Characterization of Clasts in the Glen Torridon Region of Gale Crater Observed by the Mars Science Laboratory Curiosity Rover

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Abstract The morphology and composition of clasts have the potential to reveal the nature and extent of erosional processes acting in a region. Dense accumulations of granule- to pebble-sized clasts covering the ground throughout the Glen Torridon region of Gale crater on Mars were studied using data acquired by the Mars Science Laboratory Curiosity rover between sols 2300 and 2593. In this study, measurements of shape, size, texture, and elemental abundance of unconsolidated granules and pebbles within northern Glen Torridon were compiled. Nine primary clast types were identified through stepwise hierarchical clustering, all of which are sedimentary rock and are similar in composition to the local bedrock, suggesting that most clasts were transported short distances. Several clast types display features associated with fragmentation along bedding planes and existing cracks in bedrock. These results indicate that Glen Torridon clasts are primarily the product of in-situ physical weathering of local bedrock.

Plain Language Summary Clasts are loose fragments produced by the breakdown of rock, which can be transported and reshaped by forces like water, wind and gravity. Clast shape, size, and texture are useful indicators of the clast's origin and the forces that have transported and modified it over time. The Glen Torridon region of Gale crater, the field site for the Mars Science Laboratory Curiosity rover, is covered at the surface by an abundance of granule- to pebble-sized clasts. Between Martian days (“sols”) 2300 and 2593, Curiosity acquired images and compositional data of Glen Torridon clasts along the traverse. In this study, measurements of shape, size, texture, and composition of Glen Torridon granules and pebbles were compiled for characterization, and to determine their origin and erosional history. Nine primary clast types were identified, all of which are sedimentary rock and are similar in composition to the local bedrock, suggesting most clasts were transported short distances. Several clast types display features associated with fragmentation along bedding planes and existing cracks in bedrock. These results indicate that clasts in Glen Torridon are primarily the product of bedrock fragmentation.

1. Introduction

In-place bedrock provides a reliable record of depositional and erosional history, but fragmented bedrock clasts can also be used to ascertain the dominant modes of erosion, transport, and deposition over local and regional scales. Clasts can log the nature, intensity, and evolution of the environments and transport processes they encounter from the time of their formation to the point of deposition with quantifiable parameters such as size, roundness, and shape. Compositional trends and lithological characteristics can provide insight into provenance. In the case of robotic exploration of planetary surfaces, clast characterization has the added benefit of aiding and informing rover safety evaluation, as clasts can pose hazards for traversibility. Clasts can also be used as a proxy for in-place bedrock that would otherwise be inaccessible to a rover. Since landing, the Mars Science Laboratory (MSL) Curiosity rover has been systematically acquiring images of clasts on the surface using the Mastcam and MARDI cameras in the nearfield around the rover at the completion of each of the rover's drives. Analyses of clast observations in Gale crater were performed on Bradbury Rise and along the traverse to Yellowknife Bay (Szabó et al., 2015; Yingst et al., 2010, 2013, 2016) where unconsolidated clasts were abundant. Building on the analysis of Yingst et al. (2013, 2016), this study focuses on the characterization of clasts in the Glen Torridon region of Gale crater, where the Curiosity rover encountered an unusually dense collection of granule- to pebble-sized clasts distributed across a region known for its clay-bearing spectral signatures from orbit (Fraeman et al., 2016;
Milliken et al., 2010, 2014) and on the ground (Bristow et al., 2019), and the presence of decameter long-ridges interpreted as periodic bedrock ridges (PBRs) (Stack et al., 2022). The purpose of this study is to characterize the clasts in Glen Torridon in order to determine their origin and history, including the mechanisms of formation, transport, and subsequent modification, and to identify their relationship to the Glen Torridon PBRs.

1.1. Geologic Context

Gale crater is an ~155 km diameter impact crater situated along the martian crustal dichotomy boundary, a topographic feature which bisects the heavily cratered southern highlands and the younger northern plains. The crater, which is thought to have formed 3.8–3.6 Ga (Deit et al., 2013; Thomson et al., 2011), contains within it a 5 km thick central mound of sedimentary rock known as Aeolis Mons (informally referred to as Mount Sharp). Gale’s extensive record of sustained aqueous activity, particularly the transition from clay-bearing to sulfate-bearing strata observed within the lower reaches of Mount Sharp, motivated its selection as the landing site for the MSL mission (Grotzinger et al., 2014, 2015). Since landing at Bradbury Rise in August 2012, Curiosity has been exploring a thick sedimentary succession of fluvial, fluvial-deltaic, lacustrine, and aeolian rocks. Around Sol 700, Curiosity began its exploration of the Murray formation, an interval of the Mount Sharp group comprised primarily of finely-laminated mudstones (Fedo et al., 2019; Grotzinger et al., 2015; Rivera-Hernández et al., 2019; Stack et al., 2019). Murray formation mudstones have been interpreted to be associated with deposition in a low-energy lacustrine environment that extends nearly continuously from the Pahrump Hills outcrop to this study’s region of interest in Glen Torridon (Edgar et al., 2020; Fedo et al., 2019; Grotzinger et al., 2015; Rivera-Hernández et al., 2019; Stack et al., 2019). During this exploration of the Murray formation, the Curiosity rover has also encountered the Stimson formation of the Siccar Point group, a meter-scale cross-bedded aeolian sandstone unit that unconformably overlies the Mt. Sharp group (Banham et al., 2018, 2021).

