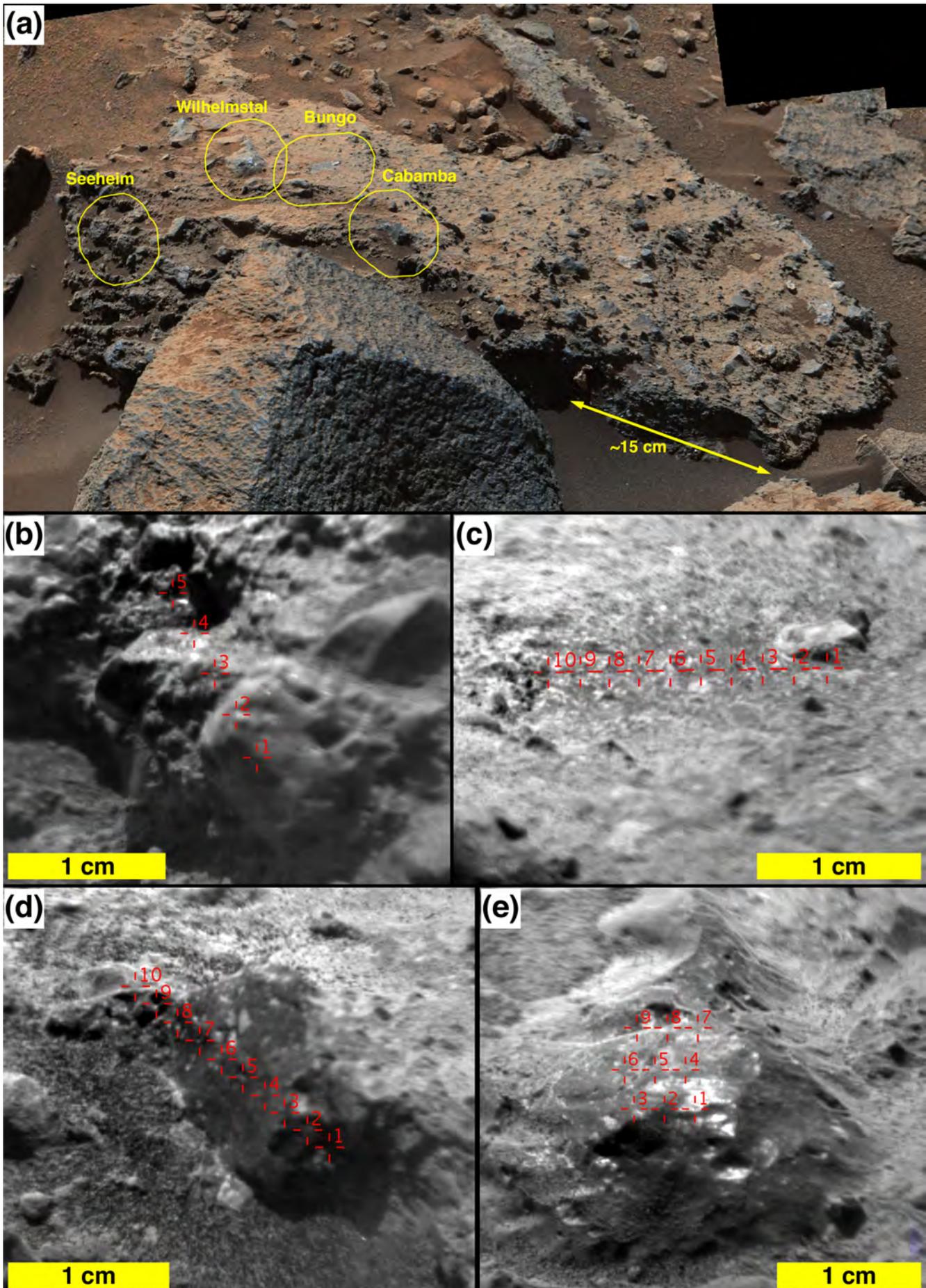


Fig. 18. (a) Conglomeratic boulder investigated via four ChemCam targets. (b-e) Respective RMI views and LIBS target areas of Seeheim, Bungo, Cabamba, and Wilhelmstal. Note the vitreous luster of Wilhelmstal, and similarity to Cabamba.

FIG 19

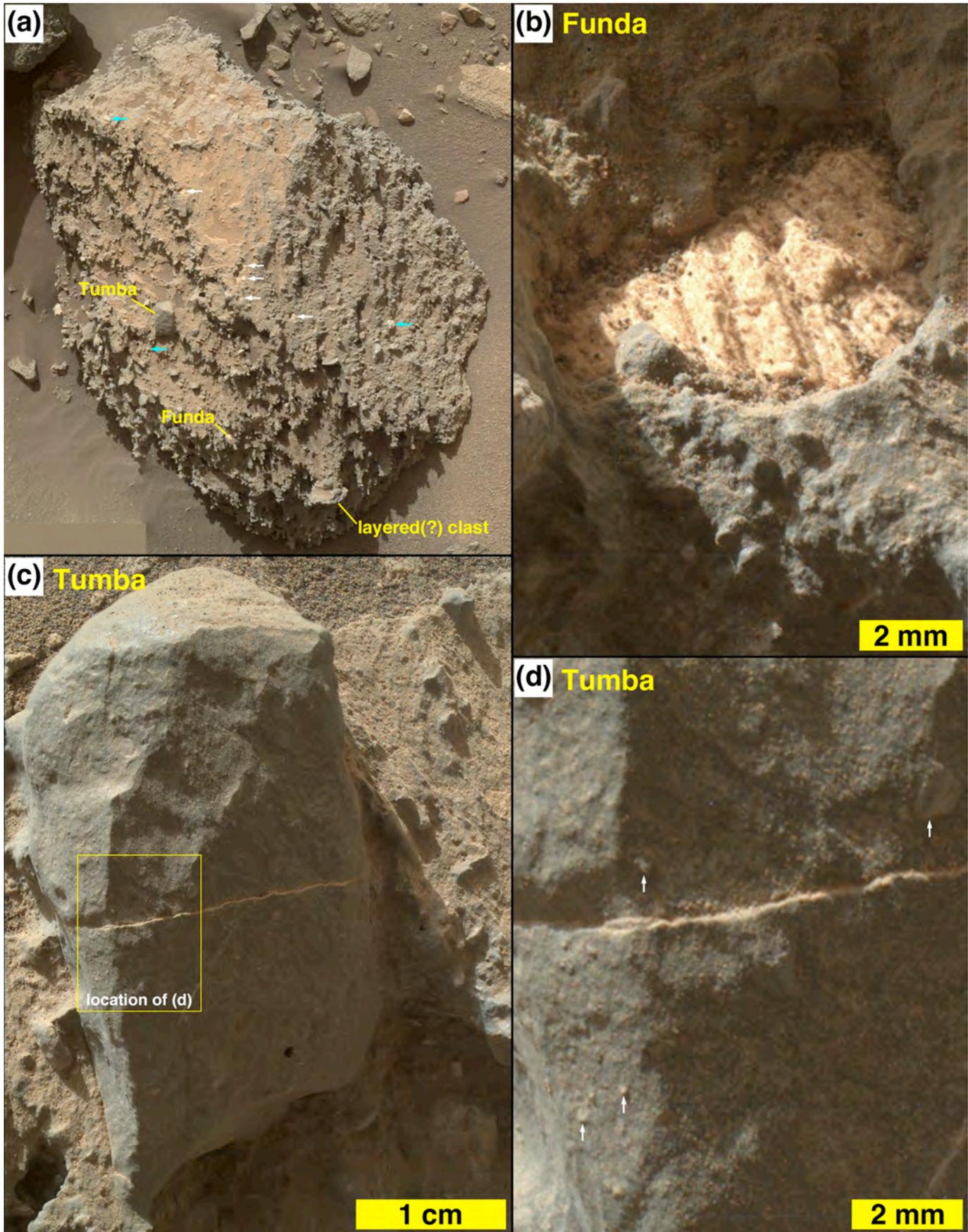


Fig. 19. (a) Conglomeratic boulder that includes the APXS/MAHLI target, Funda, and the MAHLI target, Tumba. White arrows indicate recessed white objects similar to Funda; blue arrows indicate light-gray and white protrusive pebble clasts. (b) Close-up view of white, recessed, banded object (clast or void fill) comprising the target Funda. (c) Pebble clast target named Tumba. (d) Close-up view of a portion of the Tumba pebble clast, showing that it is a sandstone; arrows point to a few example grains.

FIG 20

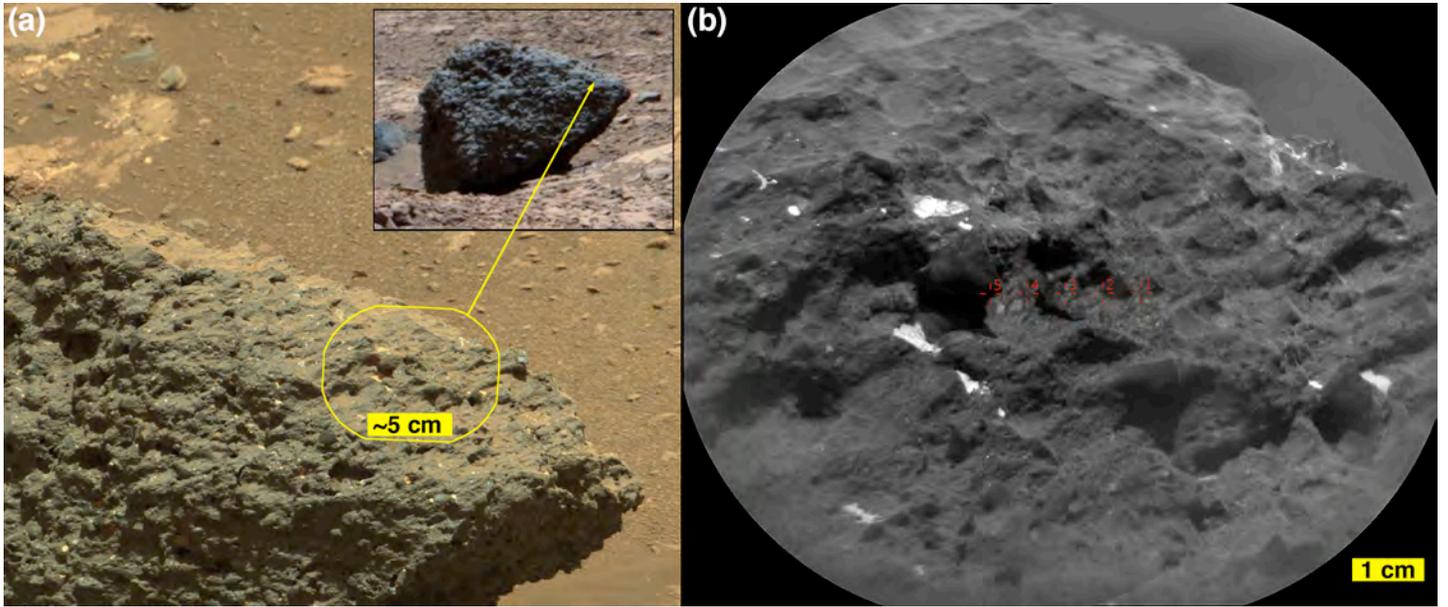


Fig. 20. (a) Conglomeratic boulder with ChemCam target, Mariental. Inset shows the entire boulder. (b) Close-up view of Mariental and the locations of ChemCam LIBS observations. Recessive white features are interpreted to be similar to Funda (Fig. 19).

FIG 21

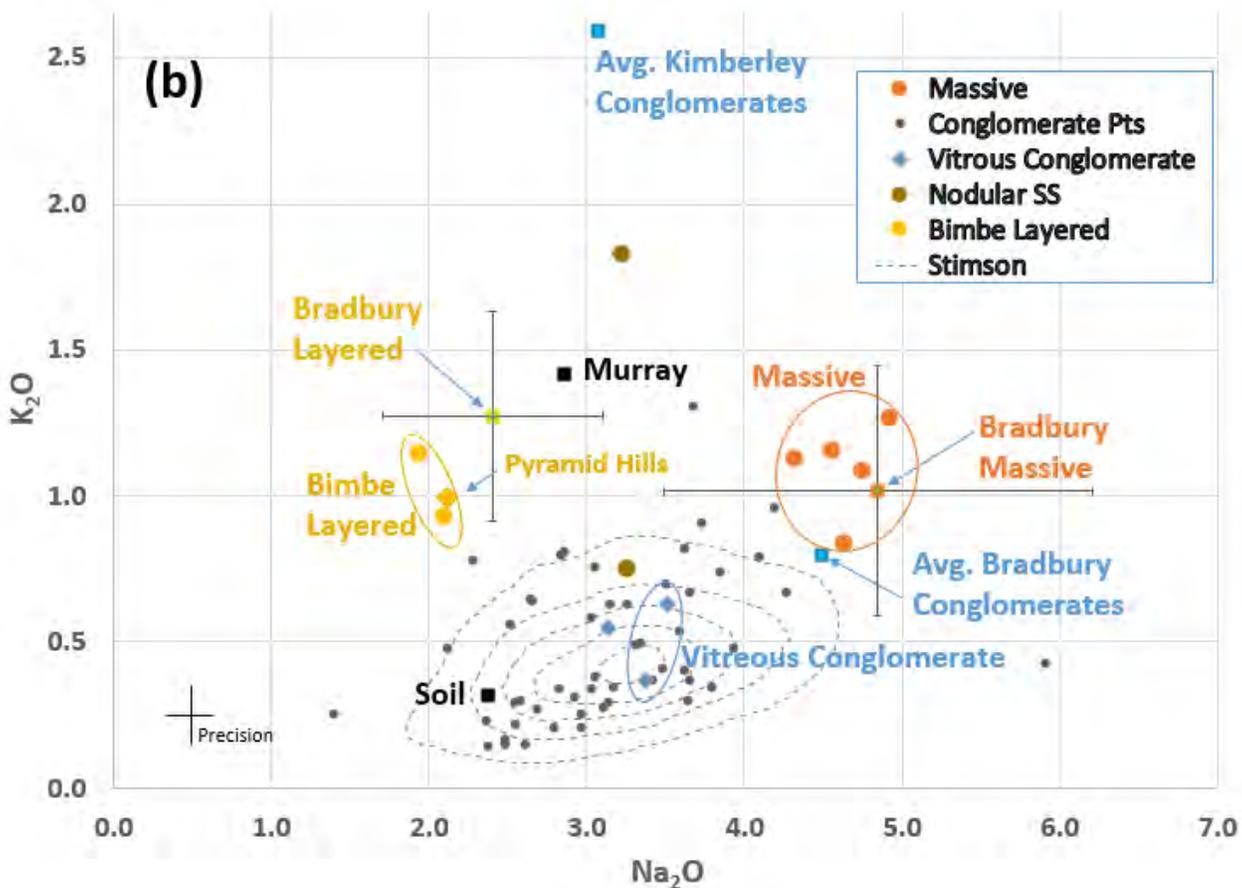
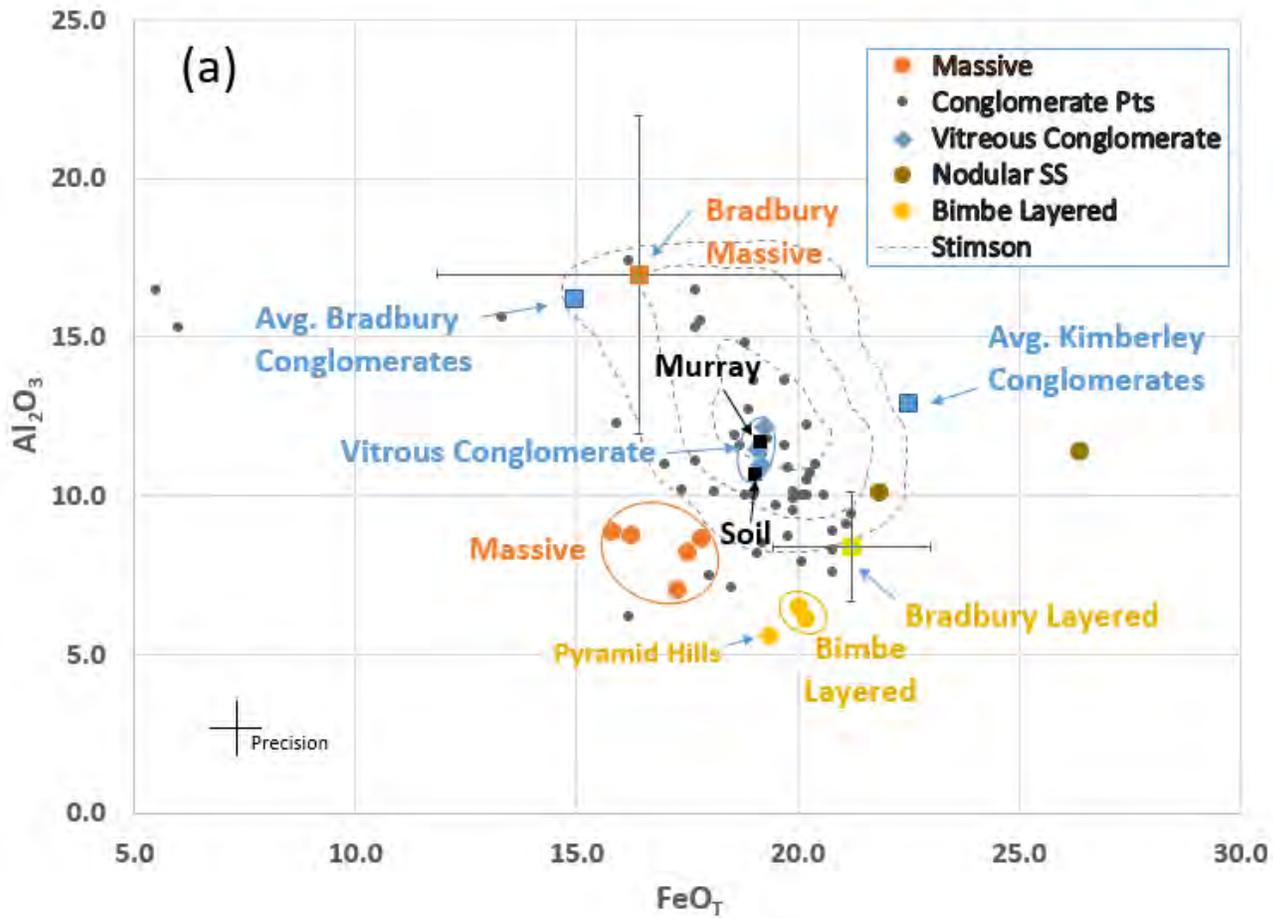


