Chapter 6

Summary and Implications

6.1 Introduction

Detailed study of rover-scale sedimentary geology and petrology allows us to constrain details about the igneous evolution of the source rocks outside Gale, early climate on Mars, and cementation of sedimentary rocks on Mars. Here we summarize key implications and future directions of this work for each of these areas of study.

6.2 Igneous Evolution

Mars lacks plate tectonics and does not have extensive continental crust, so the degree of igneous differentiation on Mars is expected to be much lower than on Earth. In line with this assumption, most of the rock samples observed by previous rover missions and in meteorites have been basaltic [*Team*, 1997; *Clark et al.*, 2005; *Gellert et al.*, 2006; *Papike et al.*, 2009], and the dust on Mars is basaltic and homogeneous on a global scale [*Yen et al.*, 2005]. However, spectroscopic observations from orbiters have shown that there is significant compositional variability in bedrocks exposed at the surface [*Ehlmann and Edwards*, 2014], and regions where more evolved igneous rocks may be present have been identified [*Christensen et al.*, 2005; *Wray et al.*, 2013]. It has also been hypothesized that melts from large impacts on Mars could be more differentiated [e.g. *Therriault et al.*, 2002]. Several recent papers have argued for the presence of granitic or very evolved magma flows in various regions on Mars, based on orbital spectroscopy and/or rover observations [*Stolper et al.*, 2013; *Wray et al.*, 2013; *Sautter et al.*, 2015; *Sautter et al.*, 2016].

The Gale crater sedimentary basin has collected rocks by fluvial and eolian processes from a significant area around the crater and likely a significant depth into the crust (~5 km). The bedrock around Gale crater is Noachian in age, and, since the crater is sitting on the dichotomy boundary, sources include rocks from both the Northern lowlands and the Southern highlands. Comparisons of Gale to other similar complex craters indicate that the original crater was deeper and had a smaller diameter, so slumping of the crater walls has likely contributed significant sediment to the filling of Gale [*Grotzinger et al.*, 2015], implying that units up to 5 km below the surface likely contributed as source rocks for the sedimentary rocks in Gale. This wide sampling of source rocks, integrated into the sedimentary rocks in Gale, allows some assessment of the degree of igneous diversity in the Gale crater region.

The work in this thesis shows that the geochemical diversity of the rocks sampled by the Alpha-Particle X-ray Spectrometer (APXS) on *Curiosity* can be accounted for with only a limited degree of igneous differentiation. The Bradbury group compositions are consistent with breakdown and sorting of a basalt or a basaltic andesite provenance with plagioclase phenocrysts. The localized high sanidine input could be sorted from another basaltic region, and only requires that alkali elements are not evenly distributed in Martian magmas (Chapter 4). The Stimson formation is consistent with average Mars crustal basaltic sources. The Murray formation is mostly distinctive because of authigenic mineral production in the lake and diagenetic minerals formed from the groundwater (Chapter 5). The Murray has some distinctive samples with particularly high silica, but with bulk chemistry alone these look similar to fracture-associated haloes in the Stimson, and can therefore be explained to some degree by fluids. Overall, based on bulk chemistry and textures, we have not seen compositions that require significant igneous differentiation processes on Mars. However, evidence from the CheMin instrument, specifically the identification of tridymite—a high-temperature, low pressure polymorph of silica—at the Buckskin sample, suggests that there could be felsic igneous rocks in the region contributing to Gale [*Morris et al.*, submitted], which will hopefully be better understood as we continue to investigate the Murray formation and formation mechanisms for tridymite.

6.3 Climate

There is ongoing debate about the climate of early Mars, particularly focused around the questions of whether or not the planet was warm enough to sustain surface water for geologically significant periods of time and whether the water was mostly liquid or ice. Early observations from the *Curiosity* rover at the Sheepbed mudstone in Yellowknife Bay indicated that there was water present for enough time to deposit and lithify 1.5 m of mudstone (Chapter 3) [*Grotzinger et al.*, 2014; *Siebach et al.*, 2014; *Stack et al.*, 2014] and that the lack of evidence for chemical weathering indicated that the climate was likely arid and potentially cold [*McLennan et al.*, 2014]. This work has shown that the absence of evidence for chemical weathering extends through at least 60 m of the Bradbury group stratigraphy, indicating that the climate remained cold and arid enough to prevent chemical weathering in the northern rim source for the Bradbury group throughout the observed section (Chapter 4). The mineral sorting trends within the Bradbury group are comparable to sorting trends in rocks that have been crushed in a lab [*Fedo et al.*, 2015], or comminuted glacially and sorted in glacial streams [*Nesbitt and Young*, 1996; *von Eynatten et al.*, 2012], so the rivers that fed the lakes in Gale may have also been glacial streams emerging from the northern rim of the crater, or rocks broken by impact processes and rounded by transport in cold floods. The Bradbury group observations alone do not require consistent water flow, and likely formed from episodic flows, similar to arid streams on Earth.