Curiosity’s exploration of the Glen Torridon region (Figure 1, Bennett et al., 2022) began on sol 2300 following an ~570 sol campaign at Vera Rubin ridge (VRR) (Fraeman et al., 2020). Orbital observations of this region of Mount Sharp using the High-Resolution Imaging Science Experiment (HiRISE), Context Camera (CTX), Thermal Emission Imaging System (THEMIS), and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) revealed a topographic-low with strong phyllosilicate phases and a distinct corrugated texture (Anderson, 2010; Fraeman et al., 2016; Milliken et al., 2009). Compared to the overlying strata, which appears to be sulfate-bearing with little to no apparent clay mineral absorptions, Glen Torridon (referred to as
as “phyllosilicate-bearing trough” in Anderson (2010), “phyllosilicate layers” in Milliken et al. (2010), and “phyllosilicate unit” or “PhU” in Fraeman et al. (2016), was found to have spectral signatures consistent with Fe/Mg-bearing smectite clays (Fox et al., 2021; Fraeman et al., 2016; Sheppard et al., 2021). The transition from clay- to sulfate-bearing units is believed to chronicle a progression of climate change on ancient Mars associated with increasingly arid and acidic conditions (Bibring et al., 2006; Fraeman et al., 2016; Milliken et al., 2010).

Bedrock exposed within the northern part of Glen Torridon is interpreted to be stratigraphically equivalent to, and an extension of, the Jura member first identified on VRR (Anderson, 2010; Fraeman et al., 2016). Within Glen Torridon, the Jura member forms a 6 m thick unit of resistant and recessively layered lacustrine mudstone variably enriched in K and Mg based on ChemCam measurements (Dehouck et al., 2019). A resistant sandstone unit known as the Knockfarril Hill member overlies the Jura member within Glen Torridon (Caravaca et al., 2021; Fox et al., 2020). The Knockfarril Hill member sandstones are easily distinguished by their decimeter-scale cross-bedding and resistance to weathering. The transition between the Jura and Knockfarril Hill members is interpreted to represent a transition from a low- to higher-energy depositional setting (Caravaca et al., 2021; Fox et al., 2020).

One of the most prominent features of Glen Torridon is the presence of decameter-long linear ridges (Anderson, 2010; Milliken et al., 2014; Stack et al., 2022) interpreted as PBRs (Stack et al., 2022), which are prevalent in northern Glen Torridon. The northeast-southwest-oriented PBRs are interpreted to be carved directly into the bedrock, although they are often covered with granule- to pebble-sized clasts. PBRs identified elsewhere on Mars have been interpreted to form transverse to the prevailing wind direction, although determining the formative wind direction for the Glen Torridon PBRs is not straightforward (Stack et al., 2022). In this context, understanding the environment in which the Glen Torridon clasts formed may offer insight into the generation of PBRs and the erosion of the Jura and Knockfarril Hill members.

2. Data and Methods

2.1. Mastcam Clast Survey

Images captured by the Mast Camera (Mastcam, Malin et al., 2017) were used to determine clast size, shape, and distribution. Systematic clast imaging has been conducted since Curiosity’s landing in Gale crater (Yingst et al., 2010, 2013, 2016). Following nearly every drive completed by Curiosity, a “clast survey” image pair is taken of the ground near the rover with both the left and right eyes of Mastcam, which is mounted atop the rover's Remote Sensing Mast. The left Mastcam (M-34) has a 34 mm focal length and 18.4° × 15° effective field of view (Malin et al., 2017), resulting in a 0.22 mrad/pixel resolution. The right Mastcam (M-100) has a 100 mm focal length, a 6.3° × 5.1° field of view, and a 0.074 mrad/pixel resolution. The standard subframe for clast survey images is 1152 × 1152 pixels, corresponding to a field of view of 14.4° × 14.4° for M-34 and 4.9° × 4.9° for M-100. The image scale is 0.62 mm/pixel and 0.21 mm/pixel for M-34 and M-100, respectively.

Clast survey images are taken at a consistent azimuth (120°) and elevation (−45°) in the coordinate frame of the rover, and most were acquired in the afternoon for consistent illumination in order to provide the best color contrast for distinguishing clasts from the sand substrate (Yingst et al., 2016).