FIG 21

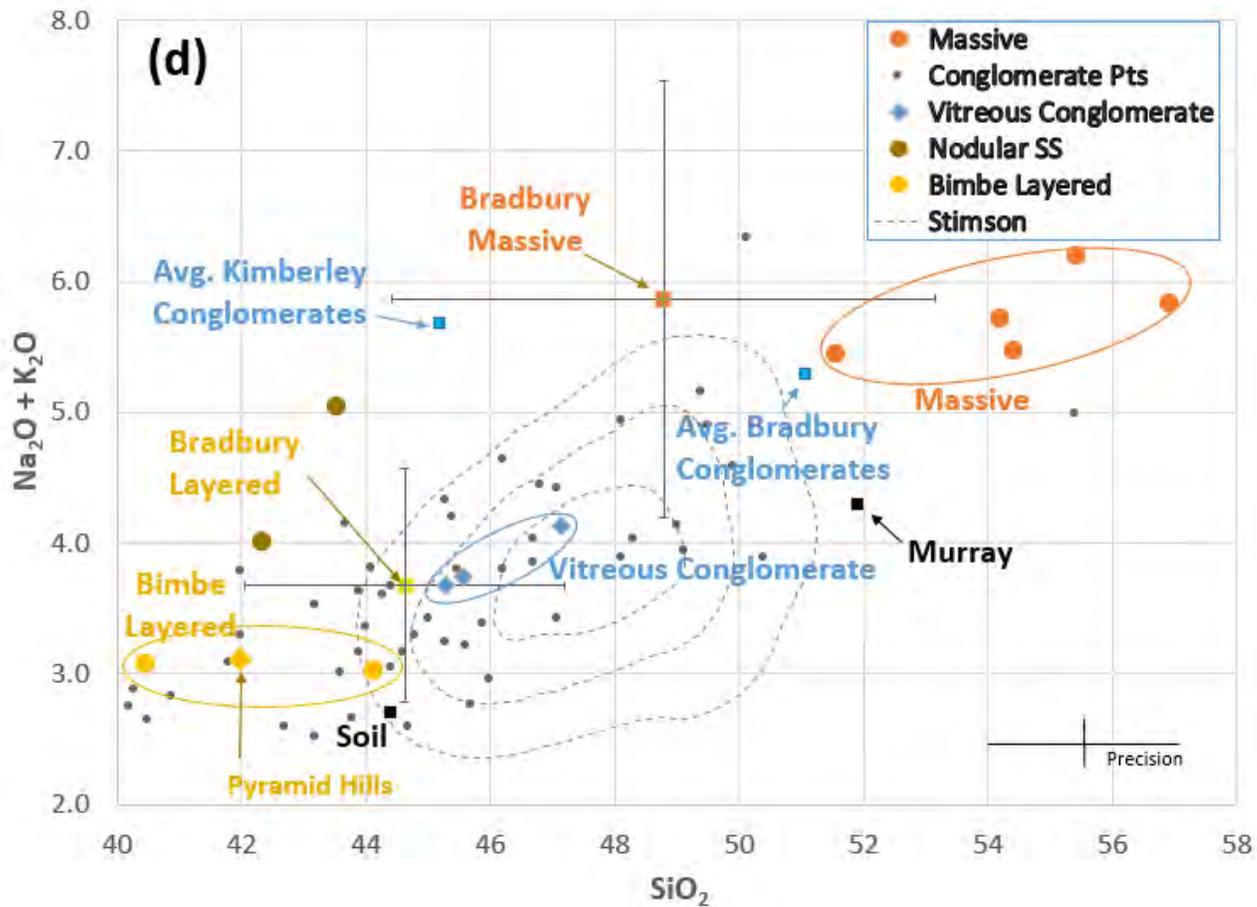
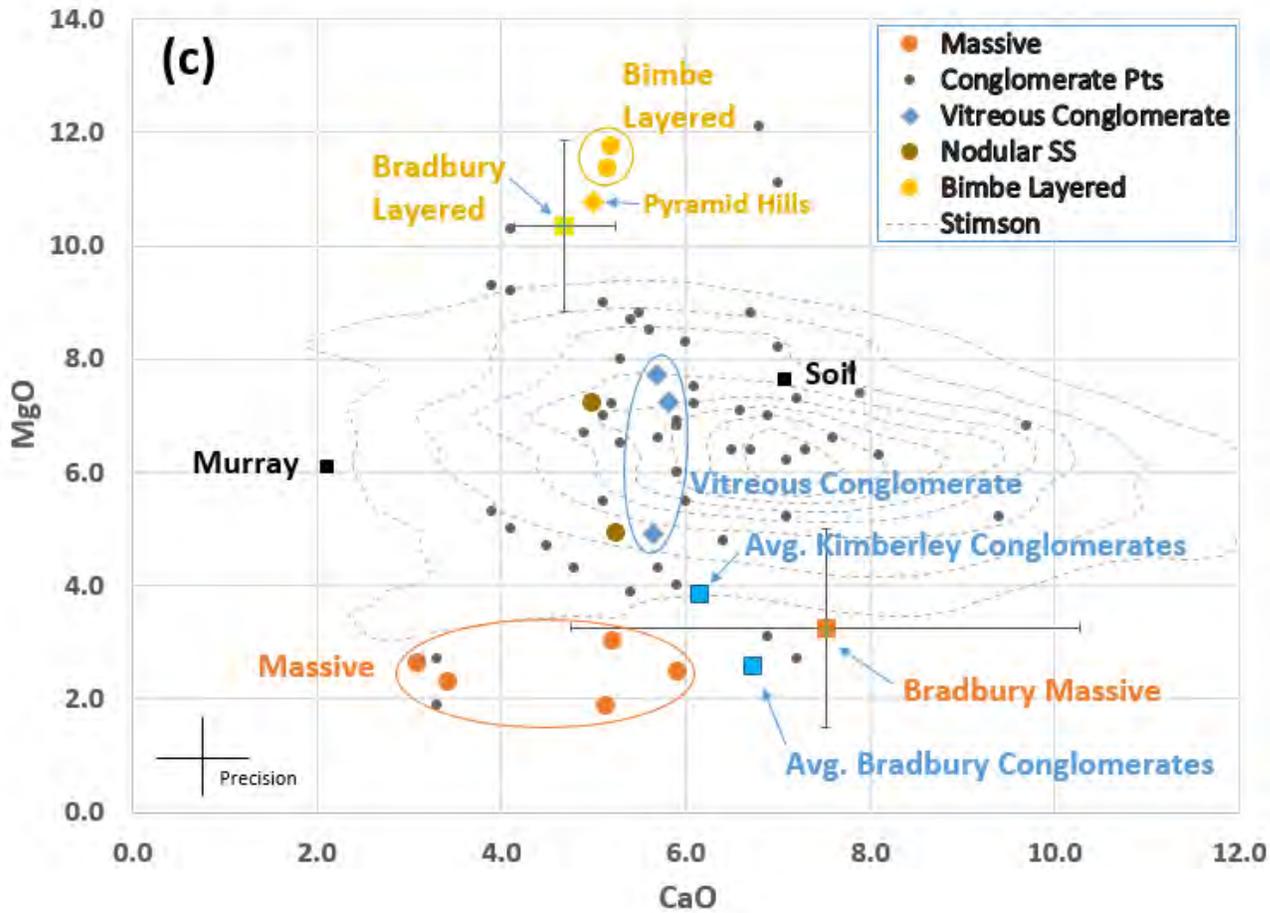


Fig. 21. Major-element abundances, in wt. %, of ChemCam targets at Bimbe. Larger symbols indicate averages of individual targets for Aussenkehr, Lucala, Seeis, Sonneblom, AEGIS_post_1406a ("Massive," red dots); Wilhelmstal, Cabamba ("Vitreous Conglomerate," blue diamonds; also includes AEGIS_post_1400a); Chinchimane, Oranjemund ("Bimbe Layered," yellow dots), Auchab and Canico ("Nodular SS," brown dots). Smaller symbols represent individual observation points for the conglomerates ("Conglomerate Pts"), which have more diverse compositions. Circles indicate groupings of Bimbe layered (yellow), massive (red), and vitreous conglomerate (blue) targets. Standard deviations between individual LIBS observation points within a target are given in Table 2. Upper limits on precision for individual point observations are shown in each panel, taken from 480 Sheepbed measurements (Mangold et al., 2015). Also shown are the mean compositions, and standard deviations of the means, of other types of targets observed nearby and earlier along the traverse. These include Murray, Mars soil, two groups of conglomerates, the ChemCam target Pyramid Hills, and a group of massive targets from Bradbury rise. Stimson formation compositions are shown as contours where each contour represents equal weighting in terms of density of samples (see text and Supplementary Material).

FIG 22

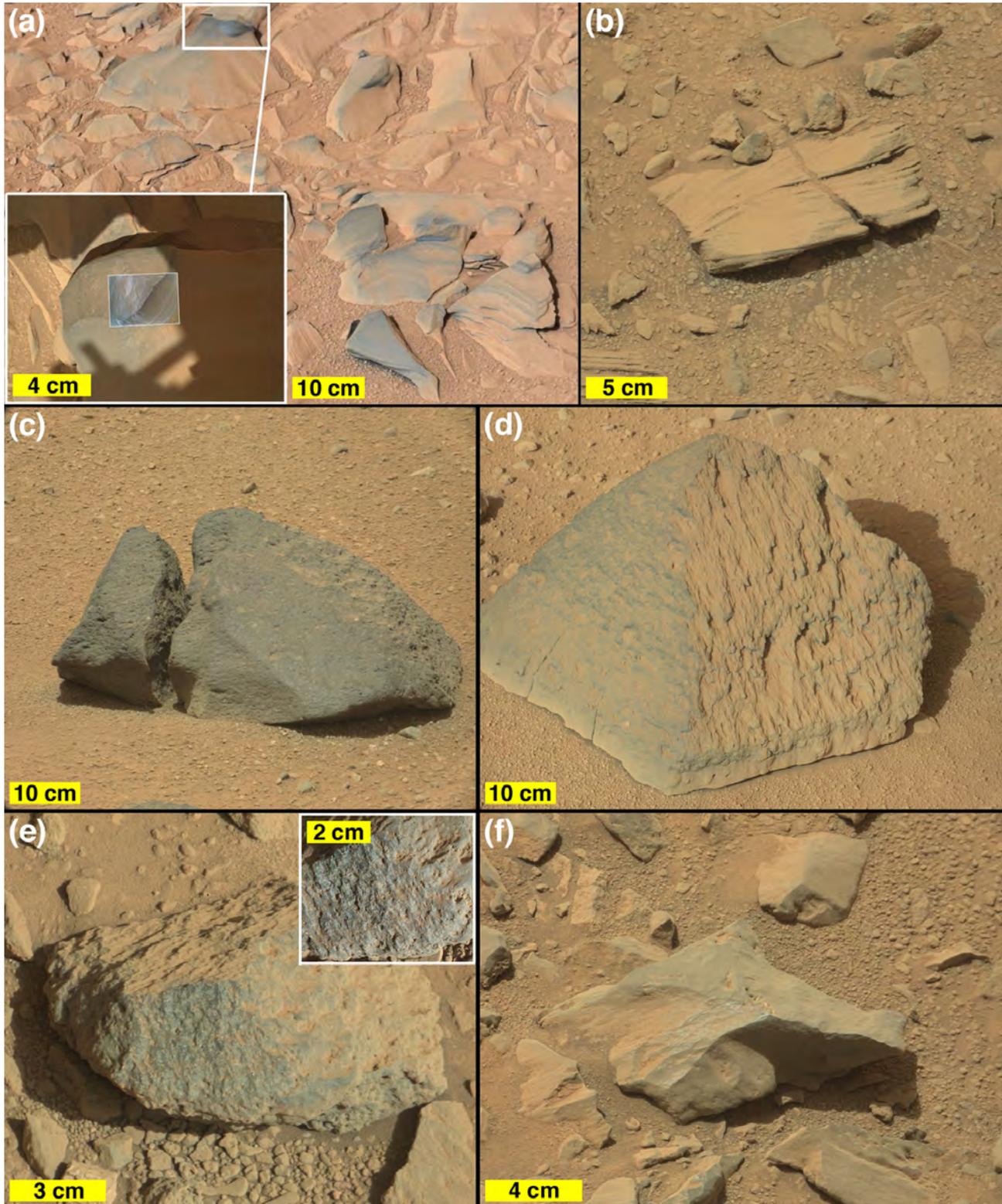


Fig. 22. Rocks observed on Bradbury rise that match Bimbe float rocks in terms of morphology and composition in some cases, and only in morphology in other cases. (a) Bathurst_Inlet, observed Sol 55, and (b) Nullataktok (Sol 336), found in the same area, have similar compositions and morphologies to the Bimbe layered clasts. Bradbury massive targets (c) Bull Arm and (d) Jake_M do not match the compositions of the Bimbe massive targets, although they bear morphological resemblances. (e) Oscar (observed Sol 516) does match the Bimbe massive target compositions. (f) Pyramid Hills (observed north of Hidden Valley on Sol 692) is a close match to the Bimbe layered compositions, as well as to the Bradbury layered targets, e.g., (a) and (b). Locations of these targets are shown on Fig. 1.

FIG 23

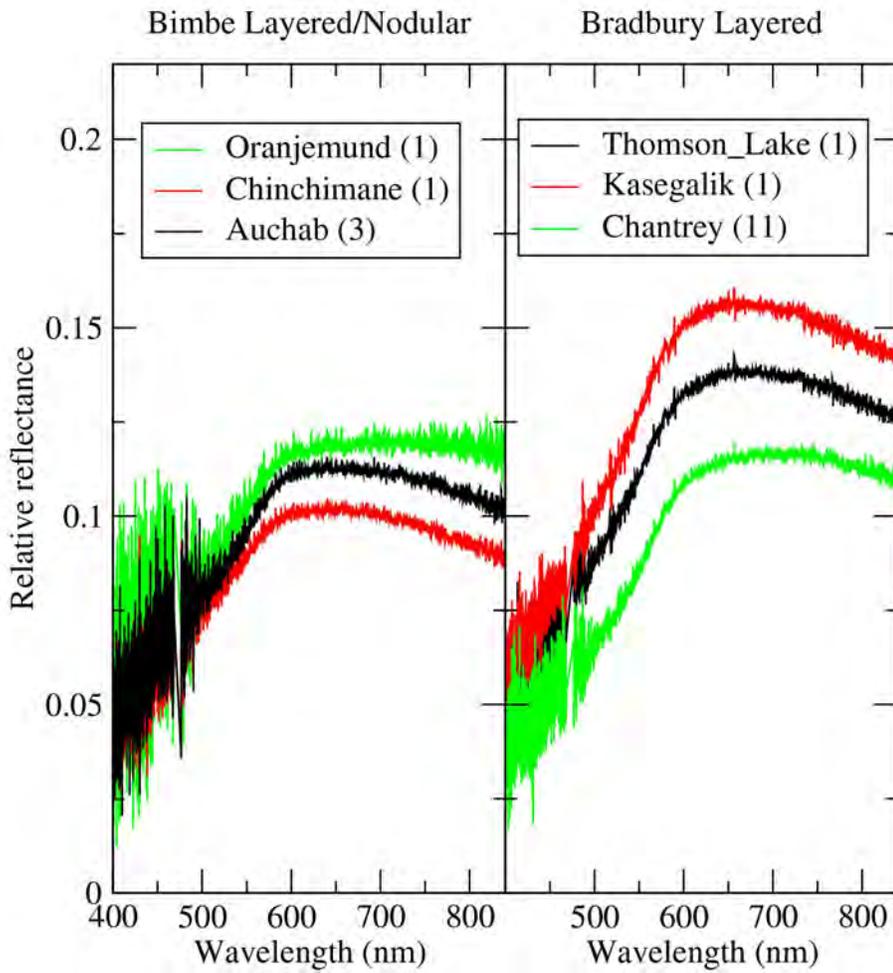
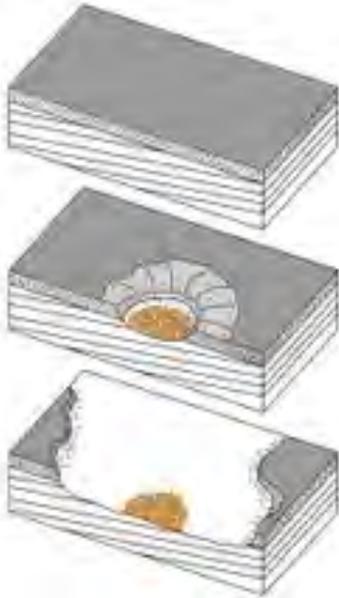


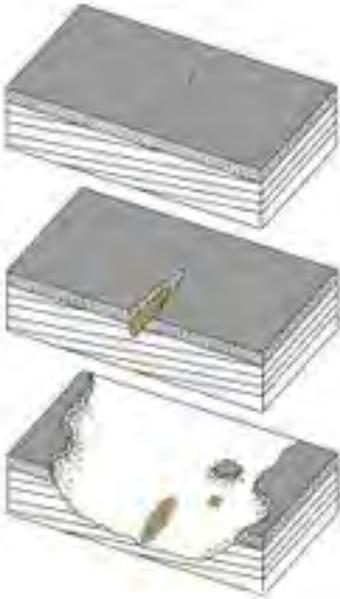
Fig. 23. ChemCam relative reflectance spectra of representative samples of the Bimbe layered and nodular rocks, along with sample spectra from the Bradbury layered rocks. The Bimbe rocks show either flat near-infrared spectra or downturns that begin near 600 nm, whereas the Bradbury rocks have peak reflectance wavelengths near 650-675 nm.

FIG 24

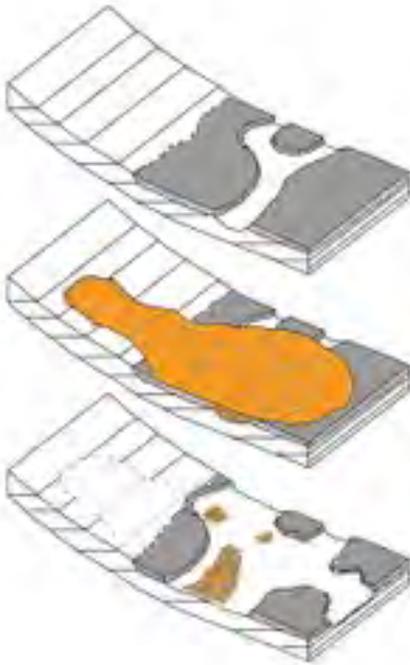
(a)



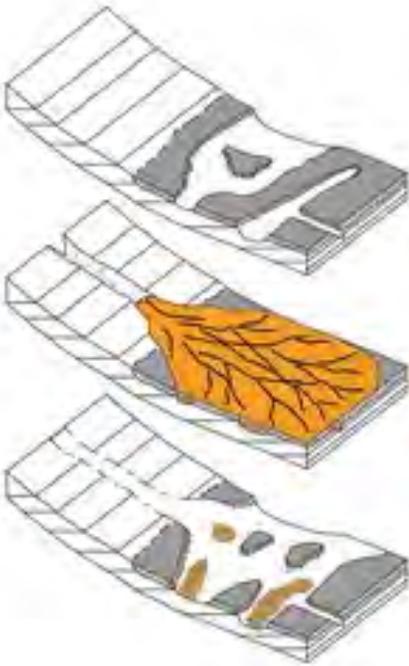
(b)



(c)



(d)



(e)

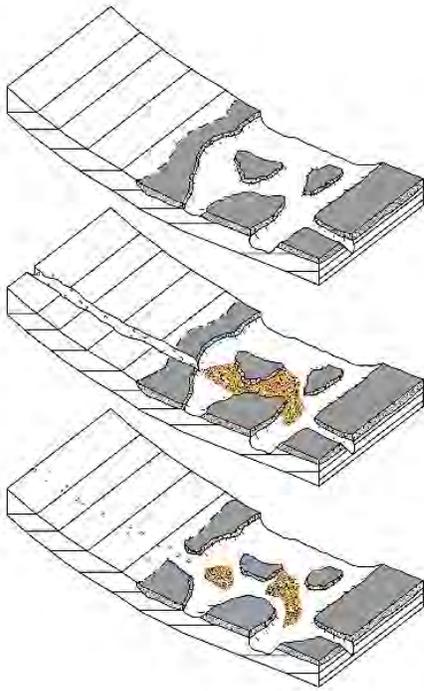


Fig. 24. Possible scenarios for formation of the heterolithic units. Each panel shows three time steps. The grey stippled top layer is the Stimson formation, the white bedded unit is the Murray, and the orange records the heterolithic unit. (a) Impact penetrates through the Stimson formation into the Murray formation, creating a crater whose walls erosionally retreat through time. (b) Incision into a resistant Stimson cap rock (either by wind or water) that creates buttes and sheds Stimson and Murray blocks into a narrow valley. Further erosional retreat leaves isolated patches. Alternately, buttes decay in place to create the heterolithic units. Sediments are protected from weathering in the original location of the incision, or boulders shed from the mesas are collected in certain areas that are not subject to erosion. (c) Mass transport of debris, either dry or by glacial processes, followed by extensive erosion that obscures the original source region. (d) Large-scale fluvial or debris flow fan deposits followed by erosion. (e) Localized fluvial or debris flow followed by erosion.

Supplemental Material

ORIGIN AND COMPOSITION OF THREE HETEROLITHIC BOULDER- AND COBBLE-BEARING DEPOSITS OVERLYING THE MURRAY AND STIMSON FORMATIONS, GALE CRATER, MARS

R.C. Wiens et al.

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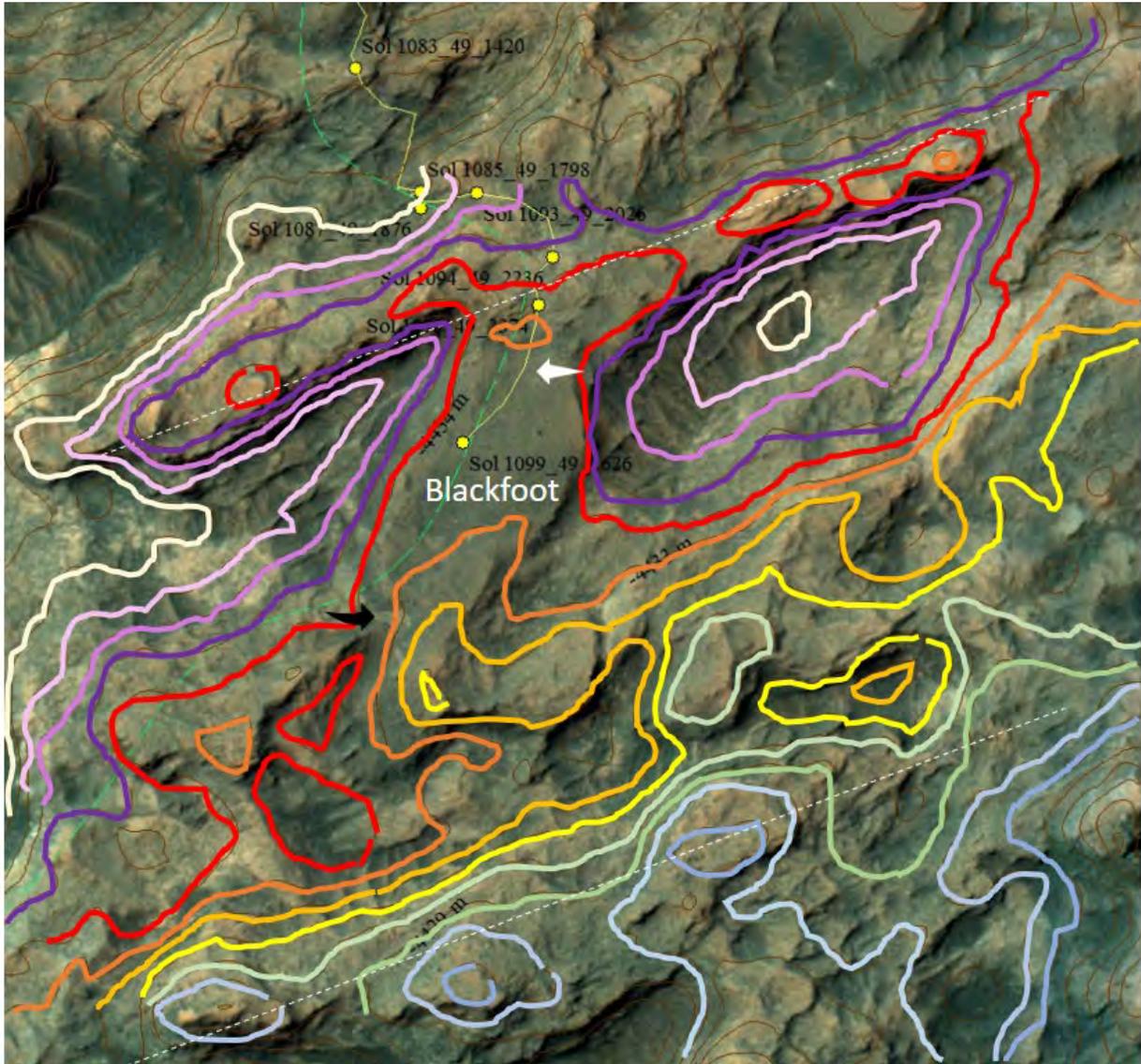
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1. Figures Showing Contour Lines Near the Heterolithic Units