Curiosity's observations of the Bradbury group and Murray mudstone have been interpreted to show that individual lakes were stable on the surface of Mars for minimum durations of 100 to 10,000 years due to the thickness of the deposit, the laminations, and the lack of evidence for mudcracks or other indicators of evaporation or surface exposure throughout the observed Murray unit [*Grotzinger et al.*, 2015]. Work in Chapter 5 indicates that while the lake may be consistently filled with water, the fluvial sources of the water are likely more intermittent and may transition from one side of Gale crater to the other side. Additionally, the Murray lake has significant amounts of dissolved ions, causing authigenic mineral precipitation and indicating that chemical weathering has occurred in some region around Gale crater, perhaps either the central peak of the crater or the southern wall. These dissolved ions must be present in the lake at the same time as the Bradbury group contributes to the lake, but the Bradbury group shows no evidence for chemical weathering and so they must be derived from other sources entering the lake. This evidence for localized chemical weathering may indicate a localized (elevation-dependent?) warmer climate, weathering of rocks influenced by hydrothermal processes associated with impact melts, or distinctive mineralogy more susceptible to chemical weathering processes.

6.4 Cementation

While sediment production on Mars was established from early Mariner 9 imagery [*McCauley et al.*, 1972; *McCauley*, 1973], sedimentary rocks were not discovered until nearly thirty years later [*Malin and Edgett*, 2000]. Part of the reason for this lag is that the process of sedimentary rock lithification and exposure involves compaction, cementation, and uplift—processes related to plate tectonics, which does not occur on Mars, and liquid groundwater, which is not present on Mars today. The first sedimentary rocks observed by a rover on Mars were the eolian sandstones of the Burns formation, which were deposited by the wind, cemented by evaporation of acidic sulfate-rich groundwater, and exposed by impact processes [*Grotzinger et al.*, 2005; *McLennan et al.*, 2005]. Groundwater evaporation and salt deposition is one mechanism for lithifying sedimentary rocks near the surface, and since the effects of this process are visible on Mars even at orbital scales (e.g. Chapter 2), salt deposition was considered to be the most likely mechanism for cementing other sedimentary rocks on Mars as well. However, *Curiosity* data paints a very different picture of materials involved in cementation than expected based on orbital data.

Curiosity's observations of sandstones and conglomerates show that these are well-cemented sedimentary rocks with very low porosity, and it is frequently difficult to distinguish grains from cements (Chapter 4) [*Williams et al.*, 2013; *Siebach and Grotzinger*, 2014b]. In a few cases, erosion-resistant structures or fracture fills have allowed identification of the precipitated cement that filled them, but most of these were localized fracture fills that formed during diagenesis. These include: iron-oxide cements in a few float rocks near the landing site [*Blaney et al.*, 2014; *Schmidt et al.*, 2014], slightly

Mg-enriched typical Mars basalt composition isopachous cements in the Sheepbed raised ridges and nodules (Chapter 3) [*Léveillé et al.*, 2014; *Siebach et al.*, 2014; *Stack et al.*, 2014], MnO and Zn-enriched fracture fill at the Stephen target near Windjana [*Lasue et al.*, 2016; *Lanza et al.*, submitted], $MgSO_4$ dendritic concretions at the base of the Murray, and ubiquitous late-stage CaSO4 fracture fills [*Nachon et al.,* 2014; *Kroynak et al.*, 2015]. Each of these distinctive fracture filling cements results from an interesting fluid composition that precipitated the cement, but these cement compositions, and likely the fluids that created them, are all restricted to small local areas or late-stage fractures and are not widespread through the observed rock units. Instead, the observed sandstones and conglomerates in the Bradbury group and Stimson formation have compositions that are consistent with the compositions of the basaltic fragments that they are composed of, without any indication of chemical weathering or additional cements (Chapters 4, 5).