2.2. MARDI

Images from the Mars Descent Imager (MARDI, Malin et al., 2017) were used in this study to catalog qualitative morphological features of clasts (e.g., texture, angularity, erosional markers), the presence of bedrock, and clast dispersion. MARDI is a downward-pointing camera intended primarily for navigational use during MSL’s entry, descent, and landing (Malin et al., 2017). MARDI has since been used to systematically document the terrain covered by Curiosity since its landing in 2012 (Minitti et al., 2019). MARDI has a 70° × 52° field of view and an instantaneous field of view of 76 milliradians, ideal for long-range imaging. MARDI image quality decreases with spatial scale, but post-landing calibration has enabled the instrument to capture 1.5 mm resolution images of the surface directly below the rover (Malin et al., 2017). MARDI’s orientation and proximity to the ground (70 mm) offers another data set uniquely suited to clast imaging.
2.3. ChemCam
Elemental geochemistry obtained by the Chemistry and Camera (ChemCam, Maurice et al., 2012) instrument is assessed in this study to determine compositional trends between clasts and local bedrock. ChemCam uses Laser Induced Breakdown Spectroscopy (LIBS) to acquire major element abundances for SiO$_2$, TiO$_2$, Al$_2$O$_3$, FeOt, MgO, CaO, Na$_2$O, and K$_2$O (Maurice et al., 2012). The LIBS technique involves striking a nearby target with a series of laser pulses to induce a short-lived plasma, from which emitted light produced by atom decay is spectrally analyzed (Maurice et al., 2012). ChemCam is particularly well-suited for clast analysis as it is sometimes able to target multiple small clasts within a single raster and without the need for contact science. In conjunction with LIBS analysis, ChemCam captures submillimeter resolution images of targets using its Remote Micro-Imager (RMI). RMI has a field of view of 20 mrad and a pixel scale of 19.6 μrad/pixel (Maurice et al., 2012). A total of 28 RMI images were used in this study to characterize clast texture and grain size.

2.4. Analysis of Clast Characteristics
Clast lithology, including texture and grain-size, were assessed qualitatively using Mastcam clast survey images, MARDI images, and ChemCam RMI images where available. Shape and size clast measurements were obtained by analyzing 64 Mastcam clast survey image pairs, each pair consisting of one M-34 and one M-100 image, captured between sols 2302 and 2593. For unbiased clast sampling, 50 × 50 and 10 × 10 grids were superimposed onto the M-34 and M-100 images, respectively. Any clasts within a given cell in the grid were eligible to be sampled and digitally outlined in ImageJ. A total of 1,057 clasts were sampled. Following the methods of Yingst et al. (2016), we directly measured clast major and minor axis, sphericity, solidity, and roundness. Sphericity, $f$, approximates the resemblance of a particle to a sphere from its two-dimensional projection (Riley, 1941). Sphericity is a function of the largest inscribing circle diameter, $d_i$, and the smallest circumscribing circle diameter, $d_c$, of a particle given by:

$$ f = \sqrt{d_i / d_c} $$

Solidity, $S$, is a measurement of the concavity of a clast, defined as the ratio of clast area, $A$, to convex hull area, $A_c$ (Olson, 2013). As the clast becomes smoother and more rounded, the area of the clast and that of its convex hull area will converge to 1. Since surface roughness and protrusions strongly affect the value of $A_c$, solidity can be used as a proxy for surface texture.

$$ S = A / A_c $$

Roundness is a measure of corner sharpness. Roundness classes defined by Powers (1953) include very-angular (VA), angular (A), sub-angular (SA), sub-rounded (SR), rounded (R), and well-rounded (WR). Clast roundness in this work is determined by visual assessment.

Additionally, the inverse aspect ratio, $I/L$, compares the minor ($I$) and major ($L$) axes to characterize the overall clast shape. The $I/L$ ratio is used by Domokos et al. (2015) to approximate the degree of fragmentation experienced by a population of clasts.

The accuracy of morphological measurements is highly dependent on image resolution and surface illumination. For the purposes of this study's analysis, the resolution limits on major axis (minimum major axis of 12 mm for M-34 and 4.2 mm for M-100) and shape parameters (minimum major axis of 60 mm for M-34) defined by Yingst et al. (2016) were adopted, with the exception of the minimum major axis limit for shape resolution on M-100 images, which is reduced from 21 to 20 mm to incorporate more clasts given the quantity of small pebbles in the region. Any sampled clasts below these threshold values were marked and bundled as “fines.” All 1,057 sampled clasts were above the major axis resolution limit, whereas only 108 clasts were above the shape axis resolution limit. To calculate the inverse aspect ratio, $I/L$, any pebbles with major and minor axes above the major axis resolution limit were included, a total of 958 clasts.

Error in clast morphology measurements is predominantly caused by human error and the use of a two-dimensional projection to estimate the parameters of a three-dimensional shape (Yingst et al., 2010), an issue potentially exacerbated by the fact that the fixed orientation of the Mastcam for clast survey images means clasts deposited along slopes are angled differently than those on level ground. Although we acknowledge several potential sources of
error, Riley (1941) and Cailleux (1947) show this error to be less than 10% for pebble- to cobble-sized clasts that are sub-angular to well rounded, which is the case for the vast majority of clasts observed in this data set.