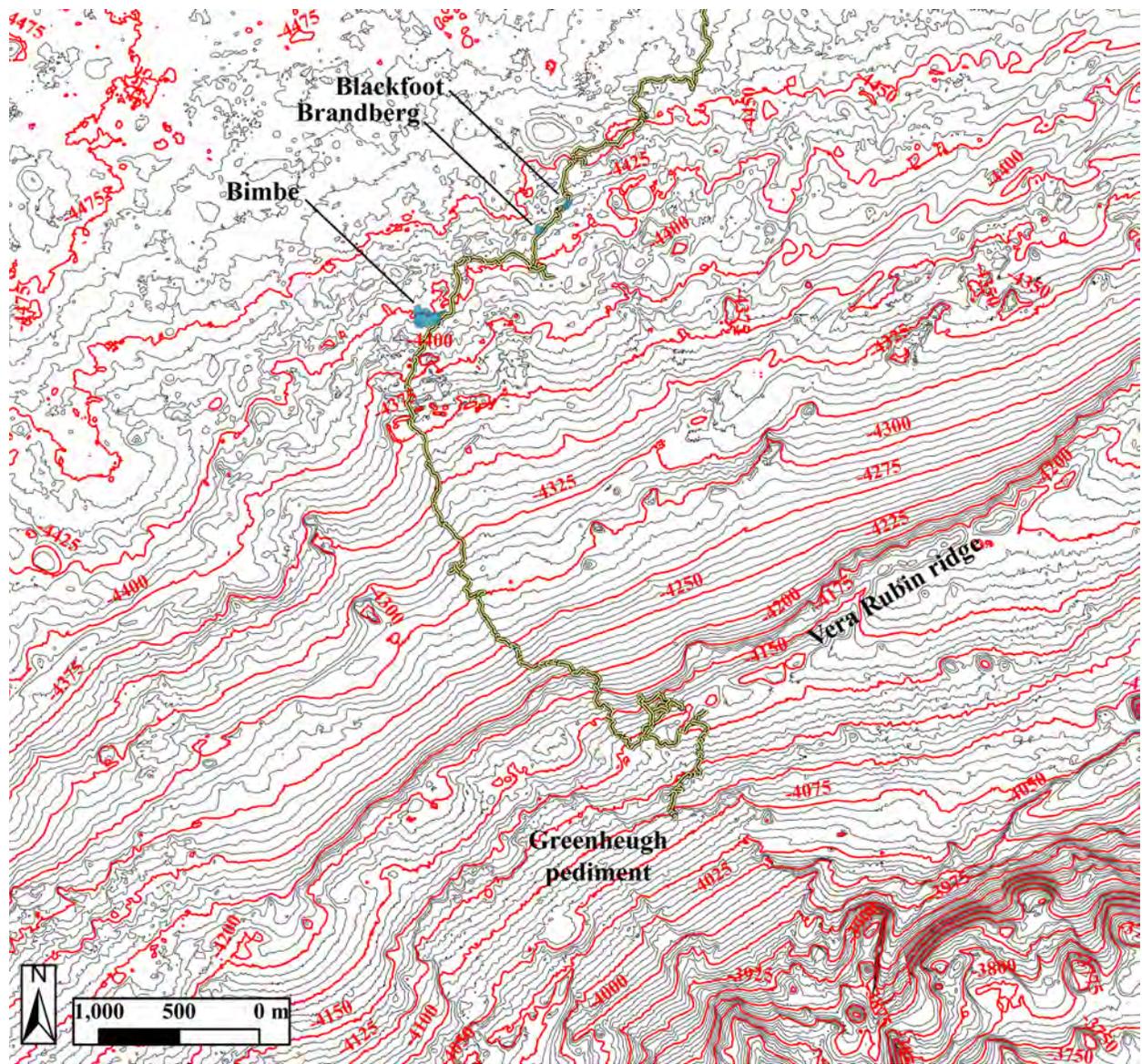
Supplemental Fig. 1-1. HiRISE image mosaic and 1 m elevation contour map (highlighted with brightly colored lines) that shows the Blackfoot deposit to be an erosional remnant that crosses the scour trend of the topography. Blackfoot is the smooth grey-toned deposit (Sol 1099 marks center area). Black and white arrows mark where Blackfoot is overlying the Murray (black) and Stimson (white) formations. Colored contours reveal the parallel ridges (dashed lines) that Blackfoot bridges and the aligned depressions bordering the deposit.



Supplemental Fig. 1-2. HiRISE image mosaic with colored 1 m elevation contours showing the location and elevation of Brandberg relative to Blackfoot.



Supplemental Fig. 1-3. HiRISE image with 10 m elevation contour intervals. Orange contour crosses the Bimbe deposit. Red contour crosses a similar deposit to the north.



Supplemental Fig. 1-4. Topographic map of a larger area along the rover traverse from the lower edge of Gediz Vallis (lower right center) and Greenheugh pediment to the heterolithic units, showing contour lines at 5 m intervals, and red contour lines at 25 m intervals. Compare with Fig. 1.

2. Description of Particle Size Measurements

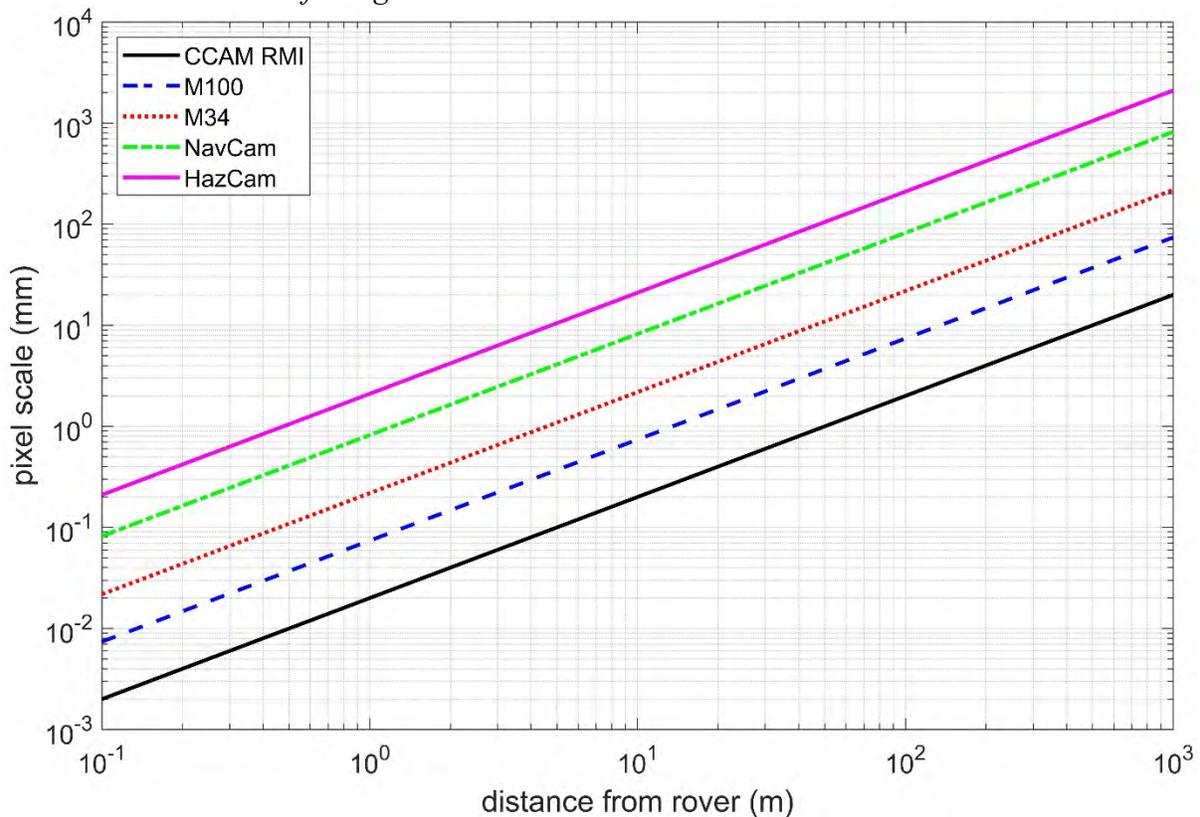
Four steps were taken to arrive at a particle size distribution for each heterolithic unit. 1) Mastcam Mosaics that provide extensive close view of particles across a patch were inspected, and then individual photographs were selected for analysis. 2) For each image, a line was drawn across the field of particles. These transects were chosen based on being close to the rover, appearing representative of the deposit, and to be approximately equidistant from the rover at all points. 3) For all stones bigger than three pixels, the major and minor axes of each stone that crossed the transect were measured manually. 4) Conversion from pixels to millimeters was made using Eq. 1 given the Instantaneous Field of View (IFOV) for each camera and a manually-estimated distance from the rover. Measurements of Mastcam-100 (M100) and Mastcam-34 (M34) images were made. The number of stones counted for each heterolithic unit ranged from 150 to 319 (Table 1). The M100 analysis gives a finer size distribution than the M34 dataset. Values used here rely on the more highly resolved M100 data.

$$D_i = 1000(x \tan \alpha) \quad (1)$$

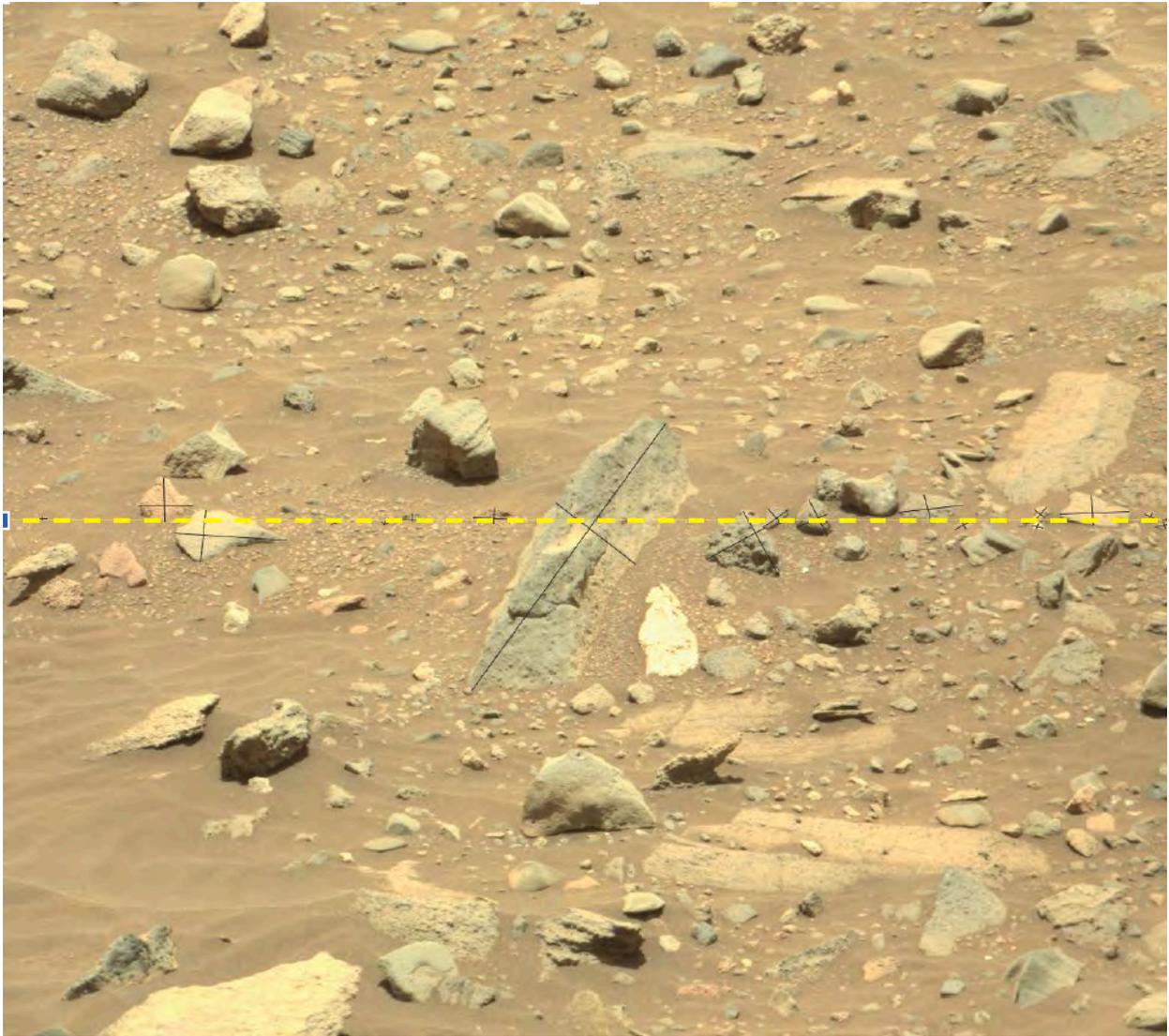
where D = particle size along dimension i (mm)

x = distance from rover (m)

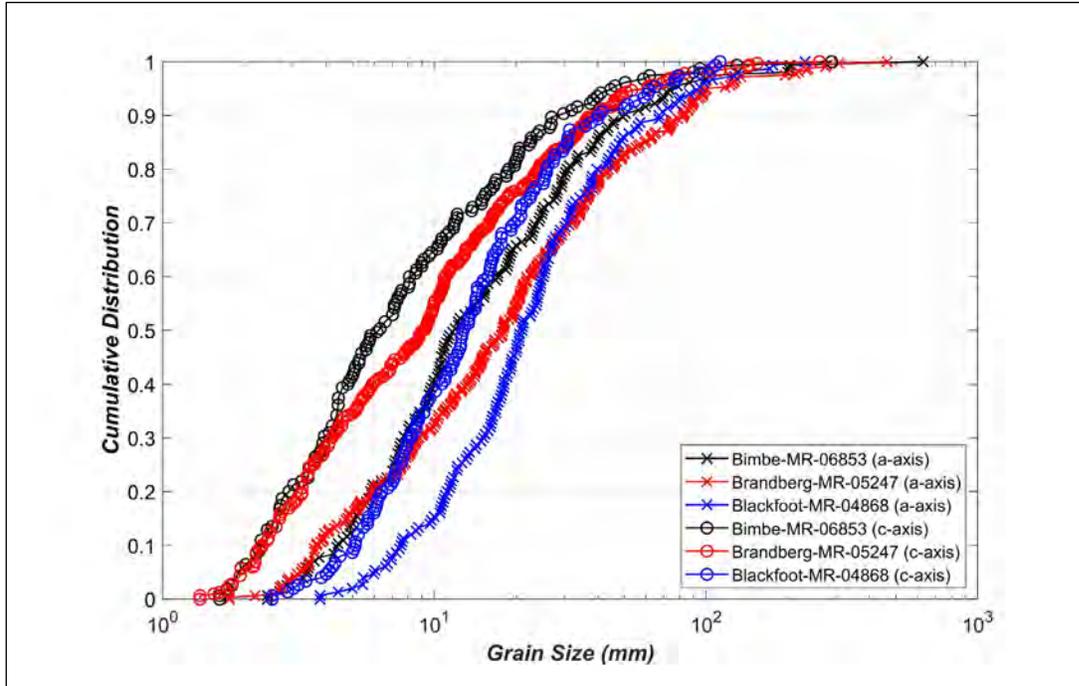
α = IFOV for a given camera



Supplemental Fig. 2-1 IFOV curves for several cameras onboard Curiosity.



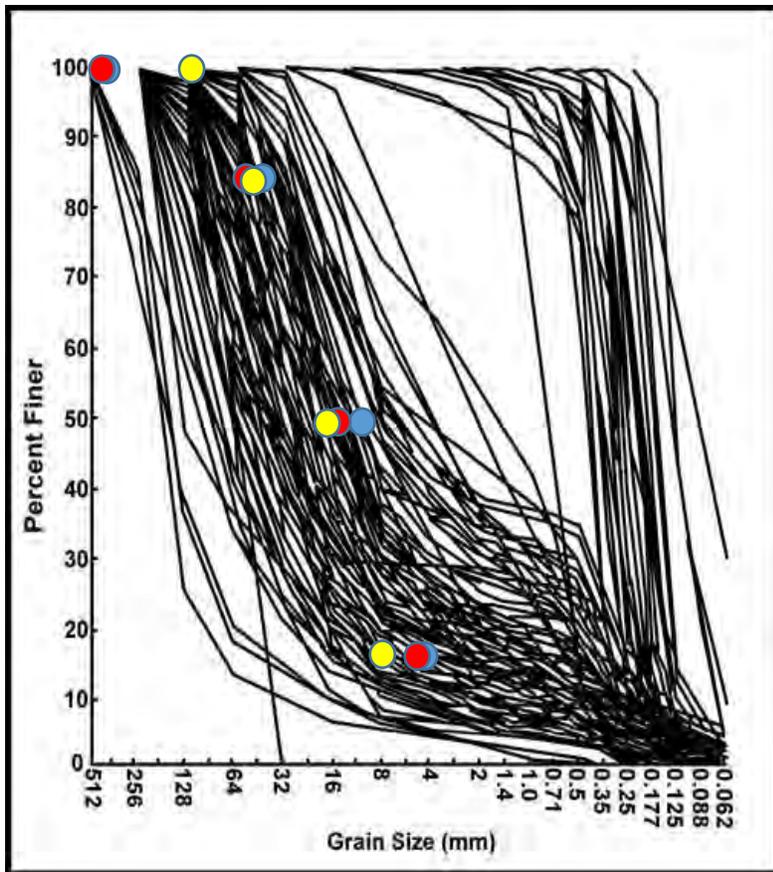
Supplemental Fig. 2-2. Example of measurements made along a transect across the Bimbe deposit.



Supplemental Fig. 2-3. Size distribution by short and long axis for the three heterolithic units.

	Bimbe		Brandberg		Blackfoot		Bimbe	Brandberg	Blackfoot
	MR-06853		MR_05247		MR_04868				
	a-axis	c-axis	a-axis	c-axis	a-axis	c-axis	b-axis	b-axis	b-axis
n	155	155	319	319	150	150			
Mean (mm)	27.3	14.6	22.7	17.2	31.6	19.8	21.7	24.3	25.4
D50 (mm)	11.9	6.3	17.9	9.2	21.1	12.9	9.3	13.2	16.0
D84 (mm)	38.3	21.3	55.2	29.6	46.6	30.2	32.9	44.1	39.9
D16 (mm)	5.3	2.7	4.9	2.8	10.5	6.0	3.8	4.3	7.0
Min (mm)	2.4	1.3	1.8	1.4	3.8	2.5	3.0	1.7	3.4
Max (mm)	630.0	290.0	464.6	261.7	231.4	112.6	370.8	409.3	111.8

Table 2-1. Results of particle size analysis. The intermediate axis was calculated by estimating the Corey Shape Factor (CSF) to be 0.6 and solving for the intermediate axis in the definition $(CSF = c/(ab)^{1/2})$.



Supplemental Fig. 2-4. Size analysis results for the three heterolithic units, Blackfoot (blue), Brandberg (red), and Bimbe (yellow), compared to 174 river bed deposits analyzed in 12 rivers in Alberta, Canada (reported by Shaw and Kellerhals, 1982). Scattered boulders, not counted in the line transects analyzed, occurred in all three deposits.

3. Description of Reference Points and Contours in Figure 21, and Supporting Figures.

Targets were chosen to represent typical chemistry of the formations (eolian Stimson and lacustrine Murray) and soil in Gale crater. A few targets were chosen to represent each class by picking homogeneous targets without obvious diagenetic textures (nodules, high-silica halos, etc.), within 4 m target distance of the instrument at the time of analysis, and major-element oxide totals close to 100% (except soils), while removing points in bedrock targets that hit Ca-sulfate veins, soil, and relatively rare out-of-focus points. Each plotted reference point is the average composition of the ChemCam observation points.

Murray formation: To represent Hartmann’s Valley (HV) Murray, 33 points from the following targets were used: “Andara” (sol 1375), “Okoloti” (sol 1375), “Khorixas” (sol 1375), “Koes” (sol 1380), “Onawa” (sol 1380), “Rundu” (sol 1382), “Aegis_post_1383a,” and “Epembe” (sol 1385). These targets represent the area from just above the “Oudam” drill location to a location due east from Bimbe between Bimbe and Helgas Dune. HV Murray is stratigraphically just below Bimbe and serves as a comparison of the Murray bedrock that underlies Bimbe. The soil data point is represented by 20 points from three soils observed throughout the mission up to Sol 1108: “Portage” (Sol 89), “Kings_Peak” (Sol 778), and “Utopia” (Sol 1108).