The cementation of the Stimson sandstone formation is particularly enigmatic. The sandstone is an eolian deposit sitting above an unconformity that appears to follow the modern shape of Mount Sharp (Figure 6.1)[*Watkins et al.*, 2016], implying that the Murray formation lake deposits had already been cemented and significantly eroded when this eolian sand was deposited. The rock is so well-cemented that there is almost no visible porosity, even on broken rock surfaces (Figure 6.2) [*Siebach and Grotzinger*, 2014b]. To achieve such low visible porosity, up to 10-20% of the rock volumetrically should be full of cement (based on an assumption of closest packing). Significant grain compaction is not observed and would be unlikely due to reduced gravity on Mars [*Grotzinger et al.*, 2015], so the cement must be deposited by fluids. Compositionally, however, the sandstone is very homogeneous and matches the composition of average Mars crust, which is expected for the sediment itself, which integrates eroded particles from regional surfaces, but does not explain the cementing component (Chapter 5). Mineralogy of the unit shows only primary basaltic minerals and amorphous material with a composition similar to basaltic glass. If the cementing fluids dissolved components of the rock and migrated, more soluble cations would be depleted. If, alternately, cementing fluids carried dissolved components from other sources, some cations would be enriched relative to average Mars crust. Based on the observed evidence, we are forced to conclude that the cement is an x-ray-amorphous