A modified approach to hierarchical clustering (Murtagh & Contreras, 2012, 2017) was used to segment clasts with broadly similar properties into groups called types. Traditional hierarchical clustering links individual observations if they display a high degree of similarity; the resulting clusters are then grouped into progressively larger clusters until a multilevel hierarchical tree is formed. In this study, we adopt a top-down approach to clustering by performing dissimilarity analysis along one parameter at a time. The clast population is subdivided into two or three dissimilar clusters based on a given size or shape parameter, such as major axis. The process is repeated on each new cluster for a different parameter until the desired number of clusters are reached. Garvin et al. (1981) used a similar clustering method to classify the rock populations at the Venera and Viking landing sites on Venus and Mars, respectively, with great success. Hierarchical clustering proved effective in establishing clusters using only major axis, $I/L$, and roundness as inputs (Figure 2). Roundness, in particular, proved to be a very strong driver for classification, differentiating clasts with similar sphericities and solidities from one another. However, three-dimensional features such as facets and texture were not well accounted for in these groupings, producing clusters with a mixture of platy and blocky clasts. The resulting nine clast types are described in Section 3.1.

2.5. Approach to Clast and Outcrop Geochemistry

ChemCam targets of in-place bedrock outcrops analyzed between sols 2225 and 2579 were identified as either Jura or Knockfarril Hill member based on their stratigraphic position (elevation) and on a visual assessment of lithology: Jura member is comprised of laminated mudstones; Knockfarril Hill is typically comprised of coarse-grained sandstones (Caravaca et al., 2021; Dehouck et al., 2019). To visualize the major geochemical trends of both members, density contour plots were generated from the bedrock target data. Density contours are two-dimensional histograms used to plot bivariate distributions, which are smoothed using kernel density estimation for this analysis. The contour lines connect points with the same probability density values and are adjusted according to the number of targets per unit. The major element oxide wt.% for in-place bedrock outcrop targets is averaged across a target in order to express the effective bulk composition of the target rock. Density contours generated from in-situ Jura and Knockfarril Hill member bedrock targets were then plotted together with clast compositions in order to determine the degree of compositional similarity between the two populations. Since rasters of clasts often targeted multiple clasts at once, rather than a single rock, plots show the composition of individual raster points instead of target averages to represent the Glen Torridon clasts.

3. Results

3.1. Clast Types

Nine primary clast types were identified using stepwise hierarchical clustering analysis of shape, size, and texture (Table 1 and Figure 3). Clast type 1 is distinguished by its large size ($L > 42$ mm), subrounded shape, and additional features such as pitting and faceting. The remaining clast types may differ in size, roundness
Table 1
Shape and Size Ranges for Clast Types 1–9

| Clast type | Major axis (mm) | I/L    | Sphericity | Solidity | Roundness | Additional characteristics | Ex. |
|------------|----------------|--------|------------|----------|-----------|---------------------------|-----|
| Type 1     | 50–42          | 0.74–0.27 | 0.83–0.54  | 0.96–0.88 | SA       | Sometimes pitted; some with one or more flat faces | Figure 3a |
| Type 2     | 30–23          | 0.84–0.69 | 0.83–0.75  | 0.96–0.84 | VA—A     | Mixture of platy and massive clasts; smooth to rough textured | Figures 4a and 4b |
| Type 3     | 31–24          | 0.54–0.27 | 0.69–0.52  | 0.94–0.77 | VA—A     | Elongated; some platy; often laminated; some with one or more flat faces | Figure 3c |
| Type 4     | 34–23          | 0.91–0.64 | 0.87–0.73  | 0.96–0.89 | SA—SR    | Some show keel joining facets; faint laminations | Figure 3c |
| Type 5     | 33–24          | 0.60–0.28 | 0.75–0.54  | 0.96–0.82 | SA—SR    | Elongated; smooth textured; some with one or more flat faces | Figure 3d |
| Type 6     | 23–20          | 0.90–0.39 | 0.87–0.60  | 0.95–0.79 | VA—A     | Mixture of platy and massive clasts; smooth to rough textured; often laminated; some with one or more flat faces | Figures 4c and 4d |
| Type 7     | 23–20          | 0.84–0.54 | 0.86–0.70  | 0.97–0.89 | SA—SR    | Smooth textured; few laminations; some with one or more flat faces | Figure 3e |
| Type 8     | 22–20          | 0.45–0.33 | 0.67–0.59  | 0.96–0.87 | SA—SR    | Elongated; smooth textured; some with one or more flat faces | Figure 3f |
| Type 9     | 21–4           | 0.60–0.35 | 0.75–0.60  | 0.96–0.94 | R—WR     | Smooth textured; strongly rounded | Figure 4e |

Figure 3. Plot of clast types as a function of I/L, roundness, and solidity. Given shape parameter resolution limit, only clasts with a major axis >20 mm are plotted.
and $I/L$, but share other notable features. Type 2 and Type 6 clasts are either laminated and platy or very angular massive clasts. Types 3, 5, and 8 are elongated clasts, with $I/L$ values less than 0.6 and roundness ranging from very angular to subrounded. At least 30% of the clasts categorized as Types 4, 5, and 7 have one or more exposed facets.