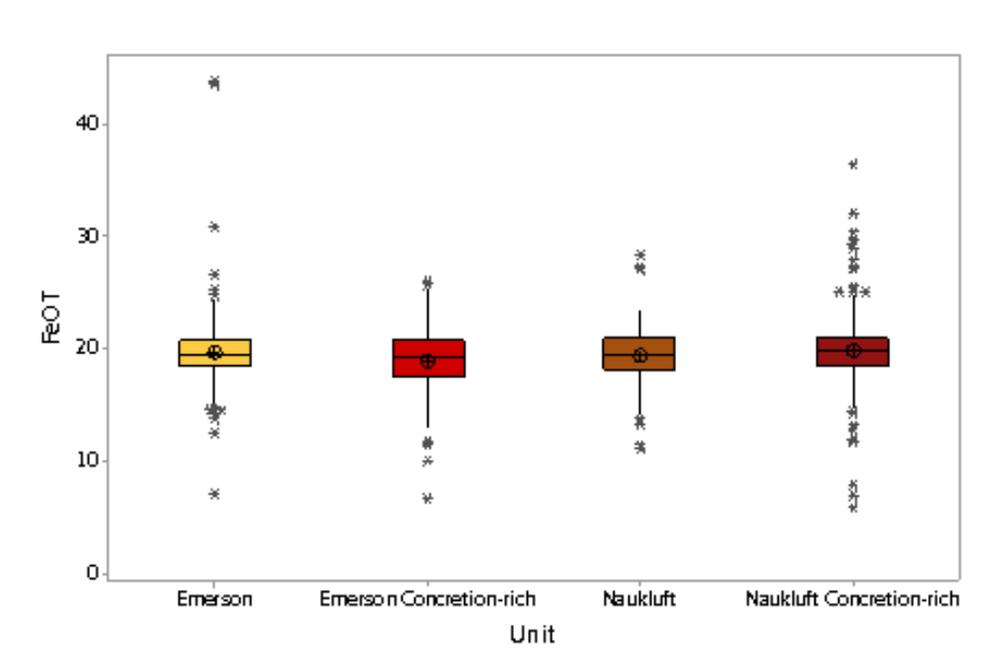
Stimson formation compositions are based on ChemCam observation points targeting both normal and concretion-rich Stimson facies at the Emerson plateau (sols 990-1154) and Naukluft plateau (sols 1279-1352) localities. ChemCam observation points of the Stimson formation that targeted obvious alteration features such as calcium-sulfate mineral veins or fracture associated halos were excluded from the dataset, as were those outside the 95–105 % total sum of oxide range. Contours for FeO_T , Al_2O_3 , MgO , CaO , Na_2O , K_2O , SiO_2 and total alkalis used 331 points for observations at distances < 4 m.

The density contour plots in Fig. 21 show the density distribution of a dataset between x and y composition variables, similar to a 2D histogram. Targets within 4 m of the instrument were used. Due to the small sampling footprint of the ChemCam LIBS laser (350–550 μm for distances of 2–7 m from the rover mast, Maurice et al., 2016), analyses of sedimentary targets with a heterogeneous mineral assemblage are often not representative of whole rock compositions, particularly if the target is coarse-grained (grain diameter > 1 mm; Cousin et al., 2017). Density contours generate a better approximation of the bulk composition than the mean as the focus is not skewed by extreme outlying values. Density contours can also highlight subgroups of data with unique compositions aiding in the identification of endmembers within the dataset. This method has proven useful to illustrate the compositional foci and geochemical trends across stratigraphic groups in Gale crater (Bedford et al., 2019), in addition to determining volcanic/magmatic endmember compositions for Gale igneous float and clast (Edwards et al., 2017).

Contours for the ChemCam Stimson formation are generated using the MATLAB `dscatter` algorithm (MathWorks Inc, 2003-2004). Density is calculated by the number of data points within each pixel (bin) of a grid and smoothed according to the methods of Eilers and Goeman (2004). For the Stimson formation dataset we generated the density contours using a bin size of

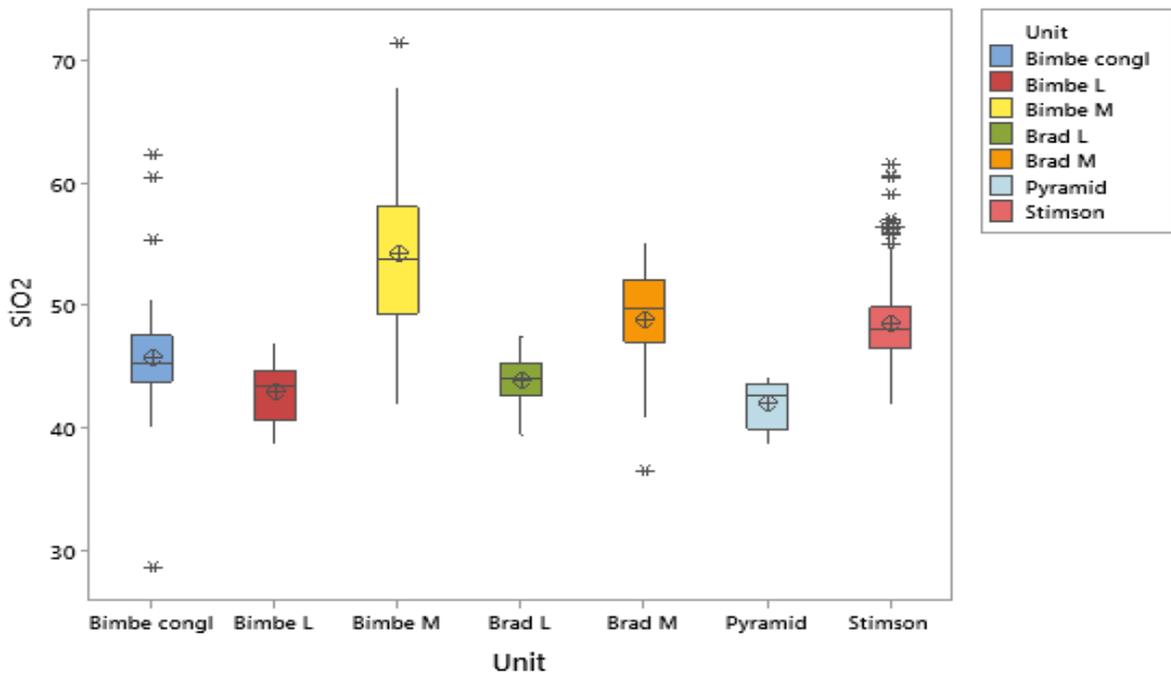
100 x 100 and a smoothing factor of 20 using a total of 331 ChemCam observation points. Contour lines are defined as the number of smoothed data points within each bin and are based on their level step which is set in this study to 1×10^{-3} . The average number of smoothed data points per bin represented by the contour can be calculated by multiplying the sample number by the level step and contour number. For example, the fourth contour towards the focus for the Stimson formation will have an average of $331 * 1 \times 10^{-3} * 4 = 1.3$ smoothed data points per bin.

The Stimson formation bedrock has a high density of concretions in certain areas. Overall, the concretions do not show much deviation from bulk rock composition but for FeO_T there are a number of extreme outliers to high iron concentrations, particularly in the Naukluft plateau locality (see the boxplot below). These concretions seem to relate to preferential cementation of the sandstone. If this is true, the sandstone of the Stimson formation is predominately iron-oxide forming from olivine diagenesis when Stimson formation precursor material was buried (e.g., Hausrath et al., 2018). So if the nodular Bimbe is derived from overlying Stimson then it would be possible that it could have Fe-rich concretions based on what has been analyzed and interpreted for the concretions at the Emerson and Naukluft plateaus. If these features don't distort any sedimentary structures (like laminations) then they are more likely to be concretions.

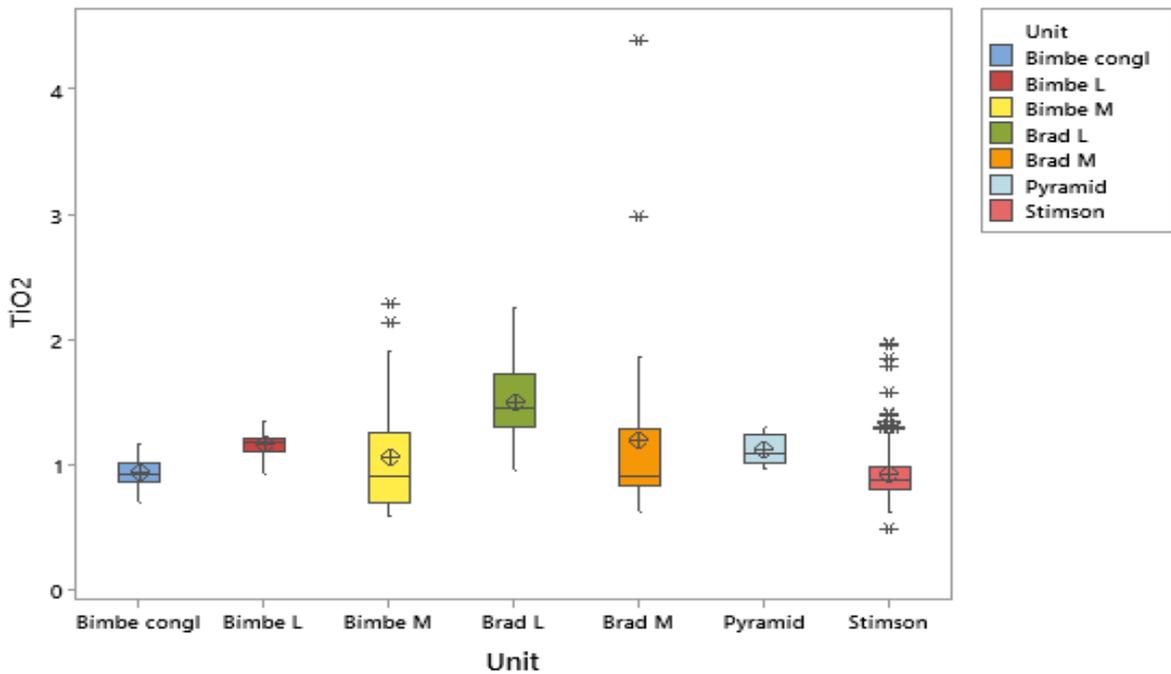


Supplemental Fig. 3-1. Boxplot showing distribution of FeO_T in different populations of Stimson formation targets. Circles with crosses indicate the means; asterisk symbols indicate outliers.

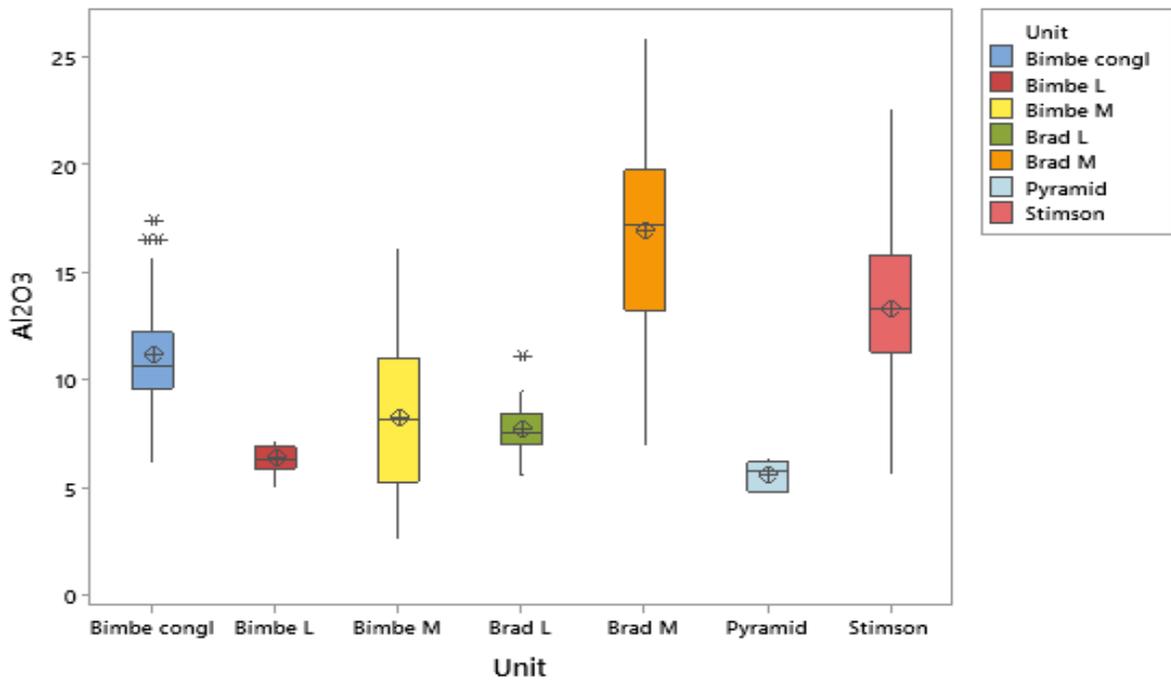
The boxplot figures below are provided to supplement Fig. 21. Circles with crosses indicate the means; asterisk symbols indicate outliers. L = layered; M = massive.



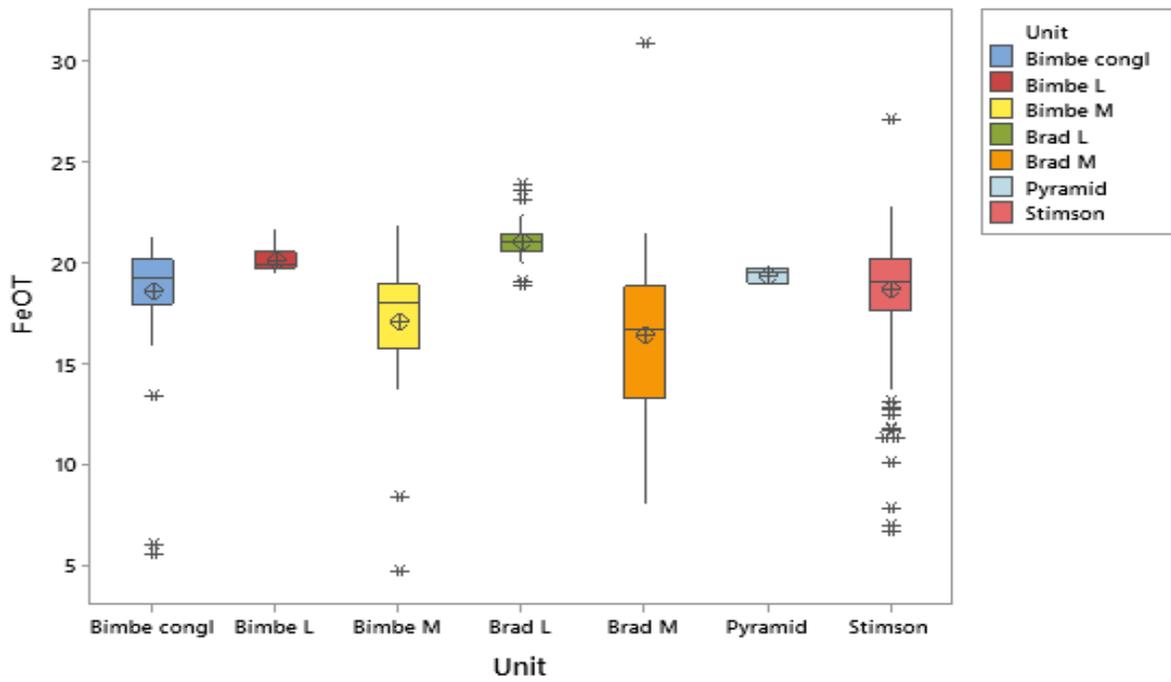
Supplemental Fig. 3-2. Boxplot of SiO₂. See details above.



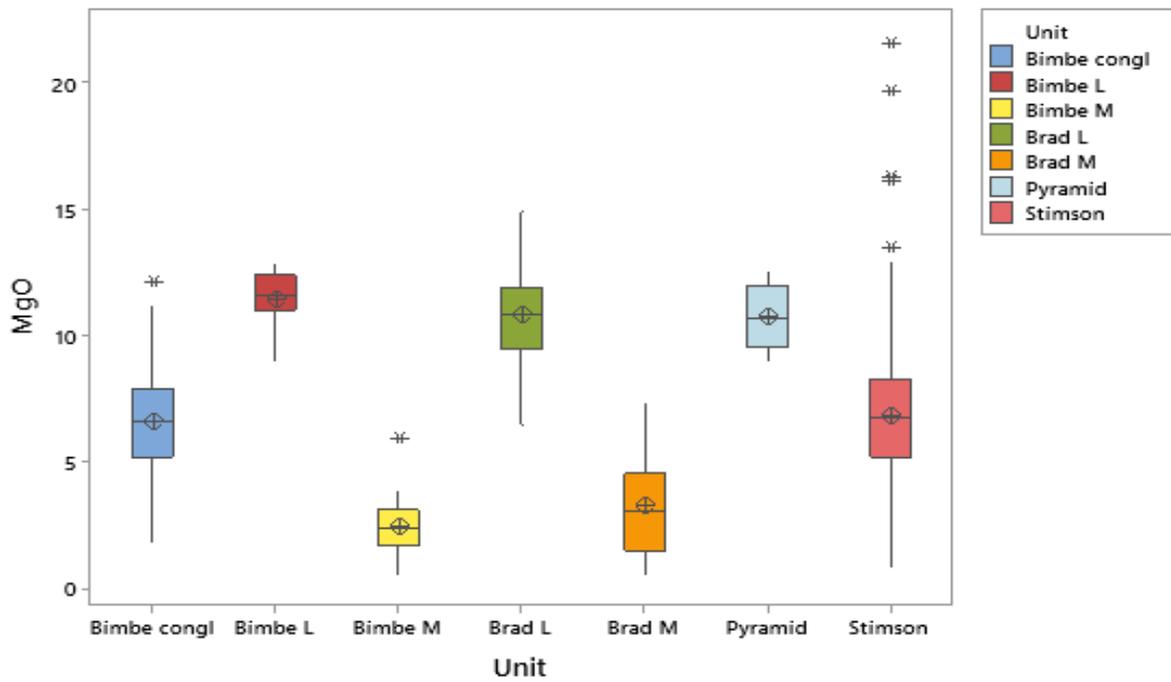
Supplemental Fig. 3-3. Boxplot of TiO₂. See details above.



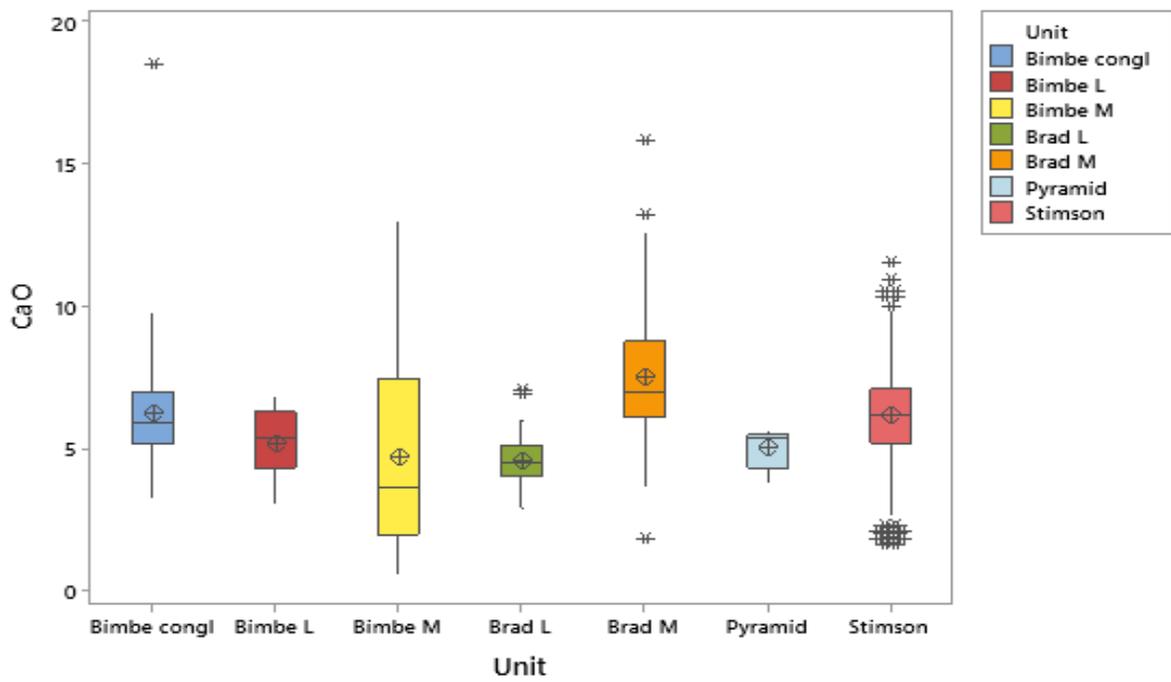
Supplemental Fig. 3-4. Boxplot of Al_2O_3 . See details above.



Supplemental Fig. 3-5. Boxplot of $FeOT$. See details above.



Supplemental Fig. 3-6. Boxplot of MgO. See details above.



Supplemental Fig. 3-7. Boxplot of CaO. See details above.

4. Description and Results of Equivalence Tests

Two-sample equivalence tests were conducted using Minitab v17 for each major element oxide (SiO_2 , TiO_2 , Al_2O_3 , FeO_T , MgO , CaO , Na_2O , and K_2O) that defines the datasets. More details are given in Appendix D of Bedford et al. (2019). The precision of the measurements were based on the standard deviations of the Sheepbed Mudstones, a large ensemble of measurements on a fine-grained homogeneous bedrock at Yellowknife Bay (Mangold et al. 2015). Equivalence tests were carried out between Bimbe Massive and Bradbury Massive sandstone targets, Bimbe Layered and Bradbury Layered targets, and Bimbe conglomerates and Stimson sandstones. The results are given below. Although Fig. 21 and the boxplots in the previous section indicate significant similarities between the two layered groups and between Bimbe conglomerates and Stimson, the equivalence test does not give a unanimously positive response. In the case of the layered groups, care must be exercised due to the small sample size for Bimbe.

Table 4-1, Bimbe conglomerates and Stimson (reference).

	Diff of means	SE of diff	EI	Difference \leq -EI T-value	P-value	Difference \geq -EI T-Value	P-value	Equiv (Y/N)
SiO_2	-2.79	0.69	± 3.30	0.74	0.23	- 8.85	0.00	N
TiO_2	-0.01	0.02	± 0.20	12.15	0.00	-10.59	0.00	Y
Al_2O_3	-2.21	0.39	± 0.90	-3.37	1.00	-8.00	0.00	N
FeO_T	-0.11	0.43	± 1.20	2.55	0.01	-3.07	0.00	Y
MgO	-0.28	0.32	± 1.40	3.48	0.00	-5.22	0.00	Y
CaO	-0.09	0.32	± 1.00	3.44	0.00	-2.89	0.00	Y
Na_2O	-0.12	0.13	± 0.30	1.40	0.08	-3.16	0.00	N
K_2O	-0.09	0.06	± 0.20	1.86	0.03	-4.61	0.00	Y

Table 4-2, Bimbe massive and Bradbury massive sandstone targets (reference).