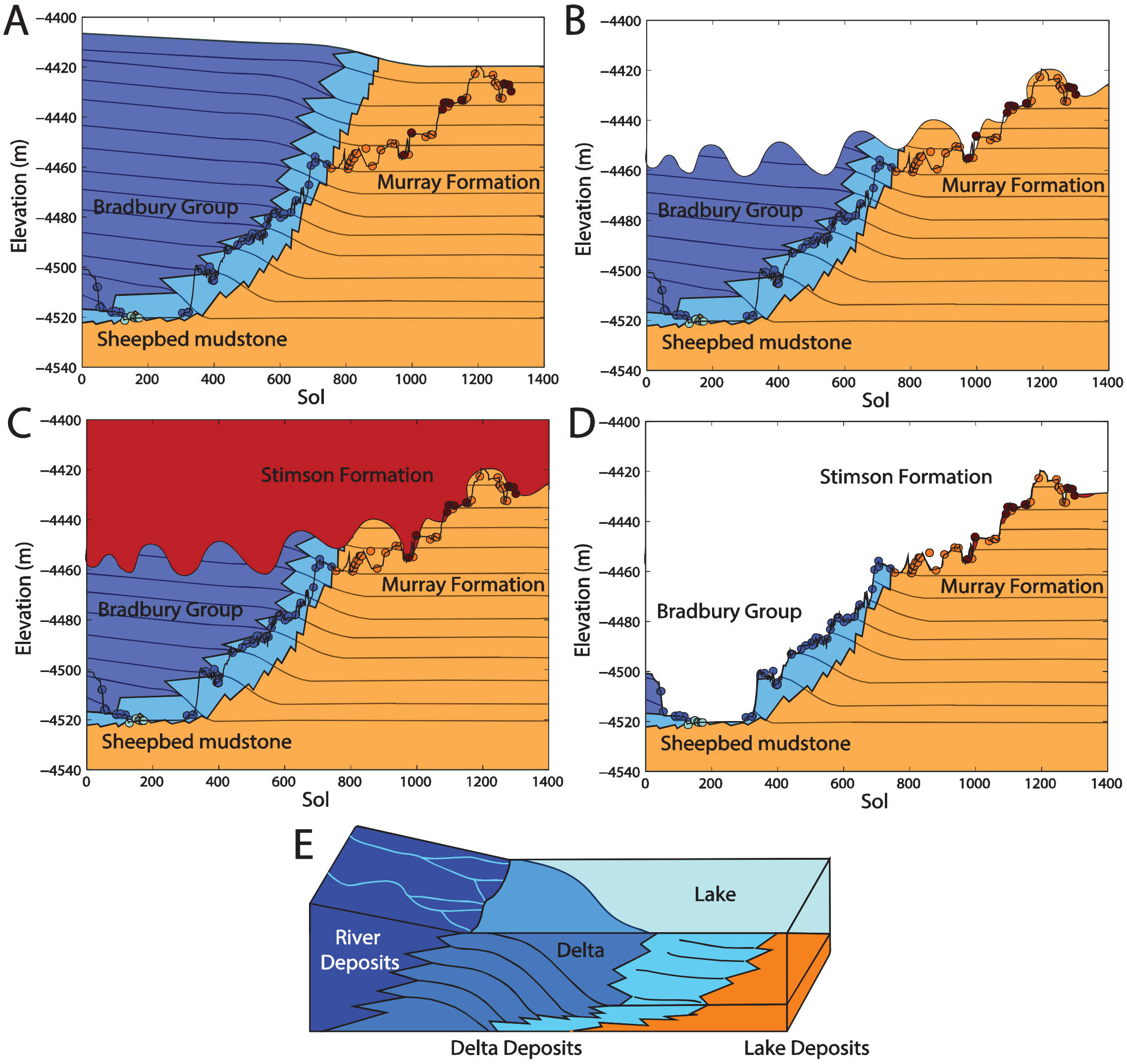

Figure 6.1 Schematic of Depositional Sequence in Gale Crater
Parts A-C shows the rover traverse in sol (i.e. distance traveled) vs. elevation (i.e. stratigraphic position) plots, with the APXS analyses plotted as circles and the key depositional units highlighted. Part E is a reference for the depositional facies in a delta system, modified from NASA/JPL. Part A shows the deposition of the Bradbury and Murray groups as a fluvio-deltaic system. Part B represents the initial erosion event that created the paleotopography that the Stimson sandstone formation (Part C) was unconformably deposited over. Part D represents the modern erosion, exposing all units along the rover traverse.

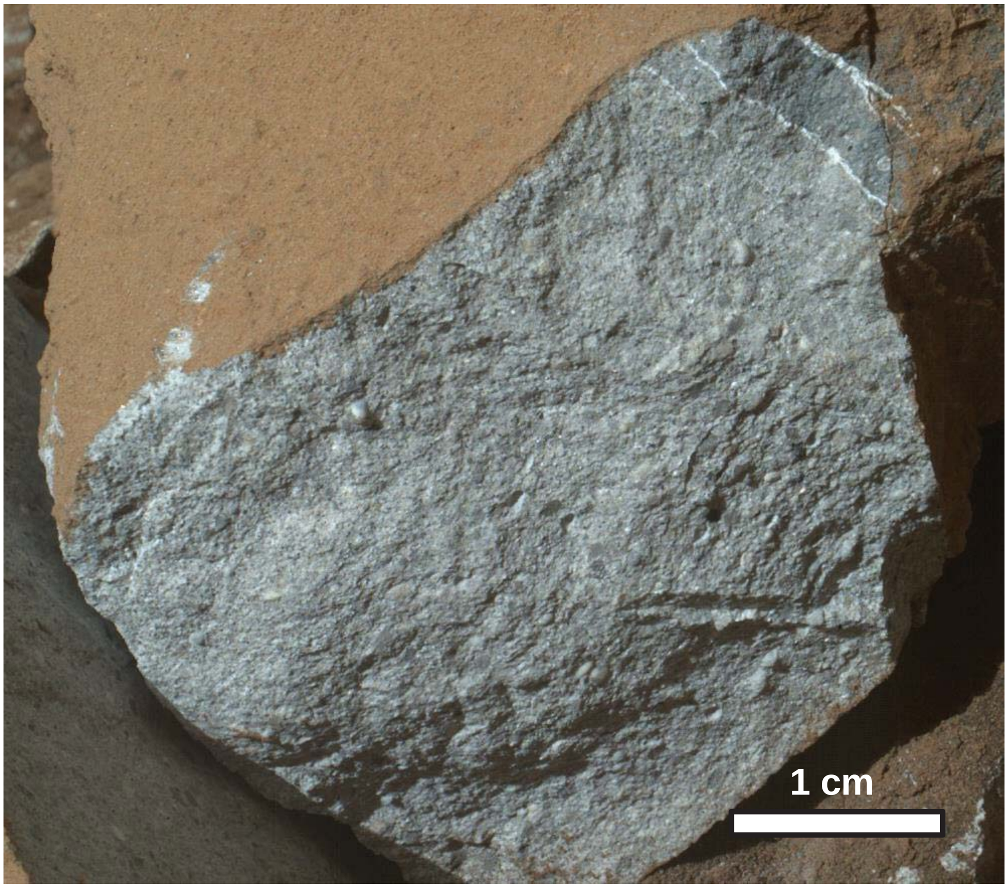

Figure 6.2 MAHLI Image of Stampriet Target in Stimson Formation
This is a 5 cm standoff image taken on sol 1344 of the Stampriet target, a broken rock in the Stimson sandstone that shows the lack of porosity in that formation.

precipitate formed in place from dissolved components of the sandstone. The cement may be x-ray amorphous because the nucleated crystals are too small for x-ray detection or because desiccation cycling under Mars climate conditions can cause some materials to become amorphous [*Vaniman et al.*, 2004]. This type of amorphous cement also explains why the Bradbury group sandstones and conglomerates also lack clear evidence for a distinctive cementing component. More detailed characterization of this amorphous cement depends on our ability to model the compositions of the amorphous components on Mars and better understand x-ray amorphous cements on Earth.