The lithology of all clast types observed in Glen Torridon is interpreted to be sedimentary. These clast types commonly exhibit laminations, smooth surface textures, and fine grain sizes down to RMI scale images (Figures 4 and 5). These characteristics are similar to that of in-place Jura and Knockfarril Hill member bedrock (Bennett et al., 2022; Caravaca et al., 2021; Fedo et al., 2019), as well as other Murray formation rocks observed along Curiosity's traverse through Gale crater (Bennett et al., 2022; Caravaca et al., 2021; Fedo et al., 2019), however, clast types do not appear to indicate stratigraphy. Additionally, no clasts observed in this study displayed porphyritic textures. However, many of the clasts in Glen Torridon are coated with a layer of dust that obscures color, fabric, and grain size, complicating the characterization and comparison of lithology among clast types and in-place bedrock.

3.2. Distribution of Clast Types

The spatial distribution of clast types in the Glen Torridon region is mapped in Figure 6. Clast Types 4, 5, 6, and 7 are observed throughout Curiosity's traverse of Glen Torridon, with no apparent bias toward any locality of Glen Torridon or any of its geologic features. Type 1 clasts appear frequently near PBRs and other ridges, including three of the PBRs studied in more detail in Section 3.3. Type 2 clasts occur predominately in two zones, one near the northeast sector of Curiosity's traverse through Glen Torridon, and another toward the south starting

![Figure 4. M-100 images of clast types](image-url)
at sol 2481. Type 3 clasts occur extensively at lower elevations in the northern portion of Curiosity's traverse near an area of in-place bedrock exposure at the base of VRR. Type 8 clasts begin to appear in abundance along Curiosity's traverse toward southern Glen Torridon. No significant up-section trends in clast type distribution are observed.

**Figure 5.** M-100 images of clast types, (a) Type 2 clast with platy morphology, sol 2422 (b) Type 2 clast, sol 2407. (c) Type 6 clast with platy morphology, sol 2420, (d) Type 6 clasts, sol 2304, (e) Type 9 clasts, sol 2466. The matrix is a mixture of dust and sand-sized grains which is relatively uniform throughout the region.

**Figure 6.** Spatial distribution of clast types along the Curiosity traverse. Markers represent sites where at least one occurrence of a clast type was imaged. Not shown are Types 4, 5, 6, and 7, which are well distributed in the region.
3.3. Proximity to Periodic Bedrock Ridges

Three PBRs were traversed by the rover, with Mastcam clast survey images taken within 15 m of the PBR crests. PBR 1 (sols 2302–2309) is located near the southern edge of the VRR in northern Glen Torridon. The rover approached the PBR 1 crest to the south of a Knockfarril Hill member outcrop which caps the Jura member comprising the lower part of the ridge. PBR 2 (also known as Teal ridge, sols 2436–2447) is near the transition between the Jura and Knockfarril Hill members. The rover approached PBR 2 where it terminates at a large Knockfarril Hill member outcrop. PBR 3 (sols 2586–2590) is in the Knockfarril Hill member near the transition with the Glasgow member.

Trends in clast shape and size parameters along the ridge profile are illustrated in Figure 7. Sphericity and solidity are lowest at the ridge crests for PBRs 1 and 3, indicating clasts are rough and non-spherical. Sphericity approaches a maximum within 5–10 m of the ridgecrest in both the NW/SE directions. Solidity is maximized in the SE direction. PBR 2 deviates from these patterns, showing an overall increase in sphericity and solidity toward the crest. Trends in size are less consistent. Major axis is maximized at the crest of PBR 1, but minimized...
at the crest of PBR 3. At PBR 2, major axis is higher than average at the crest, but increases to its maximum value approximately 10 m to the northeast of the ridgecrest. Larger clasts at or near the crests of PBRs 1 and 2 is likely due to the presence of coherent bedrock caps. Along the PBR flanks, clasts are also found to be more angular and poorly sorted, or in small densely-packed patches. At the troughs, clasts are rounded, well-sorted and more deeply embedded in the sand matrix.

3.4. Geochemistry

Major element abundances measured by the ChemCam instrument show clast composition is closely correlated with nearby corresponding bedrock composition (Figure 8), consistent with the findings of Dehouck et al. (2019). Over 63% of the ChemCam raster points on clasts are enriched in K₂O (>1.5 wt. %), suggesting a majority of clasts in Glen Torridon are sourced from the Knockfarril Hill member, which is enriched in K₂O relative to the underlying Jura member (Dehouck et al., 2019). Glen Torridon clasts depleted in K₂O tend to display an enrichment in MgO, a characteristic of the Jura member bedrock. These compositional trends are reflected in the Glen Torridon drill targets, which sample both the Jura member bedrock (targets Aberlady and Kilmarie) and the Knockfarril Hill member bedrock (targets Glen Etive 1 and Glen Etive 2). These results together strongly indicate that the provenance of the clasts analyzed in this study is relatively local and primarily within Glen Torridon.