	Diff of means	SE of diff	EI	Difference \leq -EI		Difference \geq -EI		Equiv (Y/N)
				T-value	P-value	T-Value	P-value	
SiO ₂	5.54	1.23	±3.30	7.19	0.00	1.82	0.96	N
TiO ₂	-0.13	0.15	±0.20	0.47	0.32	-2.25	0.02	N
Al ₂ O ₃	-8.76	1.02	±0.90	-7.73	1.00	-9.50	0.00	N
FeO _T	-0.67	0.94	±1.20	2.00	0.03	-0.57	0.29	N
MgO	-0.81	0.34	±1.40	1.75	0.04	-6.49	0.00	Y
CaO	-2.83	0.69	±1.00	-2.63	1.00	-5.52	0.00	N
Na ₂ O	-0.24	0.27	±0.30	0.23	0.41	-1.97	0.03	N
K ₂ O	0.06	0.11	±0.20	2.27	0.01	-1.25	0.11	N

Table 4-3, Bimbe layered and Bradbury layered targets (reference).

	Diff of means	SE of diff	EI	Difference \leq -EI		Difference \geq -EI		Equiv (Y/N)
				T-value	P-value	T-Value	P-value	
SiO ₂	-0.98	0.64	±3.30	3.62	0.00	-6.67	0.00	Y
TiO ₂	-0.33	0.04	±0.20	-3.21	1.00	-12.87	0.00	N
Al ₂ O ₃	-1.35	0.18	±0.90	-2.51	0.99	-12.63	0.00	N
FeO _T	-0.92	0.17	±1.20	1.61	0.06	-12.36	0.00	N
MgO	-0.64	0.35	±1.40	5.87	0.00	-2.17	0.02	Y
CaO	0.61	0.32	±1.00	5.06	0.00	-1.23	0.12	N
Na ₂ O	-0.11	0.07	±0.30	2.68	0.01	-5.94	0.00	Y
K ₂ O	-0.26	0.10	±0.20	-0.58	0.72	-4.46	0.00	N

5. Some Unique Compositional Features of the Bimbe Float Rocks

ChemCam observation point #3 of the conglomerate Balombo revealed one of the stronger fluorine peaks observed by ChemCam, calibrating to ~1.5 wt. % F. This corresponded to a relatively strong increase in calcium, to ~18 wt. % CaO, suggesting the presence of a small amount of CaF₂ in this observation. Among the 30 spectra obtained on this observation point (one per laser pulse), the compositions remain steady, indicating that the Ca-F enrichment region is deeper than the laser pit. The pit itself appears light toned. Fluorine has been observed in other locations in Gale, including in soils and sediments as well as in igneous float rocks. It was often observed associated with Al and P, suggesting fluorapatite, but other times associated only with Ca, suggesting fluorite (Forni et al., 2015; Cousin et al., 2017; Nachon et al., 2016).

6. The Heights of the Murray Buttes

Measurements were made to estimate the heights of the Murray Buttes using the MSL WebGIS. The topography is from Parker and Calef (2016), derived from HiRISE stereo pair DEMs registered to MGS MOLA elevations. An example plot below shows how the measurements were made, along with a table of the results. The butte designations are those adopted by the MSL team. The rover path is also shown, from north (top), past Bimbe, and to the south. A key issue is that all of the Murray Buttes occur on a slope; thus, the terrain north of each butte is lower than the terrain south of each butte. This means that the maximum height of a given butte is really from the north side to the highest point on the butte top. Instead of doing just a “maximum” height, a minimum and maximum were estimated. Overall, with one exception, these range from about 7 m (minimum) to 17 m (maximum) with an average of 8 m (min) to 12 m (max).



Butte name	highest elevation on butte (m)	low elevation on one side (m)	low el. on other side (m)	max height (m)	min height (m)
M1a	-4404	-4419	-4416	15	12
M1b	-4402	-4410	-4409	8	7
M2	-4400	-4408	-4409	8	9
M3	-4400	-4412	-4408	12	8
M4	-4392	-4407	-4402	15	10
M5	-4395	-4407	-4402	12	7
M6	-4389	-4398	-4398	9	9
M7a	-4379.4	-4396.7	-4383.8	17.3	4.4
M7b	-4384.6	-4398.5	-4393.4	13.9	8.8
M8	-4369.7	-4385.4	-4374.7	15.7	5.0
M9a	-4376.6	-4388.0	-4386.0	11.4	9.4
M9b	-4374.4	-4386.2	-4381.2	11.8	6.8
M9c	-4373.4	-4385.5	-4381.8	12.1	8.4
M9d	-4370.6	-4380.7	-4377.3	10.1	6.7
M9e	-4369.7	-4378.2	-4377.2	8.5	7.5
M10	-4389.4	-4406.2	-4395.9	16.8	6.5
M11	-4380.0	-4394.0	-4388.3	14.0	8.3
M12	-4370.5	-4383.5	-4379.5	13.0	9.0
			Averages	12.4	7.9

7. Additional References for Supplemental Section

Bedford C.C., Bridges J.C., Schwenzer S.P., Wiens R.C., Rampe E., Frydenvang J., and Gasda P.J., 2019. Alteration trends and geochemical source region characteristics preserved in the fluvio-lacustrine sedimentary record of Gale crater, Mars. *Geochim. Cosmochim. Acta* 246, 234-266, doi:10.1016/j.gca.2018.11.031.

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Eilers P.H.C., and Goeman J.J., 2004. Enhancing scatterplots with smoothed densities: *Bioinformatics* 20(5), 623-628, doi:10.1016/j.sab.2013.05.003.

Forni O., et al., 2013. Independent component analysis classification of laser induced breakdown spectroscopy spectra. *Spectrochim. Acta B* 86, 31–41.

Shaw J. and Kellerhals R., 1982. The composition of recent alluvial gravels in Alberta river beds, Alberta Research Council Bulletin 41, 151 pp., https://ags.aer.ca/publications/BUL_041.html.

8. Compositions of Individual ChemCam Observation Points, Bimbe

Also included are accuracies and standard deviations of the individual spectra (25) within each observation point. Observation points are arranged consecutively for each target.

Target	SiO2	acc	stdev	TiO2	acc	stdev	Al2O3	acc	stdev	FeOT	acc	stdev	MgO	acc	stdev	CaO	acc	stdev	Na2O	acc	stdev	K2O	acc	stdev	Total
Auchab	45.9	5	0.8	1.04	0.5	0.03	15.2	3.6	0.5	24.1	4.5	1.3	3.9	1.8	0.1	5.3	1.8	0.3	4.24	0.74	0.1	2.81	1.17	0.08	102.47
Auchab	43.8	5.1	0.5	1.02	0.5	0.04	11.7	3.6	0.6	28.2	4.7	1.1	8.8	2.4	0.4	3.9	1.4	0.2	3.17	0.63	0.17	1.54	1.09	0.08	102.09
Auchab	41.6	5.3	0.5	0.91	0.47	0.02	9.2	3.5	0.3	29.7	4.8	0.7	7.7	2.2	0.4	4.5	1.6	0.4	2.81	0.62	0.07	1.73	1.14	0.11	98.17
Auchab	41.6	5.3	0.7	0.87	0.47	0.04	9.8	3.5	0.5	28.4	4.7	1.3	7.5	2.2	0.3	5.6	1.9	0.5	2.98	0.62	0.14	1.59	1.11	0.13	98.08
Auchab	44.7	5	0.6	0.89	0.47	0.04	11.3	3.5	0.4	22.1	4.3	0.8	8.1	2.3	0.4	5.7	1.9	0.5	2.97	0.62	0.11	1.43	1.06	0.08	96.92
aeqis_post_1400a	45.3	5	0.7	0.84	0.46	0.02	11.3	3.5	0.7	19.2	4	0.5	6.9	2.1	0.2	5.9	1.9	0.5	3.65	0.67	0.19	0.67	0.72	0.03	93.73
aeqis_post_1400a	44.8	5	0.3	0.84	0.46	0.02	8.3	3.4	0.2	20.8	4.2	0.2	10.3	2.6	0.8	4.1	1.5	0.9	2.64	0.62	0.09	0.65	0.71	0.1	92.33
aeqis_post_1400a	42.2	5.5	1.02	0.5	0.04	10.1	3.5	0.3	19.9	4.1	0.2	5.5	1.9	0.1	5.1	1.7	0.4	3.15	0.63	0.2	0.63	0.7	0.06	87.46	
aeqis_post_1400a	48.1	4.9	1.2	0.82	0.45	0.03	15.5	3.6	2.5	17.8	3.8	1	5.5	1.9	0.7	6	2	0.5	3.48	0.65	0.33	0.41	0.61	0.03	97.7
aeqis_post_1400a	45	5	0.5	0.81	0.45	0.02	10	3.5	0.6	18.8	3.9	0.4	8.8	2.4	0.3	6.7	2.2	0.3	3.05	0.63	0.15	0.38	0.6	0.03	93.67
aeqis_post_1400a	46.7	4.9	0.3	0.87	0.47	0.03	14.8	3.6	1.4	18.8	3.9	0.3	6	2	0.3	5.9	2	0.2	3.35	0.64	0.15	0.5	0.65	0.02	96.98
aeqis_post_1400a	44.7	5	0.5	0.7	0.42	0.01	7.5	3.4	0.3	18.8	3.5	0.5	12.1	2.9	0.5	6.8	2.2	0.4	2.12	0.63	0.09	0.48	0.64	0.03	92.39
aeqis_post_1400a	45.5	5	0.7	0.94	0.48	0.07	13.6	3.6	1.5	19.7	4	0.7	6.5	2.1	0.4	5.3	1.8	0.6	3.3	0.64	0.28	0.49	0.64	0.06	95.27
aeqis_post_1400a	45.4	5	0.3	0.9	0.47	0.02	11.9	3.6	0.2	18.6	3.9	0.3	8	2.3	0.6	5.3	1.8	0.4	3.5	0.65	0.16	0.7	0.73	0.03	94.33
Aussenkehr	48.5	4.9	1.7	1.46	0.61	0.09	5.3	3.1	0.5	20.3	4.1	1.1	7.1	1.6	0.6	4.6	1.6	1.2	4.38	0.76	0.1	0.93	0.84	0.19	87.56
Aussenkehr	53.8	5	1.7	0.63	0.4	0.06	8.2	3.4	0.8	19	3.9	1.4	2.1	1.6	0.3	2.6	1.1	0.7	4.47	0.62	0.24	0.83	0.79	0.1	88.46
Aussenkehr	54.6	5.1	1.9	1.11	0.52	0.12	9.4	3.5	0.7	15.1	3.4	0.9	1.4	1.5	0.1	3.4	1.3	0.5	5.45	0.93	0.42	0.96	0.85	0.17	91.42
Aussenkehr	42.1	5.2	0.6	0.69	0.42	0.02	2.7	2.8	0.3	19.4	4	0.2	3.5	1.7	0.1	12.9	3.2	0.6	2.05	0.63	0.1	0.2	0.54	0.06	83.65
Aussenkehr	56.1	5.2	1.7	1.01	0.5	0.08	11.6	3.5	0.5	18.9	3.9	0.6	1.3	1.5	0.2	3.6	1.3	0.6	4.61	0.8	0.36	1.71	1.14	0.16	98.81
Aussenkehr	48.6	4.9	0.7	0.8	0.7	0.39	8.2	3.4	0.8	15.8	3.5	0.7	2.1	1.6	0.2	6.9	2.2	0.4	2.27	0.74	0.07	0.41	0.97	0.11	88.91
Aussenkehr	55.8	5.2	1.4	0.63	0.4	0.03	9.6	3.5	0.8	15.3	3.4	1.7	1.4	1.5	0.2	7.7	2.4	0.6	5.47	0.93	0.43	1.61	1.11	0.26	97.54
Aussenkehr	56.2	5.2	1.2	0.6	0.39	0.04	11.7	3.6	0.8	18.5	3.9	0.8	1.4	1.5	0.1	2.4	1.1	0.5	4.54	0.79	0.26	1.75	1.15	0.2	97.13
Aussenkehr	52.2	5	0.5	0.91	0.78	0.23	8.1	3.2	0.3	15.6	3.4	0.9	1.7	1.6	0.1	1.7	1.2	0.4	4.83	0.84	0.12	0.93	1.12	0.1	94.76
Aussenkehr	49.4	4.9	1.1	0.79	0.45	0.08	8.8	3.5	0.9	16.3	3.6	1.6	1.7	1.6	0.4	5.7	1.9	0.7	4.16	0.72	0.23	0.93	0.84	0.24	87.84
Canico	40	5.5	0.8	1.05	0.5	0.04	8.1	3.4	0.4	23.4	4.1	1	5	1.9	0.2	5.1	1.7	0.6	2.54	0.62	0.08	0.66	0.71	0.06	85.38
Canico	36.4	6	0.5	1.11	0.52	0.04	8.7	3.5	0.3	28.5	4.7	0.8	5	1.9	0.2	3.1	2.4	0.2	2.73	0.62	0.1	0.86	0.81	0.06	86.38
Canico	44.7	5	0.5	0.78	0.44	0.03	8.3	3.4	0.2	18.7	4	0.4	7.1	1.7	0.4	4.1	1.7	0.2	2.75	0.62	0.11	0.73	0.75	0.05	89
Canico	38.5	5.7	0.4	1	0.49	0.04	8	3.4	0.2	24.6	4.5	1.1	5.1	1.9	0.1	6.8	2.2	0.9	2.54	0.62	0.1	0.76	0.76	0.05	87.45
Canico	52	5	0.4	0.81	0.45	0.01	17.3	3.7	0.4	13.5	3.2	0.5	2.1	1.6	0.1	6.4	2.1	0.4	5.77	0.96	0.16	0.73	0.75	0.04	98.66
Chinchirname	40.4	5.4	0.5	1.32	0.57	0.06	6	3.2	0.6	20.3	4.1	0.2	12.4	3	0.7	4.3	1.5	0.4	2.01	0.63	0.1	1.15	0.94	0.11	87.95
Chinchirname	41.8	5.2	0.8	1.18	0.53	0.05	6.4	3.2	0.5	18.7	4	0.2	6.2	2.9	0.4	2.1	1.7	0.2	3.62	0.99	0.1	1.17	1.11	0.11	88.99
Chinchirname	40.4	5.4	0.6	1.1	0.52	0.05	5.9	3.2	0.3	20.6	4.1	0.3	12.9	2.8	0.5	5.8	1.8	0.6	1.78	0.64	0.09	0.98	0.86	0.11	88.27
Chinchirname	38.8	5.6	0.6	1.2	0.54	0.06	5.9	3.2	0.3	20.5	4.1	0.6	12.6	3	1.2	4.5	1.6	0.7	1.77	0.64	0.08	0.99	0.87	0.13	86.3
Chinchirname	40.7	5.4	0.4	1.05	0.5	0.06	6.2	3.2	0.4	19.9	4.1	0.3	10.4	2.7	0.9	6.8	2.2	0.6	2.03	0.63	0.12	1.01	0.88	0.13	88.02
aeqis_post_1406a	46.4	5.2	0.7	0.84	0.47	0.01	4.5	3.1	0.5	18.4	3.9	0.6	1.7	1.7	0.1	1.8	1.2	0.4	5.72	0.93	0.43	0.27	0.71	0.06	92.42
aeqis_post_1406a	58.4	5.2	1.5	0.98	0.49	0.04	4.6	3	0.6	20.9	4.2	1.7	2.5	1.6	0.1	3.7	1.4	0.3	7.27	1.04	0.23	0.55	0.67	0.16	98.81
aeqis_post_1406a	71.5	5.5	2.2	0.8	0.45	0.07	8.6	3.4	1.3	14.1	3.2	2.3	1.8	1.6	0.2	2.2	1.1	0.4	4.43	0.77	0.43	1.26	0.99	0.27	104.64
aeqis_post_1406a	51.1	5	0.4	1.56	0.63	0.12	6.3	3.2	0.6	17.8	3.8	0.9	3.3	1.7	0.2	6	2	0.6	4.93	0.86	0.3	0.83	0.79	0.09	91.85
aeqis_post_1406a	63.3	5	0.8	0.88	0.47	0.11	12.3	3.6	1.8	13.8	3.2	1.8	1.2	1.5	0.2	5.4	0.9	0.4	3.93	0.84	0.23	2.07	1.19	0.2	102.05
aeqis_post_1406a	57.1	5.2	2.8	0.83	0.46	0.04	8.7	3.5	0.8	21.8	4.3	0.8	2.5	1.6	0.7	0.7	0.9	0.5	4.14	0.72	0.52	1.23	0.98	0.18	97.02
aeqis_post_1406a	47.7	4.9	0.5	1.2	0.54	0.08	8.6	3.4	0.2	20.9	4.2	1.2	3.5	1.7	0.3	1.8	1	0.3	3.29	0.64	0.27	0.81	0.1	87.8	
aeqis_post_1406a	49.7	4.9	0.4	1.22	0.54	0.08	6.7	3.3	0.5	18.5	3.9	0.7	3.7	1.7	0.3	2.6	1.1	0.2	3.4	0.65	0.26	0.93	0.84	0.2	86.72
aeqis_post_1406a	53.2	5.1	0.4	0.91	0.47	0.03	10.5	3.5	0.8	24.5	4.3	1	2.1	1.6	0.2	5.1	1.7	0.4	2.88	0.62	0.08	1.14	0.52	0.01	91.39
Lucala	59.6	5.3	2.8	0.62	0.4	0.02	11.5	3.5	1.4	13.7	3.2	2.8	2.2	1.6	0.6	1.9	1	0.6	5.19	0.9	0.59	1.69	1.13	0.32	96.54
Lucala	47.5	4.9	0.9	1.87	0.72	0.15	4.4	3	0.7	18.3	3.8	0.5	3.1	1.7	0.2	7.9	2.5	0.5	4.28	0.74	0.34	0.59	0.68	0.07	87.92
Lucala	51.8	5	0.6	2.33	0.79	0.13	2.9	2.8	0.4	15.6	3.4	0.5	2.6	1.6	0.1	3.7	1.4	0.4	6.13	0.98	0.19	0.5	0.65	0.05	85.34
Lucala	58	5.2	0.8	1.73	0.68	0.12	12.3	3.6	0.7	15.7	3.5	0.7	1.2	1.5	0.5	0.7	1.2	0.6	1.57	0.62	0.12	0.99	1.19	0.1	94.76
Lucala	60.1	5.3	5	0.69	0.42	0.27	12.5	3.6	1.5	15.8	3.5	3.5	2.3	1.6	0.9	0.6	0.9	0.2	3.78	0.68	0.15	1.54	1.09	0.34	97.3
Cabamba	40.9	5.3	0.9	1.04	0.5	0.03	10	3.5	1.4	20.6	4.1	0.3	6.4	2	0.9	6.7	2.2	0.4	2.54	0.62	0.31	0.29	0.57	0.06	88.3
Cabamba	46.8	4.9	0.9	1.01	0.5	0.02	13.6	3.6	1.2	19	3.9	0.6	4.8	1.8	0.1	5.7	1.9	0.3	3.62	0.66	0.15	0.82	0.79	0.1	94.79
Cabamba	46.2	5	1	1.1	0.52	0.03	11	3.5	0.3	20.4	4.1	0.3	4.8	1.8	0.1	5.9	1.9	0.4	2.72	0.67	0.12	0.94	0.81	0.13	93.22
Cabamba	49.9	5	0.4	1.16	0.53	0.04	11.8	3.6	0.5	19.3	4	0.3	4.3	1.8	0.2	4.8	1.7	0.2	3.84	0.68	0.11	0.74	0.75	0.04	95.96
Cabamba	49.1	4.9	0.4	1.03	0.5	0.03	17.4	3.7	0.4	16.2	3.5	0.8	2.7	1.6	0.3	7.2	2.3	0.3	3.64	0.66	0.2	0.3	0.57	0.03	97.56
Cabamba	49.4	4.9	0.3	1.11	0.52	0.05	12.2	3.6	0.6	20.2	4.1	0.2	4.7												

9. Compositions from Individual ChemCam Observation Points: Blackfoot, Brandberg

Major-element abundances (wt. %) of all ChemCam observation points in (and in some cases near) the Blackfoot and Brandberg units, as well as several targets on Zabriskie Plateau that appear related to the Bimbe Layered targets. Columns are included for accuracies and for standard deviations of the 25 individual spectra within each observation point. Observation points are arranged consecutively for each target. Data from target Gibeon were of low quality and were not archived.