4. Discussion

4.1. Origin of the Glen Torridon Clasts

We examine four possible mechanisms by which the clasts in Glen Torridon could have originated: (a) impact cratering, (b) fluvial or debris flow, (c) glacial erosion, and (d) in-situ bedrock fragmentation.

4.1.1. Impact Cratering

Impacts can produce clasts with a variety of shapes, textures, and sizes. Diagnostic features of impact ejecta blocks include shocked minerals, impact melts, melt-brecciation, shatter textures, and shatter cones (Newsom et al., 2015; Osinski & Pierazzo, 2012). Shocked minerals may be expressed as linear striations at the clast-scale (Osinski & Pierazzo, 2012). At higher pressures, clasts can undergo partial or complete melting, resulting in vesicular and porphyritic textures (Newsom et al., 2015; Spray et al., 2010; Therriault et al., 2002). Melts may also incorporate local fragments to form impact melt breccias, or consolidate into smooth, glassy, well-rounded spherules (Glass, 1990; McCall, 2001). Newsom et al. (2015) identified potential spherules earlier in the mission during the traverse of Bradbury Rise that appear similar in size and shape to some Type 9 clasts in Glen Torridon. Type 9 clasts do not exhibit the smooth and glassy surface texture typical of other candidate impact spherules observed on Mars, although this dull appearance could be the result of a dust coating. Small, well-rounded clasts could also form as lapilli, a type of proximal ejecta that accrete ash and glass as they fall back to the surface (Newsom et al., 2015). However, with the possible exception of some Type 9 clasts, little evidence exists of impactite features on or within the broader Glen Torridon clast population. While shock features such as shatter cones may be overprinted by other erosional processes, there are no observations of brecciation or textures associated with melting in Glen Torridon.

Most importantly, the uniformity of clast lithology and composition is inconsistent with an impact formation interpretation. If Glen Torridon clasts are an accumulation of ejecta blocks from impacts across Gale crater and have persisted as gravel and pebble lag through time, we would expect far greater lithochemical diversity than what is observed in the Glen Torridon clast population. As described in Section 3.4, nearly all clasts analyzed in
this study are lithologically and compositionally similar to each other, and in-family with in-place observations of Jura or Knockfarril Hill member bedrock. Impact ejecta may constitute of small portion of the clasts in Glen Torridon, but impact events are unlikely to be the primary source of clast formation in the region.

### 4.1.2. Fluvial or Debris Flow

Fluvial or debris flows are capable of transporting and depositing large quantities of gravel-, pebble-, and cobble-sized clasts. Debris flows are able to transport granule- to cobble-sized clasts (Whipple & Dunne, 1992), and studies of the Peace Vallis alluvial fan at the crater rim indicate that fluvial flows transported clasts up to \(\sim 10\) cm in diameter (Cousin et al., 2021; Sautter et al., 2014, 2015; Szabó et al., 2015; Williams et al., 2013). Fluvial or debris flow transport could explain the quantities of rounded clasts found throughout Glen Torridon, specifically some Type 4, 7, and 9 varieties, which are predominately subrounded to well-rounded. More angular clasts could be explained by shorter transport distances, although the co-occurrence of rounded and angular clast types together throughout Glen Torridon makes this explanation less compelling.

If the Glen Torridon clasts were transported to their current location by fluvial and debris flows entraining sediments from the upper slopes of Mount Sharp, the crater rim, or terrain outside Gale, lithological and geochemical diversity, like that observed on Bradbury Rise (Cousin et al., 2021; Mangold et al., 2016) would be expected. The uniformity in clast lithology and composition, as well as the angularity of many clasts, does not support fluvial or debris flow transport of the clasts found within Glen Torridon.

The Glasgow member and the Greenheugh pediment south of Glen Torridon toward Mount Sharp are distinct both lithologically and compositionally. The Glasgow member, in particular, is depleted in K\(_2\)O and MgO compared to the mean Jura and Knockfarril Hill member compositions (O’Connell-Cooper et al., 2021). It is unlikely that Glen Torridon clasts are sourced from either of these units. While Jura member present on VRR may be a source for clasts in Glen Torridon, only about 30% of Glen Torridon clasts observed in this study are interpreted as Jura member. Fluvial and debris flows from VRR would not account for the majority of clasts in the region.

### 4.1.3. Glacial Erosion

Glacial processes can form and transport pebble- to boulder-sized clasts. Depending on the thermal regime and transport path through the glacier, glacial clasts can range from sub-angular to sub-rounded, and exhibit faceted or “flat-iron” morphologies (Atkins, 2003, 2004; Benn & Evans, 2014; Boulton, 1978; Sharp, 1982). Flat-iron clasts are wedge-like and occasionally wear in an asymmetrical fashion: rounded at the stoss-side and angular at the lee-side. The most commonly cited feature of glacial clasts is linear striae, which can be several centimeters deep at the clast-scale (Atkins, 2003). Striae are known to form near parallel to the long-axis direction and grow deeper in proportion to the size of the clast. The presence of both facets and striae on a clast is considered a strong indicator of glacial transport (Atkins, 2003, 2004).

Glen Torridon clasts do not support a glacial origin. While some of the clasts in Glen Torridon have wedge-like shapes, none display asymmetrical wear patterns or striae associated with glacial erosion. As with the aforementioned clast formation processes, glacial deposits are also expected to have a degree of lithochemical diversity which is not observed in Glen Torridon.

### 4.1.4. In Situ Bedrock Fragmentation

Another pathway capable of producing the quantity and types of clasts observed in Glen Torridon is through the breakdown of local bedrock into cobbles, pebbles and granules. In this scenario, clasts detach from bedrock along pre-existing fractures and bedding planes. Cracks are known to form and expand by mechanisms such as frost heave, freeze-thaw, diurnal thermal fluctuations, crystal growth, and dirt cracking, among others (Bloom, 1978; Bourke & Viles, 2007; Eppes et al., 2015; Ollier, 1965; Tesson et al., 2020; Viles et al., 2010). Fragmentation resulting from these processes can produce clasts with varying shapes and degrees of roundness, and lithology strongly controls the pattern and occurrence of fractures formed by these breakdown processes (Bourke & Viles, 2007).

The Jura and Knockfarril Hill members of Glen Torridon both display a tendency to fracture in accordance with this model. The Woodland Bay outcrop of the Jura member has interbedded thick and thin layers separated by vein fill material presumed to be CaSO\(_4\) (Figure 9b). Clasts in the immediate vicinity of Woodland Bay, identified as Type 5, 6, and 7 clasts, exhibit similar morphologies as the blocks that make up bedding layers of
this outcrop. Similarly, outcrops of the Knockfarril Hill member are well-bedded and appear to fracture along fracture fills and bedding planes. Near the Risk target in the Knockfarril Hill member are clasts which appear to have recently detached from the bedrock (Figure 9c), including faceted clasts (Type 4, 5, and 7) and angular clasts reminiscent of Type 2 and 6 clasts. Clasts at Risk appear to be fractured unevenly across multiple bedding planes, and have a rough texture which may be associated with the preservation of fracture fill material on the rock surface. The presence of smectite clay-minerals in Glen Torridon may also have contributed to the friability of both members. Smectite clays are susceptible to swelling when exposed to water, and the hydration and dehydration of clay minerals in Glen Torridon could have contributed to the tendency of the Jura and Knockfarril Hill members to break and form clasts.

The strongest support for in situ fragmentation is the similarity in lithology and composition between the Glen Torridon clasts and in-place bedrock exposures of the Jura and Knockfarril Hill members throughout Glen Torridon. Local breakdown of relatively resistant Knockfarril Hill member sandstones overlying and upslope of the Jura member as Mount Sharp erodes via deflation and abrasion likely explains the prevalence and accumulation of Knockfarril Hill-like clasts throughout Glen Torridon.
4.2. Erosional Continuum for the Glen Torridon Clasts

The strong similarities in clast morphology, lithology, and composition to the local bedrock points to in-situ bedrock fragmentation, possibly linked to thermal fluctuations, as the most likely source of the clasts in Glen Torridon. Clasts near bedrock outcrops are generally more angular, blocky or platy—reflecting the relatively recent breakdown of the in-place bedrock. Many clasts also exhibit laminations, a distinctive feature of the Jura and Knockfarril Hill members. Unlike the fluvial, debris flow, glacial erosion, and impact cratering models, in-situ bedrock fragmentation explains the agreement between clast lithology and composition with the local bedrock (Section 3.4).

Since the overlying Knockfarril Hill member is exposed to erosion before Jura, and is also comprised of relatively resistant sandstones, its descendant clasts accumulate downslope in the Glen Torridon region atop the Jura member.

Outcrops such as Woodland Bay, North Berwick and the Glen Etive drill site illustrate clasts in the process of disconnecting from the in-place outcrop along existing discontinuities like bedding planes or vein fills. The nature of the discontinuity appears to have a strong influence on clast shape. Thicker, heavily jointed bedding such as that found at Woodland Bay fragment into faceted clasts, with at least one flat face representing the fracture plane (Figure 9b). In locations where thinly laminated bedrock is exposed, clasts fragment primarily along bedding planes to form platy, often irregularly shaped clasts. Drilling the Jura member at the Aberlady drill site provided good evidence of this mechanism occurring at an accelerated rate, when the drill appeared to cause uplift along a bedding layer (Figures 9d and 9e). Clasts formed by this mechanism are likely Type 3 and Type 6 clasts, which are commonly platy, angular, and well-laminated. Finally, fracture fill thickness may play a role in producing more irregular clasts. Thicker fracture fills can stick to clasts as they break up, resulting in angular clasts with rough surface textures—similar to Type 2 and 6 clasts. This occurs in the Knockfarril Hill member at places such as Risk (Figure 9c), where fracture fill material is visible on the clast after fragmenting.