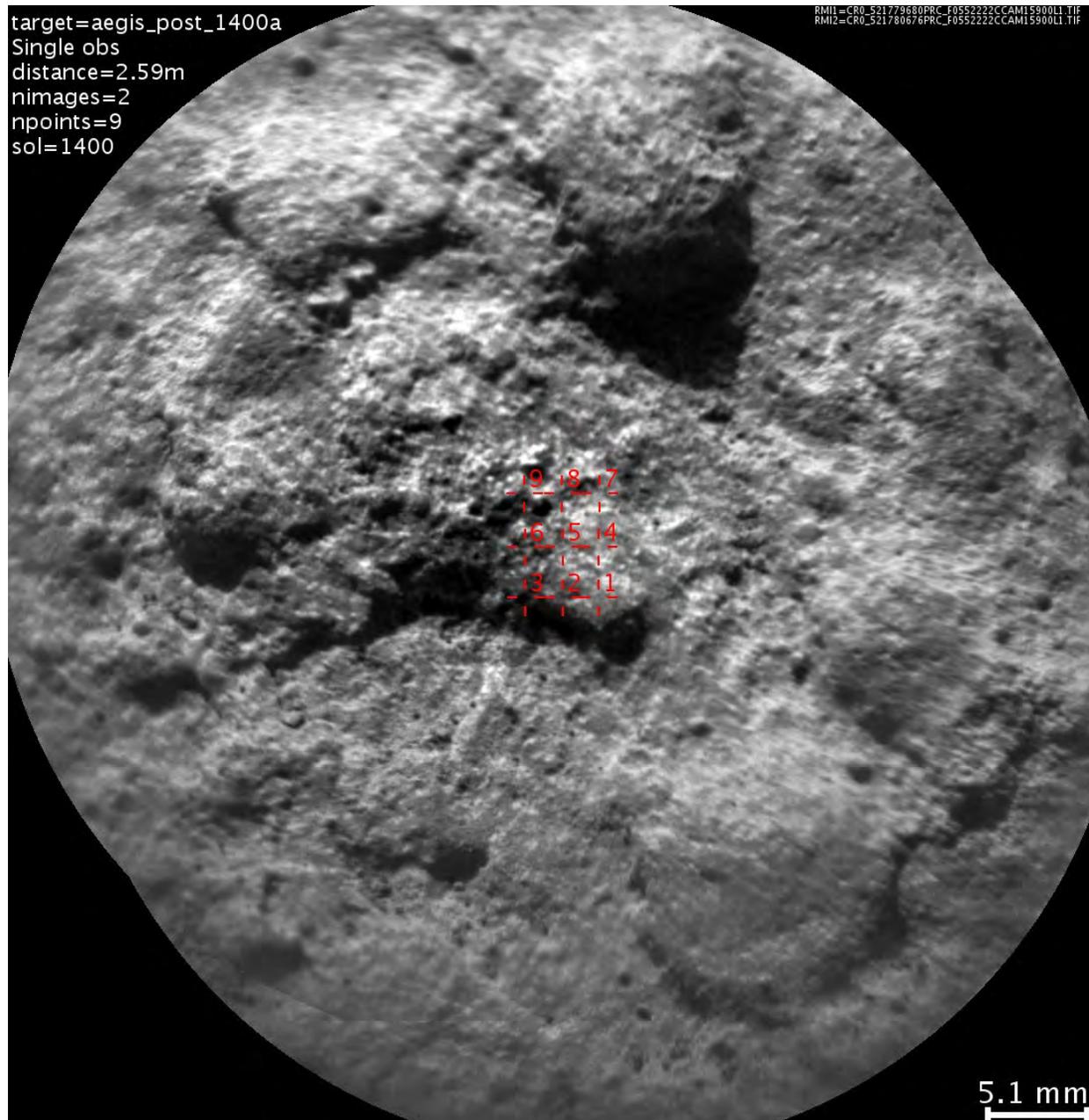
Sequence	Target	Location	Dist. (m)	SiO ₂	acc	stdev	TO ₂	acc	stdev	Al ₂ O ₃	acc	stdev	FeO ^T	acc	stdev	MgO	acc	stdev	CaO	acc	stdev	Na ₂ O	acc	stdev	K ₂ O	acc	stdev	Total
01100	Swan	Blackfoot	2.83	50.9	5	0.9	1.16	0.53	0.04	14.6	3.6	1.1	16.5	3.6	0.9	3.9	1.7	0.4	7	2.3	0.3	4.08	0.71	0.34	1.49	1.06	0.18	99.62
01100	Swan	Blackfoot	2.83	51.6	5	0.4	1.25	0.55	0.14	15.1	3.6	0.5	15.6	3.5	0.3	4.3	1.8	0.2	6.5	2.1	0.4	4.16	0.72	0.22	1.53	1.07	0.12	100.13
01100	Swan	Blackfoot	2.83	48.9	4.9	0.7	1.42	0.59	0.08	12.8	3.6	0.3	19.6	4.2	0.5	5.1	1.9	0.3	5.1	1.7	0.5	3.15	0.63	0.16	1.65	1.1	0.14	97.82
01100	Swan	Blackfoot	2.83	47.4	4.9	0.7	1.09	0.51	0.06	11.3	3.5	0.4	17.5	3.8	0.4	6.3	2	0.5	7.9	2.5	0.3	2.43	0.61	0.11	0.69	0.74	0.05	94.63
01100	Swan	Blackfoot	2.83	47	5	1.2	1.53	0.62	0.07	11	3.5	0.7	19.4	4.1	0.8	4.9	1.8	0.3	6.8	2.2	0.6	2.58	0.61	0.16	1.36	1.01	0.17	94.58
01100	Swan	Blackfoot	2.83	46.7	5	0.6	1.47	0.61	0.09	12.2	3.6	0.5	20.9	4.3	0.5	4.8	1.8	0.2	5.2	1.7	0.4	2.61	0.61	0.14	1.18	0.94	0.12	95.08
01100	Swan	Blackfoot	2.83	45.7	5	0.6	1.41	0.59	0.13	10.1	3.5	0.5	18.2	3.9	0.2	7.2	2.1	0.4	5.1	1.7	0.7	2.36	0.61	0.1	1.06	0.89	0.07	91.28
01100	Swan	Blackfoot	2.83	49.3	5	0.7	0.82	0.45	0.07	16	3.7	0.3	17.2	3.7	0.3	4.6	1.8	0.3	7.1	2.3	0.3	3.32	0.64	0.18	0.56	0.68	0.05	98.85
01100	Swan	Blackfoot	2.83	43.8	5.1	0.4	1.95	0.74	0.17	10.2	3.5	0.2	20.9	4.3	0.2	6.6	2.1	0.2	6.3	2.1	0.3	2.4	0.61	0.08	0.91	0.83	0.06	93.02
01100	Swan	Blackfoot	2.83	47.6	4.9	1.2	1.3	0.56	0.12	13.4	3.6	0.5	19.1	4.1	0.7	5.6	1.9	0.2	5.4	1.8	0.4	2.89	0.62	0.11	1.06	0.89	0.19	96.42
02100	Sunburst	Blackfoot	2.37	42.1	5.2	0.8	0.83	0.46	0.05	9	3.5	0.8	20.2	4.3	0.2	14.2	3.2	0.7	3.5	1.3	0.5	1.94	0.65	0.12	0.19	0.55	0.04	91.55
02100	Sunburst	Blackfoot	2.37	41.6	5.3	0.7	1.31	0.57	0.11	8.1	3.4	0.2	19.6	4.2	0.2	11.8	2.9	0.4	3.6	1.3	0.1	1.67	0.65	0.14	0.23	0.57	0.05	87.93
02100	Sunburst	Blackfoot	2.37	41.8	5.3	0.5	1.01	0.5	0.05	7.3	3.3	0.3	19.8	4.2	0.2	13.2	3.1	0.4	3.7	1.3	0.3	1.48	0.64	0.09	0.14	0.54	0.02	88.48
02100	Sunburst	Blackfoot	2.37	43	5.1	0.7	0.77	0.44	0.02	7.8	3.4	0.4	18.9	4	0.5	12.4	3	1.4	6.1	2	1.1	1.6	0.65	0.14	0.12	0.53	0.03	90.74
02100	Sunburst	Blackfoot	2.37	41.5	5.3	0.8	0.91	0.47	0.04	8.5	3.4	0.5	18.9	4.1	0.6	12.7	3	0.7	4.5	1.6	0.9	1.56	0.65	0.16	0.17	0.55	0.06	88.89
02100	Sunburst	Blackfoot	2.37	41.9	5.2	0.5	0.9	0.47	0.06	7.8	3.4	0.1	19.1	4.1	0.2	12.5	3	0.3	4.2	1.5	0.2	1.64	0.65	0.04	0.21	0.56	0.02	88.26
02100	Sunburst	Blackfoot	2.37	45	5	0.6	0.82	0.45	0.07	7.9	3.4	0.3	18.5	4	0.2	12.7	3	0.5	5.2	1.7	0.8	1.53	0.65	0.08	0.31	0.59	0.06	91.9
02100	Sunburst	Blackfoot	2.37	45.2	5	0.5	0.94	0.48	0.04	10.1	3.5	0.4	19.6	4.2	0.4	11.3	2.8	0.3	4.1	1.4	0.5	2.15	0.62	0.07	0.33	0.6	0.02	93.75
02100	Sunburst	Blackfoot	2.37	41.8	5.3	0.7	0.7	0.42	0.02	7.4	3.3	0.9	18.7	4	0.3	11.9	2.9	0.4	7.7	2.4	1.6	1.35	0.63	0.2	0.13	0.54	0.02	89.57
02100	Sunburst	Blackfoot	2.37	40.4	5.4	0.5	0.96	0.49	0.07	8.5	3.4	0.4	20.6	4.3	0.2	12	2.9	0.5	4.8	1.6	0.4	1.7	0.65	0.09	0.24	0.57	0.04	89.1
01102	Madison	Blackfoot	4.56	55.2	5.1	1.2	1.34	0.57	0.07	17.4	3.7	1.5	19.6	4.2	0.8	2.1	1.6	0.3	2.6	1.1	0.3	4.55	0.79	0.28	2.2	1.18	0.17	104.93
01102	Madison	Blackfoot	4.56	6.7	6.7	3	0.2	0.25	0.11	1.3	2.6	0.3	1	1.6	1.1	1.6	1.5	0.3	45	8.2	1.4	0.43	0.38	0.05	0.17	0.55	0.03	56.39
01102	Madison	Blackfoot	4.56	8.3	6.7	4.2	0.46	0.34	0.13	0.7	2.6	0.1	2.8	1.8	1.6	2	1.6	0.3	43.5	8	2.4	0.44	0.38	0.04	0.18	0.55	0.06	58.23
01102	Madison	Blackfoot	4.56	9.8	6.7	2.7	0.5	0.36	0.03	1	2.6	0.2	4.1	1.9	1	2.2	1.6	0.3	42.5	7.8	2	0.59	0.43	0.09	0.21	0.56	0.04	60.87
01102	Madison	Blackfoot	4.56	10.6	6.7	3.2	0.53	0.37	0.08	0.7	2.6	0.1	4.6	2	1.4	2.4	1.6	0.2	39.3	7.3	1.9	0.51	0.4	0.1	0.13	0.54	0.03	58.71
02102	Jefferson	Blackfoot	2.97	41.9	5.2	0.6	1.38	0.58	0.12	7.4	3.4	0.4	21.5	4.4	0.7	11.1	2.8	0.5	3.2	1.2	0.4	2.2	0.62	0.19	0.35	0.61	0.08	89.11
02102	Jefferson	Blackfoot	2.97	44.9	5	0.6	1.26	0.55	0.07	8.7	3.5	0.7	20.8	4.3	0.2	9.2	2.5	1.2	4.3	1.5	0.6	2.63	0.61	0.18	0.36	0.61	0.04	92.08
02102	Jefferson	Blackfoot	2.97	46	5	0.7	1.4	0.59	0.11	12.9	3.6	0.8	19.6	4.2	0.2	6.8	2.1	0.5	5.6	1.9	0.3	3.04	0.62	0.23	0.6	0.7	0.08	95.88
02102	Jefferson	Blackfoot	2.97	43.4	5.1	0.4	0.86	0.46	0.1	10.3	3.5	0.6	20.5	4.3	0.3	11.8	2.9	1.4	4.4	1.5	0.3	2.18	0.62	0.12	0.26	0.58	0.07	93.82
02102	Jefferson	Blackfoot	2.97	44.2	5.1	0.7	1.31	0.57	0.07	10.4	3.5	1	20.4	4.3	0.2	9.5	2.5	1.3	4.3	1.5	0.4	2.15	0.62	0.18	0.26	0.58	0.05	92.49
02102	Jefferson	Blackfoot	2.97	41.5	5.3	0.6	0.87	0.47	0.03	6.9	3.3	0.4	21	4.4	0.3	14.3	3.2	1.3	4.3	1.5	0.6	1.92	0.64	0.09	0.24	0.57	0.03	91.13
02102	Jefferson	Blackfoot	2.97	45.1	5	1.3	0.97	0.49	0.06	10	3.5	1.5	20	4.2	0.4	9	2.4	1.1	5.5	1.8	0.4	2.42	0.61	0.25	0.43	0.63	0.06	93.46
02102	Jefferson	Blackfoot	2.97	42.2	5.2	1	1.96	0.74	0.19	8.7	3.5	0.9	20.7	4.3	0.4	8.8	2.4	0.5	2.3	1.1	0.2	2.47	0.61	0.17	0.5	0.66	0.06	87.71
02102	Jefferson	Blackfoot	2.97	42.5	5.2	0.7	1.29	0.56	0.06	9	3.5	0.8	20.1	4.2	0.3	10.2	2.6	0.9	5.1	1.7	0.4	2.17	0.62	0.27	0.38	0.62	0.06	90.8
02102	Jefferson	Blackfoot	2.97	48.6	4.9	0.5	1.35	0.58	0.09	17.8	3.7	0.7	17.9	3.9	0.6	4.4	1.8	0.5	4.7	1.6	0.2	3.68	0.66	0.1	0.62	0.71	0.12	98.97
04102	Lincoln	Blackfoot	2.97	43.7	5.1	0.6	1.73	0.68	0.09	11.4	3.5	0.5	20.7	4.3	1	4.7	1.8	0.1	4.7	1.6	0.3	3.32	0.64	0.1	0.83	0.79	0.05	91.08
04102	Lincoln	Blackfoot	2.97	48.7	4.9	1.4	0.98	0.49	0.06	10.6	3.5	0.9	20.5	4.3	0.5	9	2.4	0.8	3.4	1.3	0.3	2.68	0.61	0.24	0.98	0.86	0.19	96.96
04102	Lincoln	Blackfoot	2.97	45.2	5	0.6	0.89	0.47	0.04	8.8	3.5	0.3	21.6	4.4	0.2	12.8	3	0.6	4.1	1.4	0.4	2.08	0.63	0.1	0.42	0.63	0.08	95.88
04102	Lincoln	Blackfoot	2.97	47	5	0.5	0.91	0.47	0.03	11.3	3.5	0.4	18.7	4	0.3	7.5	2.2	0.6	5.5	1.8	0.2	2.87	0.62	0.13	0.82	0.79	0.06	94.65
04102	Lincoln	Blackfoot	2.97	46.3	5	0.5	0.85	0.46	0.02	16.2	3.7	0.1	20.9	4.3	0.3	5.1	1.9	0.4	5	1.7	0.3	3.25	0.64	0.14	0.21	0.56	0.02	97.85
01160	Roter_Kamm	Brandberg	3.76	44.2	5.1	0.8	0.99	0.49	0.11	11.7	3.6	0.4	21.7	4.4	0.4	10.1	2.6	1.1	3	1.2	0.9	2.69	0.61	0.1	1.52	1.07	0.12	95.9
01160	Roter_Kamm	Brandberg	3.76	49.7	5	0.7	0.82	0.45	0.06	13.3	3.6	0.4	21.3	4.4	0.3	7.6	2.2	0.6	3.2	1.2	0.4	3.13	0.63	0.15	1.88	1.15	0.1	100.98
01160	Roter_Kamm	Brandberg	3.76	45.6	5	0.7	0.93	0.48	0.2	13.3	3.6	0.5	20.5	4.3	0.6	3.7	1.7	0.2	8.7	2.7	1	2.83	0.62	0.1	1.36	1.01	0.14	96.93
01160	Roter_Kamm	Brandberg	3.76	53.8	5.1	0.5	0.92	0.48	0.05	15.2	3.6	0.7	19.1	4.1	0.6	6.6	2.1	0.4	3.4	1.3	0.4	3.64	0.66	0.09	1.76	1.13	0.06	104.42
01160	Roter_Kamm	Brandberg	3.76	52.8	5	0.5	0.87	0.47	0.04	16.7	3.7	0.3	19	4.1	0.5	5.2	1.9	0.2	4.7	1.6	0.5	3.61	0.66	0.18	1.61	1.09	0.1	104.45
02160	Hoba	Brandberg	4.56	50	5	0.6	0.79	0.45	0.02	16.4	3.7	0.5	21	4.4	0.6	7	2.1	0.2	2.3	1	0.4	3.67	0.66	0.08	2.03	1.17	0.11	103.21
02160	Hoba	Brandberg	4.56	51.8	5	0.6	0.83	0.46	0.03	17.1	3.7	0.6	19.7	4.2	0.8	7.1	2.1	0.3	2.7	1.1	0.3	3.95	0.69	0.08	1.83	1.14	0.08	104.91
02160	Hoba	Brandberg	4.56	52.3	5	0.6	0.88	0.47	0.04	16.8	3.7	0.9	20.1	4.2	0.8	5.7	1.9	0.2	3.2	1.2	0.3	3.58						

10. Images of ChemCam Heterolithic-Unit Targets Not in the Main Body of the Paper.

These images are available with the given target names in the Planetary Data System at https://pds-geosciences.wustl.edu/msl/msl-m-chemcam-libs-4_5-rdr-v1/mslccm_1xxx/extras/



AEGIS_post_1400a, Mastcam image.



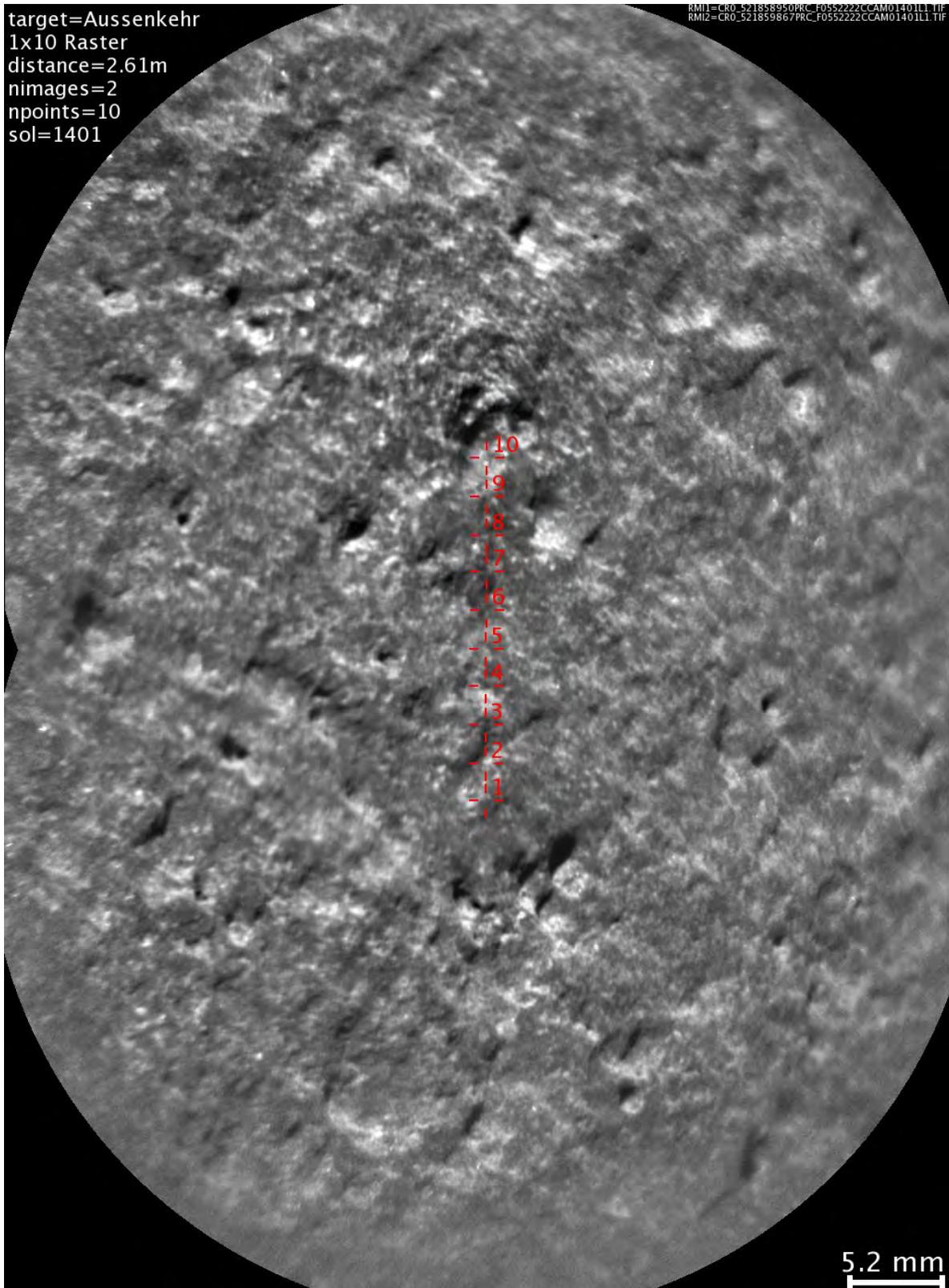
AEGIS_post_1400a, RMI mosaic.



Aussenkehr, Mastcam image.

target=Aussenkehr
1x10 Raster
distance=2.61m
nimages=2
npoints=10
sol=1401

RM1=CR0_521858950PRC_F0552222CCAM01401L1.TIF
RM2=CR0_521859867PRC_F0552222CCAM01401L1.TIF



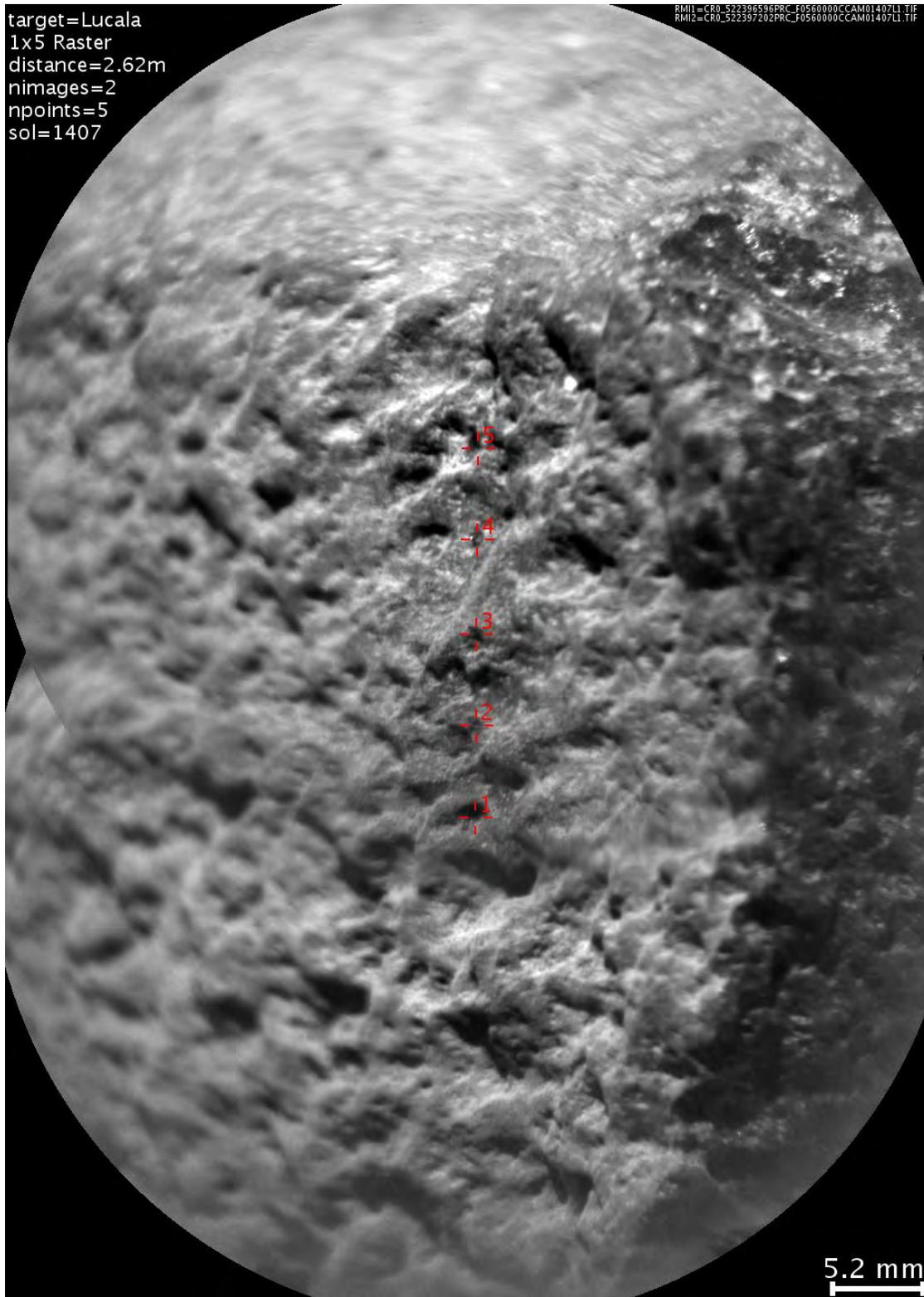
Aussenkehr, RMI mosaic.



Lucala, Mastcam image.

target=Lucala
1x5 Raster
distance=2.62m
nimages=2
npoints=5
sol=1407

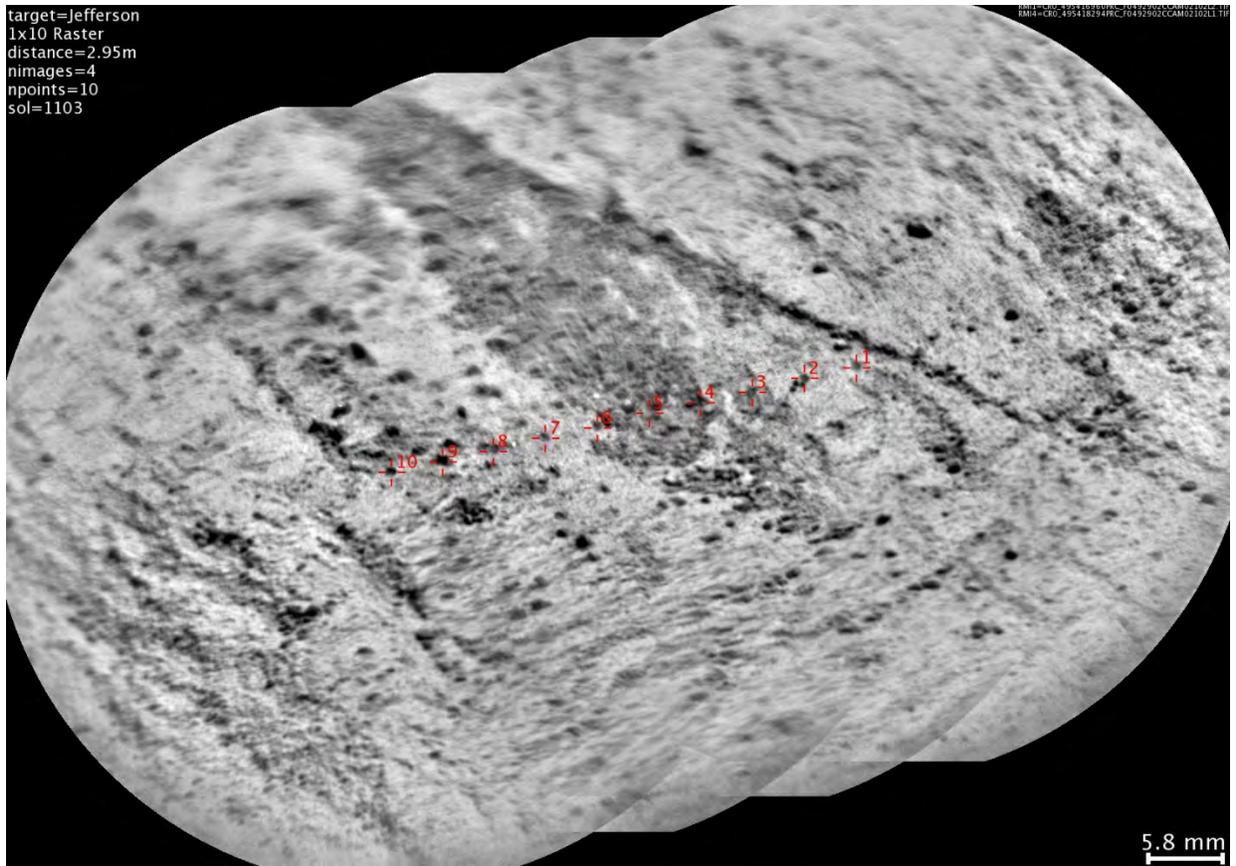
RM1=CR0_522396596PRC_F0560000CCAM01407LI.TIF
RM2=CR0_522397202PRC_F0560000CCAM01407LI.TIF



Lucala, RMI mosaic.



Jefferson, Mastcam image.



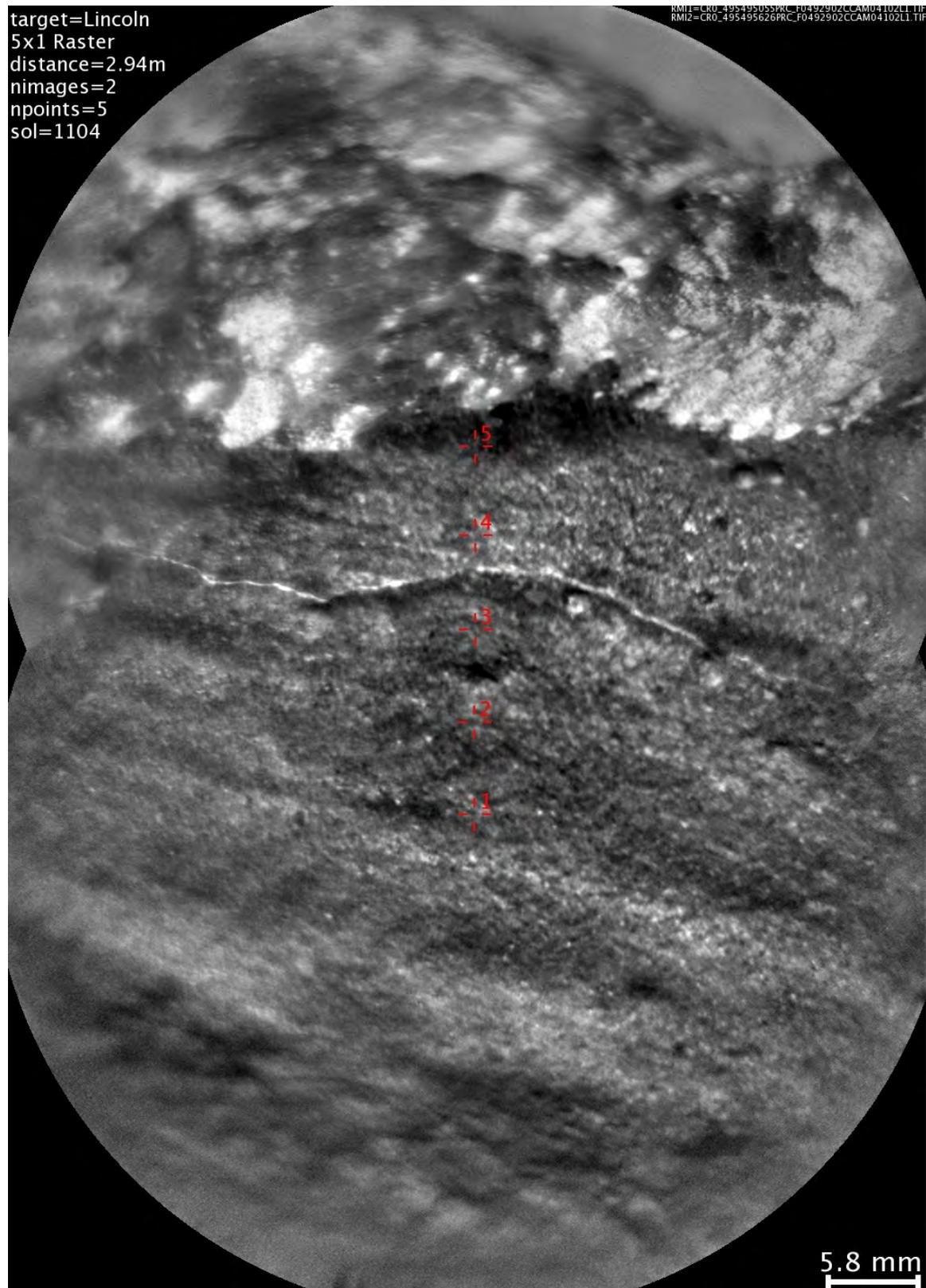
Jefferson, RMI mosaic.



Lincoln, Mastcam image.

target=Lincoln
5x1 Raster
distance=2.94m
nimages=2
npoints=5
sol=1104

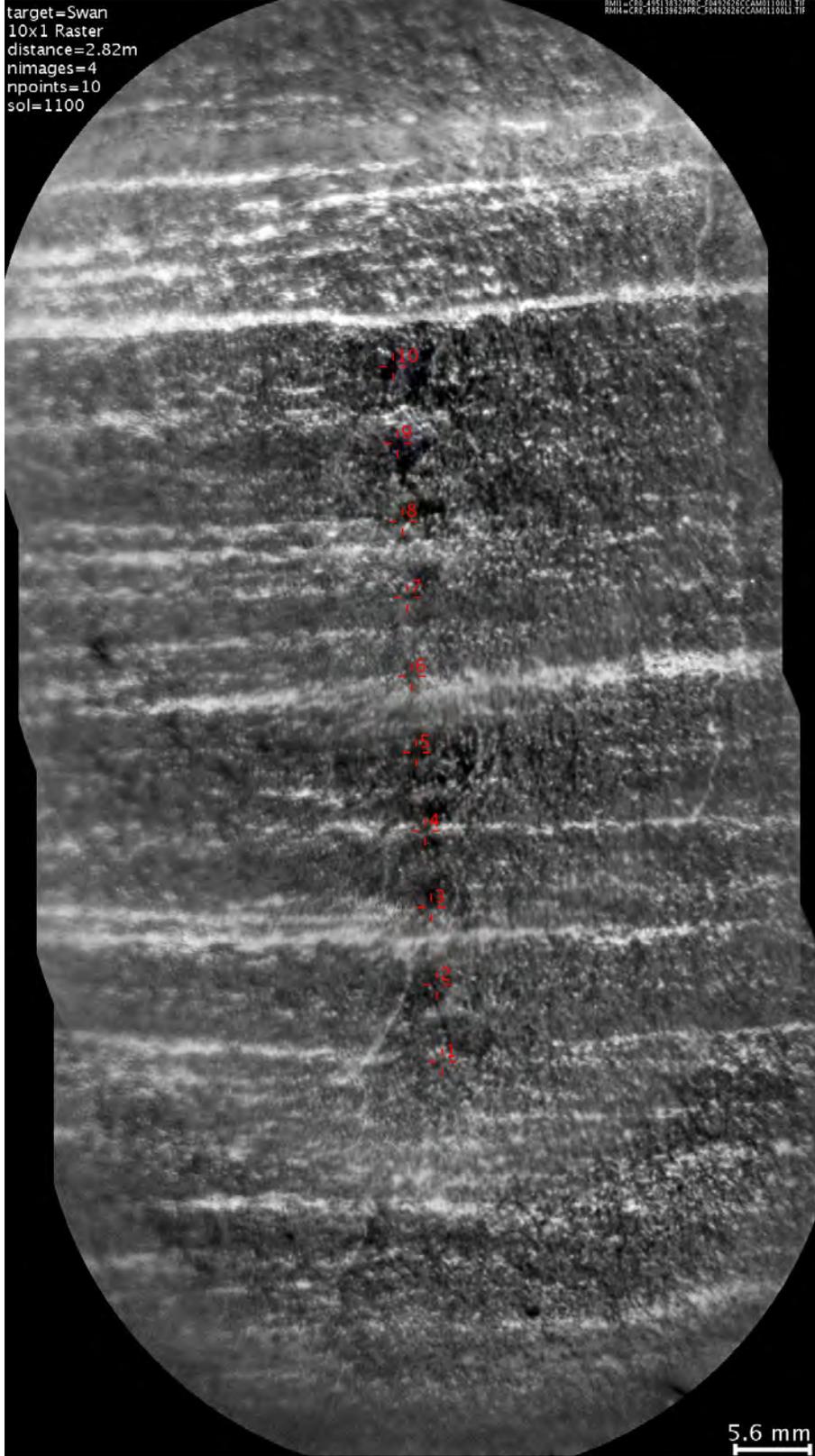
RMI1=CR0_495495055PRC_F0492902CCAM04102L1.TIF
RMI2=CR0_495495626PRC_F0492902CCAM04102L1.TIF



Lincoln, RMI mosaic



Swan, Mastcam image.



Swan, RMI mosaic.

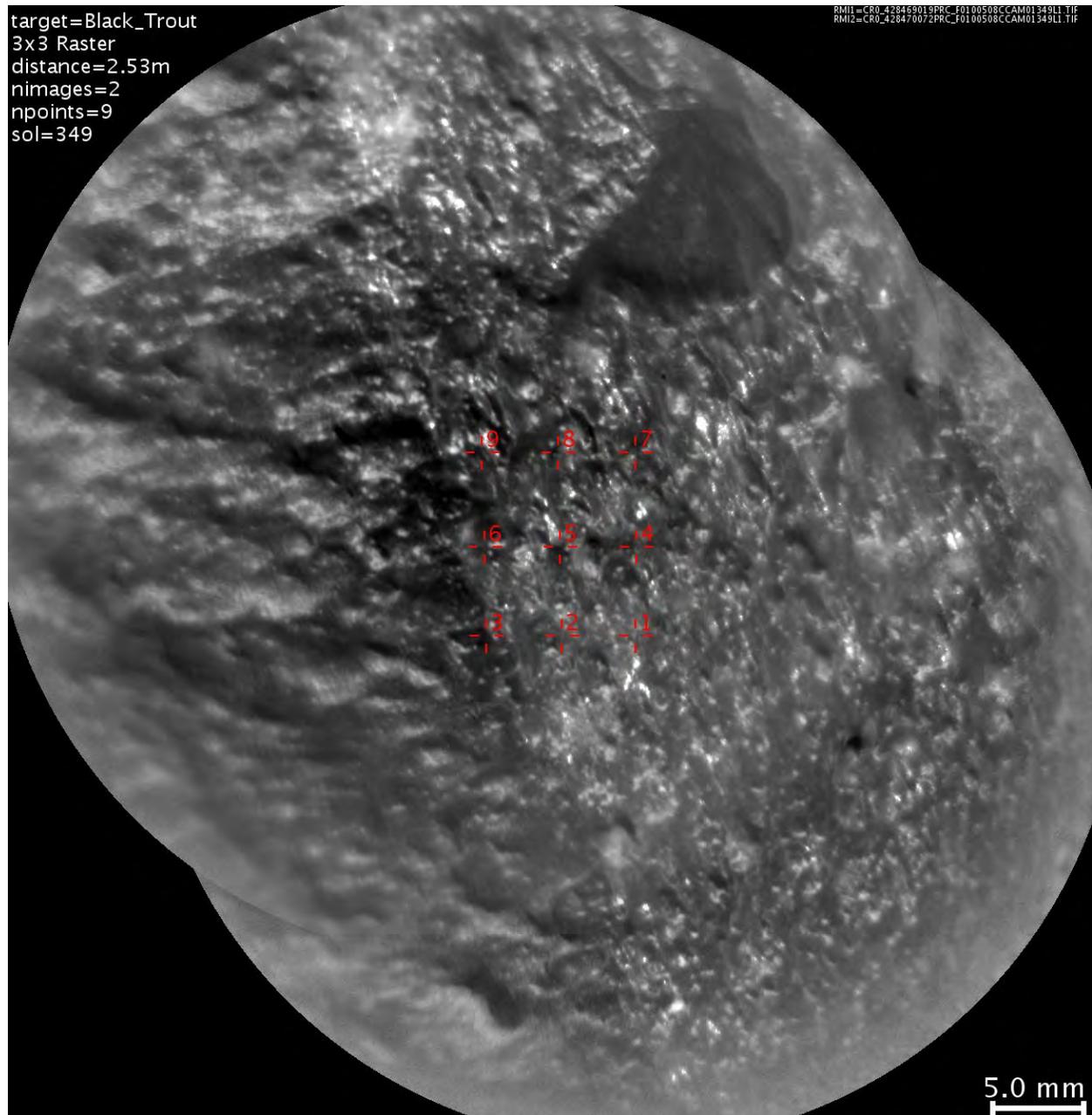
11. Images of ChemCam Bradbury Targets Not in the Main Body of the Paper.



Black Trout, Mastcam Image

target=Black_Trout
3x3 Raster
distance=2.53m
nimages=2
npoints=9
sol=349

RMI1=CRO_428459019PRC_F0100508CCAM01349L1.TIF
RMI2=CRO_428470072PRC_F0100508CCAM01349L1.TIF



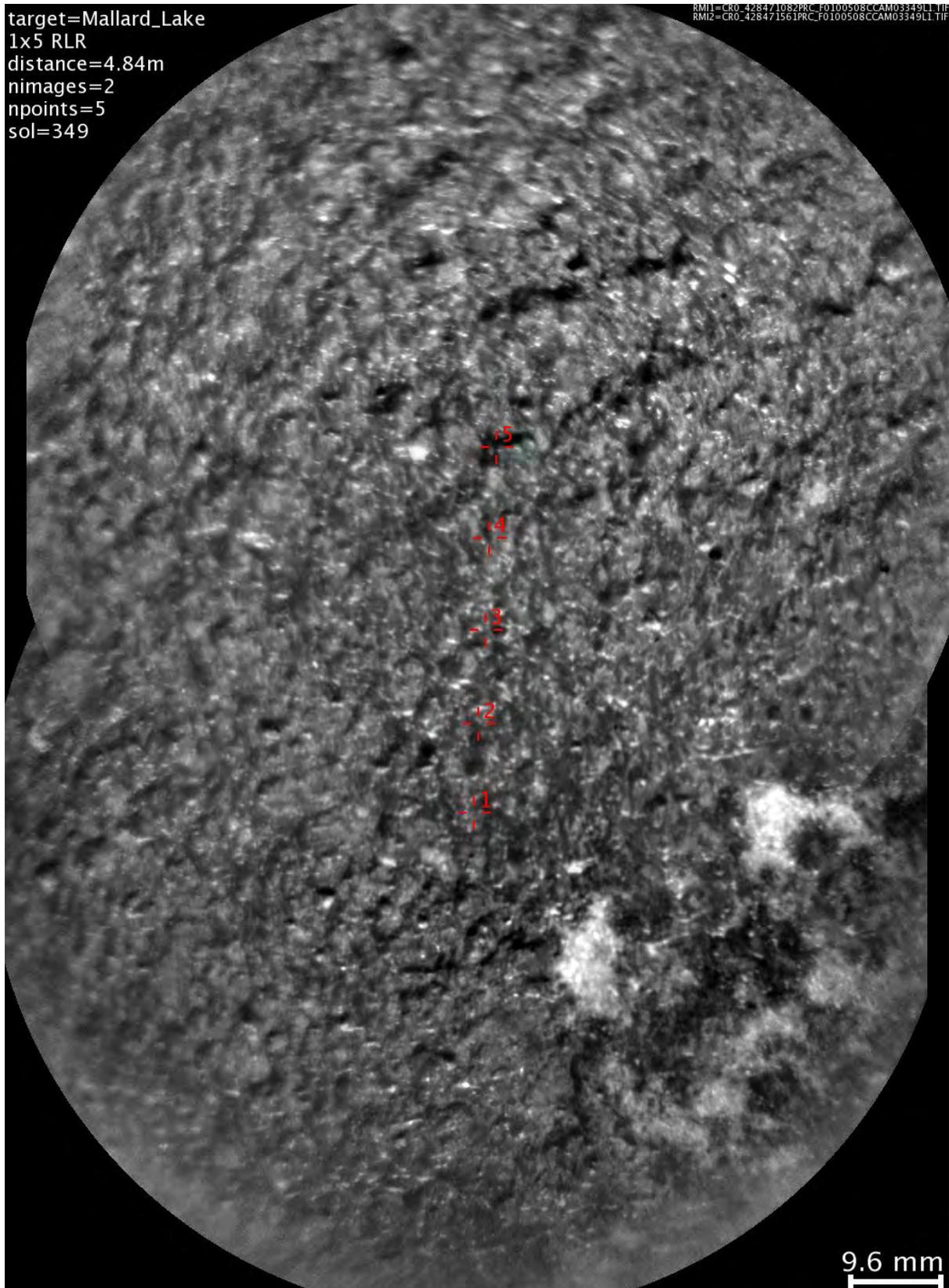
Black Trout, RMI mosaic.