Figure 10 illustrates the proposed evolution of clasts in Glen Torridon after eroding from bedrock. Given their proximity to bedrock, angularity, size, and shapes reminiscent of cracked bedding layers, Types 1, 2, and 3 clasts are presumed to be the most freshly fragmented clasts. Since clasts were grouped by roundness and I/L through hierarchical clustering, evaluating the degree of erosion and fragmentation is a straightforward process. Subsequent fragmentation produces progressively smaller Type 4, 5, and 6 clasts, which tend to become marginally more rounded and develop smoother surface textures. Erosion and more extensive fragmentation lead to the formation of Type 7, 8, and eventually 9 clasts which are small (I < 23 mm) and subrounded to rounded. Clasts appear to maintain their I/L as they evolve, suggesting that fragmentation along existing parallel bedding planes is common.

Aeolian abrasion is one potential driver of erosion and rounding of clasts in Glen Torridon. Some clasts exhibit polish and pitting characteristic of aeolian abrasion, particularly Type 1’s. Clasts may also have developed polish prior to detachment from bedrock. The sand and dust mixture that mantles Glen Torridon and makes up the nearby sand sheet at the Sands of Forvie is abundant enough to facilitate erosion.

It is worth noting that clast shape and size evolution also appears to loosely follow the model for fragmentation proposed by Domokos et al. (2015), which shows fragmented rocks originate as large, elongate shapes and disintegrate into smaller, equant pieces regardless of the breakup mechanism. As illustrated in Figure 9a, Glen Torridon clasts appear to break down into elongate shapes at significantly smaller diameters than the brittle limestone, gypsum and dolomite clasts studied in Domokos et al. (2015) before rapidly becoming isotropic. We believe this is a consequence of discontinuity-driven fragmentation, which forms clasts with diameters at or near the average spacing between joints in the bedrock. However, it is apparent that not all clast types evolve in accordance with this model. Clast types 6, 7, and 8 have low I/L values compared to their predecessors.

While bedrock fragmentation accounts for the vast majority of clasts in Glen Torridon, formation of the smallest, rounded to well-rounded clasts (i.e., most Type 9 clasts) are not as easily explained by this process. Fluvial transport is the most frequently cited cause for rounded clasts (e.g., Szabó et al., 2015), with flooding or stream channels contributing to clast rounding. However, these small, rounded clasts also show locally sourced compositions.

Figure 10. Proposed clast lifecycle. Major axis decreases and roundness goes from very angular to rounded from left to right.
While Type 9 clasts may represent the oldest, most weathered clasts in the area, understanding their origin requires further study.

4.3. Relationship to PBRs

The exposed bedrock that is eroding to form the PBRs throughout Glen Torridon is a potential source of new clasts. Trends in shape along the PBR slopes discussed in Section 3.3 suggest clast shape is controlled by local bedrock characteristics. Thin bedding layers producing larger, angular Type 1 clasts appear to dominate near the crest at PBR’s 1 and 3, while thicker bedding layers producing smaller, equant Type 4 and 7 clasts are exposed at the crest of PBR 2. As the bedrock capping the PBRs erodes, these clasts are likely transported down the slope of the PBR before settling in the flanks or becoming partially buried in the sand.

5. Conclusion

Clasts in Glen Torridon are sorted into nine types using a simple, stepwise hierarchical clustering algorithm based on measurements of major axis, roundness, and I/L. Large, angular clasts are the most freshly fragmented, and continue to break down into smaller clasts with similar aspect ratios. While many clasts in Glen Torridon do exhibit rounding, the smallest clasts in the region (Type 9; 21 mm < L < 4 mm) are especially well-rounded and not well explained by in-situ fragmentation alone. Type 9 clasts may be the result of an alternate erosional pathway, but their origin remains indeterminate.

The reflection of high Mg and high K signatures typical of Jura and Knockfarril Hill members, respectively, in clasts sampled throughout Glen Torridon indicate that most clasts are sourced from local bedrock. Taking the results of clast morphology, spatial distribution and geochemistry data together, we propose that clasts within Glen Torridon are the result of in-situ bedrock fragmentation facilitated by the presence of jointing and bedding within the rocks.

Data Availability Statement

All Mars Science Laboratory Curiosity data products and data sets, including Mars Descent Imager (Malin et al., 2017), Mastcam (Malin et al., 2017), and ChemCam (Maurice et al., 2012) data are archived at the NASA Planetary Data Systems and are available at https://pds-geosciences.wustl.edu/missions/msl/. Glen Torridon clast data are available at Khan (2022) at https://doi.org/10.5281/zenodo.7041918.

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