Mallard Lake, Mastcam image

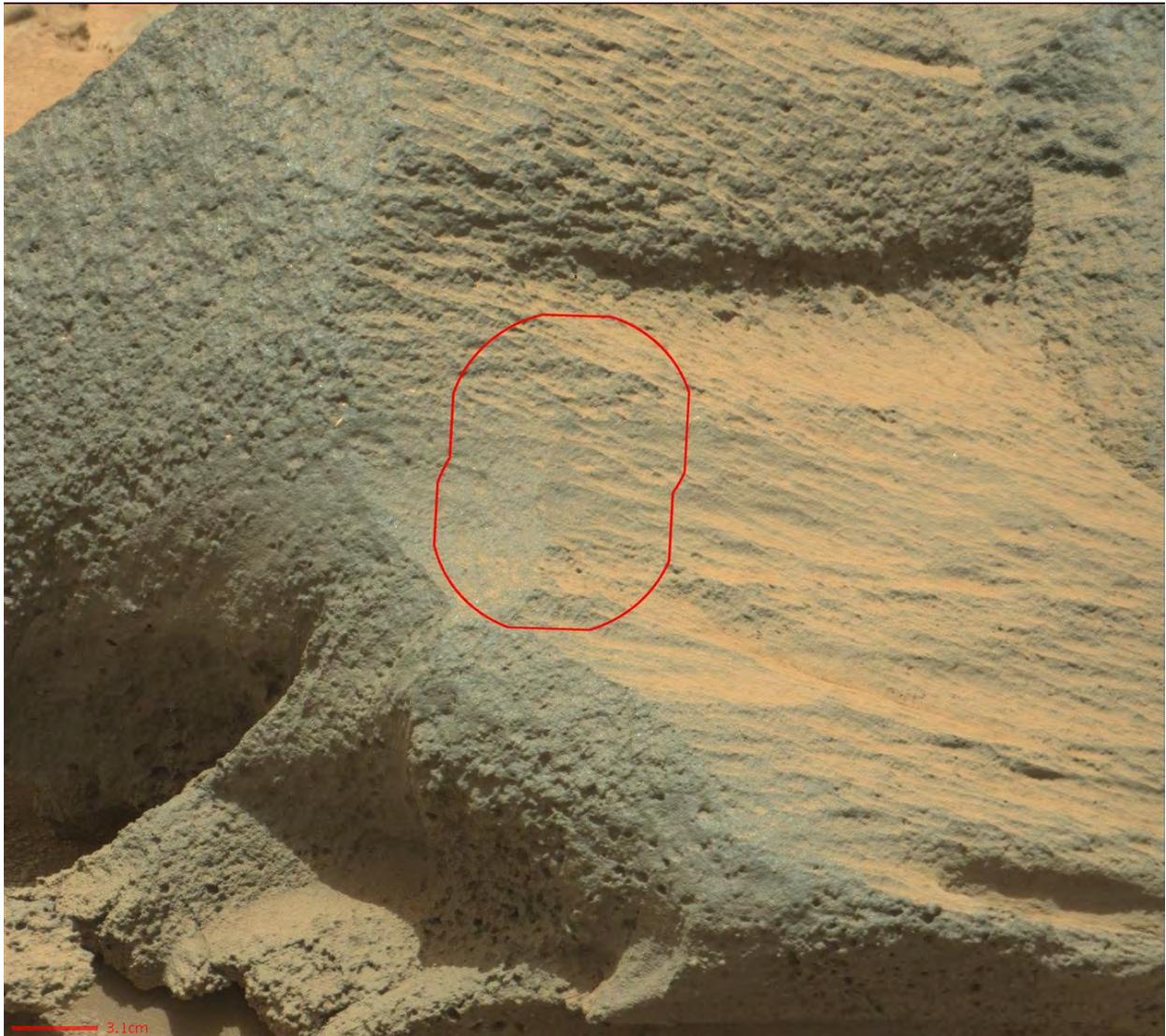
target=Mallard_Lake
1x5 RLR
distance=4.84m
nimages=2
npoints=5
sol=349

RMI1=CR0_428471082PRC_F0100508CCAM03349L1.TIF
RMI2=CR0_428471561PRC_F0100508CCAM03349L1.TIF



Mallard Lake, RMI mosaic.

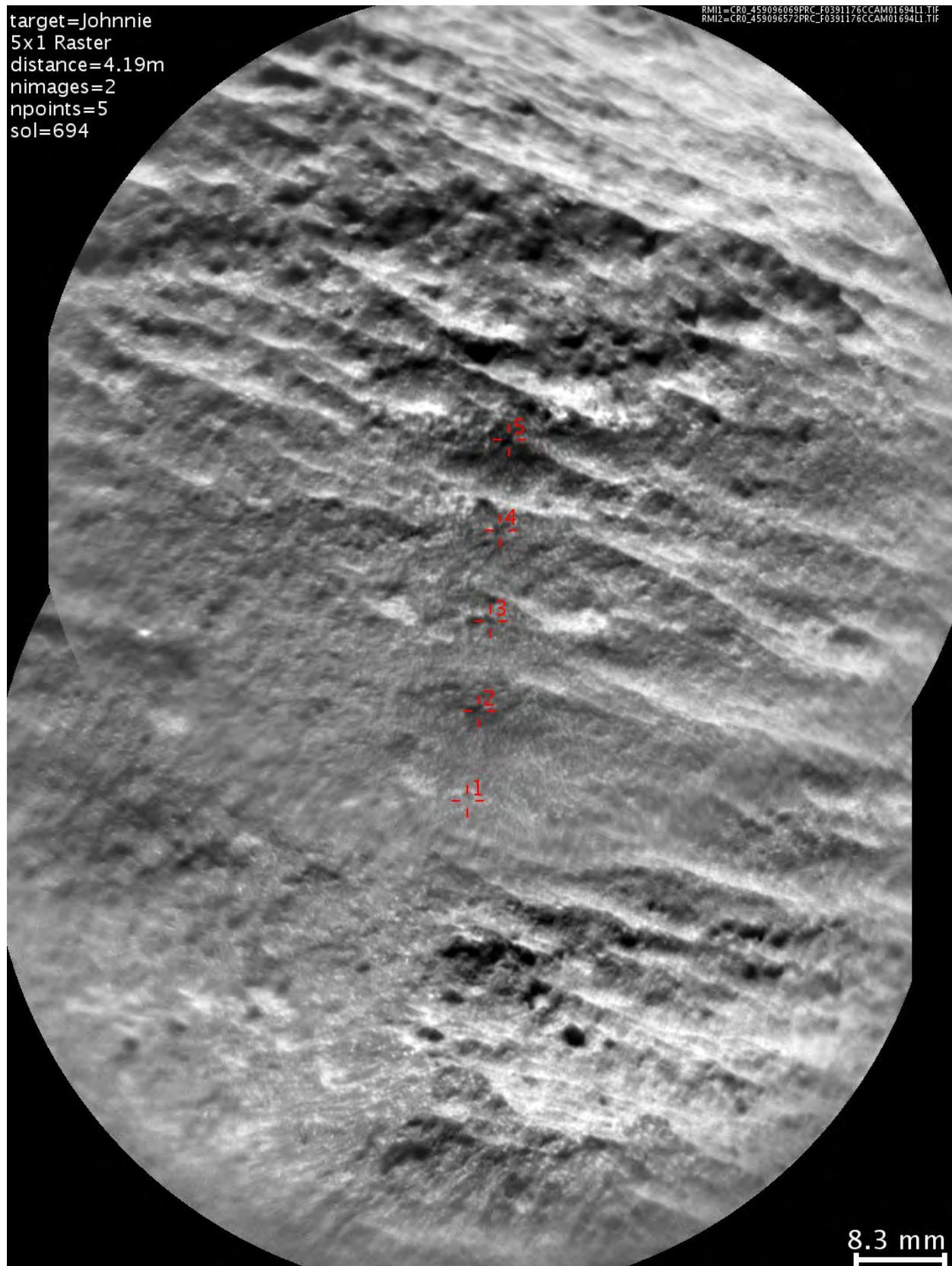
12. Images of Other Targets from Zabriskie Plateau (Johnnie, South_Park2)



Johnnie, Mastcam image.

target=Johnnie
5x1 Raster
distance=4.19m
nimages=2
npoints=5
sol=694

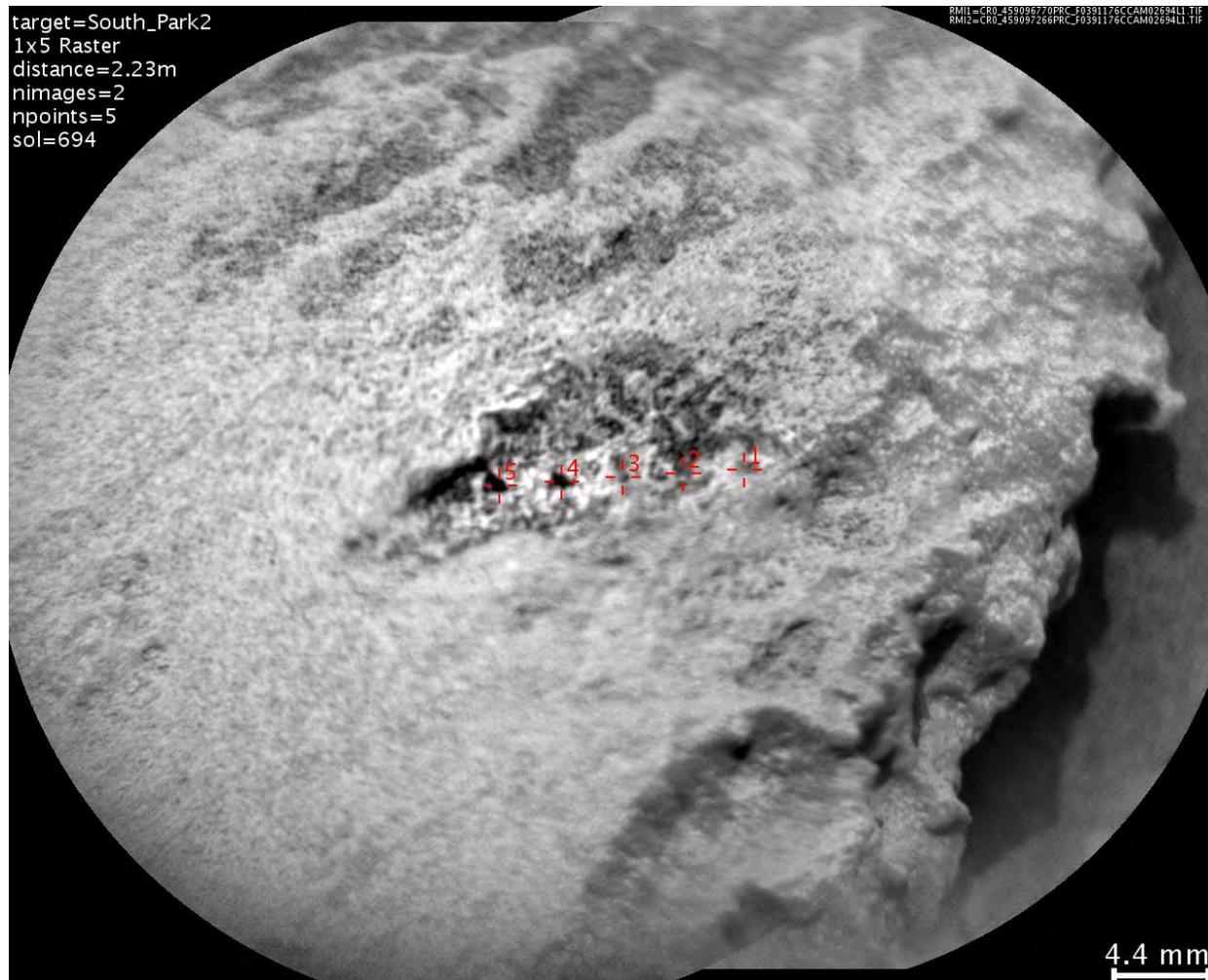
RM11=CR0_459096069PRC_F0391176CCAM01694L1.TIF
RM12=CR0_459096572PRC_F0391176CCAM01694L1.TIF



Johnnie, RMI mosaic.



South_Park2, Mastcam image.



South_Park2, RMI image.

13. Designations of Images Used in the Paper

Fig. 1: Mosaic of images acquired by the MRO CTX and HiRISE cameras assembled by Calef and Parker (2016).

Fig. 2a: HiRISE image ESP_042682_1755, acquired on 04 September 2015.

Fig. 2b: Portion of Mastcam-34 image 1100ML0048710700500554C00.

Fig. 2c: Portion of Mastcam-34 image 1100ML0048710620500546C00.

Fig. 2d-e: Portions of a Mastcam-34 Sol 1094 mosaic (sequence mcam04850).

Fig. 2f: Portion of a Mastcam-100 Sol 1099 mosaic (sequence mcam04868).

Fig. 2g: Portion of Sol 1098 Navcam Left-B camera product
NLB_494970804ILTLF0492374NCAM00266M1.

Fig. 2h: Portion of Sol 1104 MAHLI landscape image 1104MH0003250050401144E01.

Fig. 2i: Portion of a Mastcam-34 mosaic acquired on Sol 1100 (sequence mcam04871).

Fig. 3a: Portion of a Mastcam-34 mosaic acquired on Sol 1100 (sequence mcam04871).

Fig. 3b: Portion of Mastcam-100 image 1100MR0048770020600964E01.

Fig. 3c-d: Portions of a Mastcam-34 mosaic acquired on Sol 1100 (sequence mcam04871).

Fig. 3e: Portion of ChemCam RMI image product 1103_CRM_CCAM01102_Madison and a
portion of Mastcam-100 image 1103MR0048880000601026E01.

Fig. 3f: Portion of MAHLI focus merge product 1103MH0005210000401138R00.

Fig. 3g: Portion of Mastcam-34 image 1100ML0048711100500594C00.

Fig. 4a: Portion of HiRISE image ESP_043539_1755 acquired on MSL Sol 1159 (10 November
2015).

Fig. 4b: Portion of a Sol 1163 Mastcam-34 mosaic (sequence mcam05263).

Fig. 4c: Portion of a Sol 1158 Mastcam-34 mosaic (sequence mcam05242).

Fig. 4d: Portion of Mastcam-34 image 1158ML0052420350502024C0.

Fig. 4e: Portion of a Sol 1160 Mastcam-100 mosaic (sequence mcam05247).

Fig. 4f: Anaglyph created from portions of HiRISE stereo pair images PSP_009149_1750 and
PSP_009294_1750.

Fig. 5a: Portion of a Sol 1160 Mastcam-100 mosaic (sequence mcam05247).

Fig. 5b: ChemCam RMI image product 1160_CRM_CCAM2160_Hoba.

Fig. 5c: ChemCam RMI image product 1160_CRM_CCAM3160_Gibeon.

Fig. 5d: Portion of Mastcam-100 image 1160MR0052470570602057E01.

Fig. 5e: Portion of Mastcam-100 image 1277MR0059970040304226E01.

Fig. 5f: Portion of MAHLI focus merge product 1278MH0001700000500011R00.

Fig. 5g: Portion of a mosaic of Mastcam-100 images 1160MR0052470550602055E01 and 1160MR0052470620602062E01.

Fig. 5h: Portion of Mastcam-100 image 1160MR0052470310602031E01.

Fig. 5i: Portion of Mastcam-100 image 1160MR0052470600602060E01.

Fig. 5j: Portion of a Sol 1178 Mastcam-100 mosaic (sequence mcam05336).

Fig. 6: Portions of a HiRISE image mosaic constructed by Calef and Parker (2016).

Fig. 7: Base map is a portion of HiRISE image ESP_035917_1755. Insets for northeast Bimbe ridge and Bukalo are portions of a Sol 1387 Mastcam-100 mosaic (sequence mcam06815); inset for Bailundo is a portion of a Sol 1398 Mastcam-100 mosaic (sequence mcam06839).

Fig. 8: Stereo anaglyph constructed from portions of MRO HiRISE images PSP_009716_1755 and PSP_009650_1755.

Fig. 9a: Portion of a Sol 1402 Mastcam-100 mosaic (sequence mcam06869).

Fig. 9b: Portion of a mosaic of Navcam RDR image products:
 NLB_522233603ILTLF0560000NCAM00353M1.IMG,
 NLB_522233635ILTLF0560000NCAM00353M1.IMG,
 NLB_522234307ILTLF0560000NCAM07753M1.IMG,
 NLB_522234337ILTLF0560000NCAM07753M1.IMG,
 NLB_522234369ILTLF0560000NCAM07753M1.IMG,
 NLB_522234401ILTLF0560000NCAM07753M1.IMG,
 NLB_522234590ILTLF0560000NCAM00654M1.IMG,
 NLB_522234624ILTLF0560000NCAM00654M1.IMG, and
 NLB_522234657ILTLF0560000NCAM00654M1.IMG.

Fig. 10a: Portion of a Sol 1407 Mastcam-34 mosaic (sequence mcam06889).

Fig. 10b: Portion of MAHLI image 1407MH0001900010502809C00.

Fig. 10c: Portion of MAHLI focus merge product 1408MH0001630000502842R00.

Fig. 11a: Composite of a portion of Sol 1405 Navcam Left-B product NLB_522234590ILTLF0560000NCAM00654M1 and Mastcam-100 images 1409MR0068990000702206E01 (Seeis) and 1409MR0069000010702208E01 (Aegis_1406a).

Fig. 11b: Portion of Mastcam-100 image 1409MR0068990000702206E01.

Fig. 11c: Portion of Mastcam-100 image 1409MR0069000010702208E01.

Fig. 11d: ChemCam RMI image product 1406_CRM_CCAM15900_aegis_post_1406a.

Fig. 12a-b: Portions of Mastcam-100 image 1408MR0068970460702184C00.

Fig. 12c: ChemCam RMI image product 1409_CRM_CCAM03409_Oranjemund.

Fig. 13a: Portion of Mastcam-34 image 1399ML0068480000601724E01.

Fig. 13b: Portion of Mastcam-100 image 1400MR0068560000702022E01.

Fig. 13c: ChemCam RMI image product 1400_CRM_CCAM01400_Auchab.

Fig. 14a: Portion of a Sol 1401 Mastcam-34 mosaic (sequence mcam06865).

Fig. 14b: Portion of Mastcam-100 image 1401MR0068610000702028E01.

Fig. 14c: ChemCam RMI image product 1401_CRM_CCAM03401_Chinchimane.

Fig. 15a: Portion of Sol 1405 Left-B Navcam image product NLB_522233635ILTLF0560000NCAM00353M1.

Fig. 15b: Portion of MAHLI image 1407MH0006270010502776C00.

Fig. 16a: Portion of a Sol 1401 Mastcam-34 mosaic (sequence mcam06865).

Fig. 16b: ChemCam RMI image product 1401_CRM_CCAM02401_Canico.

Fig. 16c -- Portions of a Sol 1401 Mastcam-34 mosaic (sequence mcam06865).

Fig. 17a: Portion of a Sol 1407 Mastcam-34 mosaic (sequence mcam06889).

Fig. 17b-c: Portions of a Sol 1408 Mastcam-100 mosaic (sequence mcam06898).

Fig. 18a: Portion of a Sol 1409 mosaic of Mastcam-100 and Mastcam-34 images (sequence mcam06889).

Fig. 18b: Portion of ChemCam RMI image product 1409_CRM_CCAM01409_Seeheim.

Fig. 18c: Portion of ChemCam RMI image product 1407_CRM_CCAM03407_Bungo.

Fig. 18d: Portion of ChemCam RMI image product 1407_CRM_CCAM02407_Cabamba.

Fig. 18e: Portion of ChemCam RMI image product 1409_CRM_CCAM02409_Wilhelmstal.

Fig. 19a: Portion of a mosaic of MAHLI images 1407MH0006270010502774C00 and 1407MH0006270010502776C00.

Fig. 19b: Portion of MAHLI focus merge product 1411MH0005840000503006R00.

Fig. 19c-d: Portions of MAHLI focus merge product 1411MH0005840000503000R00.

Fig. 20a: Portion of Mastcam-100 image 1410MR0069050010702210E01. Inset is a portion of a Sol 1402 Mastcam-100 mosaic (sequence mcam06869).

Fig. 20b: ChemCam RMI image product 1410_CRM_CCAM05409_Mariental.

Fig. 22a: Portion of Mastcam-34 image 0052ML0002400070102217E01; inset is a composite of MAHLI images 0054MH0000160010100280C00 and 0054MH0000180010100312C00,

Fig. 22b: Portion of Mastcam-100 image 0336MR0013560000301059E01.

Fig. 22c: Portion of Mastcam-100 image 0349MR0014160000301161E01.

Fig. 22d: Portion of a mosaic of Mastcam-100 images 0044MR0002040290102567E01, 0044MR0002040220102560E01, 0044MR0002040150102553E01, and 0044MR0002040080102546E01.

Fig. 22e: Portion of Mastcam-100 image 0516MR0020340000303244E01; inset is a portion of MAHLI focus merge product 0516MH0002650000200986R00.

Fig. 22f: Portion of Mastcam-100 image 0692MR0029280000402215E01.