THE SEDIMENTARY ROCK RECORD OF MARS AS VIEWED FROM THE PAST FIFTEEN YEARS OF ORBITAL MISSIONS. L. Le Deit[1], N. Mangold[1], and E. Hauber[2], [1]LPG, UMR CNRS 6112, University of Nantes, France (Laetitia.Ledeit@univ-nantes.fr), [2]Institute of Planetary Research, German Aerospace Center (DLR), Berlin, Germany.

Introduction: Over the last fifteen years, orbital and landed missions have revealed a diverse and extensive sedimentary rock record on Mars. In the absence of plate tectonics, and because of a decline of the geological activity over time, the martian sedimentary record is well-preserved and much older than terrestrial records. No biogenic sediments have been observed at the surface so far but the study of this ancient record can provide insights on the conditions prevailing on Mars when life appeared on Earth.

Herein, we focus in particular on summarizing the current state of knowledge about the sedimentary record of the martian surface, integrating key results from the last orbiting missions. We begin with an overview of orbital instruments capabilities and a review of the major types of sedimentary deposits. Then, we present our current vision of the evolution of paleo-environmental and climatic conditions of Mars. Finally, we discuss some key questions that still have to be understood and will serve as a groundwork for future studies.

Orbital instruments capabilities: The understanding of sedimentary deposits on Mars is strongly tied to the exploration of Mars, and more specifically to the improvements in spatial resolution and coverage of imagers. Regional scale images reaching up to 6 m/pixel coupled to Digital Elevation Models (DEMs) enable to study the geometry of sedimentary deposits as well as estimating their age by crater size-frequency distribution analyses [1, 2]. High resolution images (up to 25 cm/pixel) allow to locally analyze the sedimentary layers, including determination of local dips from DEMs [3]. At this scale, the resolution is sufficiently high to determine important sedimentary features such as inverted channels, clinoforms and truncations [4]. A big step forward in the martian exploration has been the arrival of imaging spectrometers. Hundreds of layered deposits have been characterized with a high precision (up to 18 m/pixel) showing a huge variety of hydrous minerals (various phyllosilicates and sulfates, opaline silica, etc.) [5, 6]. Thermal infrared instruments have provided information on the thermophysical properties of the surfaces and hence, on their lithology [7]. Finally, subsurface radar sounding instruments have given us new insights into the nature of sedimentary deposits, demonstrating for instance the low density of a quite enigmatic large-scale deposit on Mars, the Medusae Fossae Formation [8].

Major types of sedimentary deposits: In addition to the expected impact- and volcanically-generated deposits, various clastic and chemical sedimentary rocks as well as alterites are observed on Mars.

Clastic sedimentary rocks. Some sedimentary rocks formed and deposited in local aqueous environments, i.e., alluvial, fluvial, deltaic, and lacustrine environments. Alluvial fans have been observed especially in impact craters of the southern highlands where they stand at the foot of impact rims [9]. Paleolakes are identified mainly from the presence of preserved or partly preserved deltaic deposits in open and closed basins [10]. Most of alluvial fans and deltas were formed relatively late in the early Mars (>3 Ga) history, from the Hesperian to the early Amazonian, based on crater counts and on the relatively well-preserved morphology of their host craters [11]. The scarcity of Noachian alluvial fans and deltas is likely simply tied to a lack of preservation but it shows that the aqueous activity did not stall in the late Noachian, as frequently reported, but extended far into the Hesperian and even Amazonian [11]. It is noteworthy that fine-grained deltaic deposits are among the most promising astrobiologically interesting targets in terms of preservation potential for biosignatures.

One of the major type of sedimentary deposits in terms of volume corresponds to regionally extensive layered and light-toned sedimentary deposits. With thicknesses of up to several kilometers, these deposits cover plateaus (e.g, Meridiani Planum) and fill canyons like Valles Marineris and other closed basins in the equatorial regions of Mars [12]. Containing a variety of sulfates, iron oxides, hydrated silica, sometimes interbedded with clays [13], their origin is still under debate but likely results from multiple formation processes including lacustrine evaporation (chemical sediments), groundwater alteration, hydrothermal activity, and eolian reworking [14]. Most of them were formed during the late Noachian/early Hesperian and the early Amazonian [14].

Aeolian bedforms including dm-wide ripples to km-long dunes, cemented dunes, and sand sheets are scattered throughout the globe. Km-thick deposits, locally showing highly rhythmic stratification such as in Arabia Terra are inferred to be formed by dust and are thus named duststones [15]. Note that the Opportunity and Curiosity rovers enabled the clear identification of aeolian sandstones at Meridiani Planum and Gale crater [16].

Chemical sedimentary rocks. Only scarce outcrops of carbonate-bearing deposits have been observed at the surface. While some of them correspond to Mg-carbonates interpreted to result from dissolution of olivine by hydrothermal alteration under neutral to alkaline conditions, others are carbonate-bearing layered rocks exposed from depth [17]. Some chloride-bearing deposits located in hundreds of local depressions are situated in plains across the southern highlands. They have been interpreted to be former dry lakes formed by precipitation from ponding evaporating brine derived from surface runoff and/or groundwater upwelling [18].

Alterites. Many weathering profiles abound on Noachian-aged terrains. These several meter-thick series typically consist of Fe/Mg clay layers (smectites, vermiculites and mixed-layered clays) located topographically and stratigraphically below Al clay layers (Al-rich smectites and kaolinite-group clays) [19]. These weathering profiles attests that climatic conditions allowed liquid water activity at the surface during the Noachian [19].

Evolution of paleoenvironmental and climatic conditions: Over the last fifteen years, interpretations of geomorphologic and mineralogical observations, laboratory experiments, as well as climatic modelling lead the scientific community to argue either for a "warm and wet" early Mars [5], or rather a "cold and icy" early Mars [20]. At the dawn of 2020, early Mars climate is thus still highly debated but it is generally agreed that early Mars climate was warmer and wetter than today even after the Noachian. Alluvial fans and deltas were formed during the Hesperian and Amazonian, attesting that fluvial activity occurred through these latest epochs. Whether the climatic conditions favoring widespread liquid water were sustained over prolonged periods of time or if they were transient remains unconstrained.

Some key questions: Despite the significant progress made over the past years, many key questions remain to be investigated.

Volcanic deposits vs. aeolian deposits. Volcanic ash grains may have been transported hundreds to thousands of kilometers away from their volcanic sources and are likely mixed with non-volcanic grains in sedimentary formations all across the planet. Thus, volcanic ash may be a significant constituent of duststones. In situ analyses of the grain sizes and sedimentary structures of key sedimentary formations are fundamental to better constrain the origin of a significant part of the martian sedimentary record.

Phyllosilicates: Detrital or in situ? Phyllosilicates are the most common and widespread alteration minerals on Mars. Whether phyllosilicates were formed in situ (i.e., authigenic or diagenetic), or were deposited by fluvial flows that have eroded an altered bedrock (i.e., detrital) is often difficult to determine from orbit. In this way, only the mineralogical context can help identifying possible sources for phyllosilicates upstream and hence, a detrital origin. The formation of phyllosilicates in situ has strong implications in terms of duration of water activity since it requires a long-term presence of water.

Carbonates and the missing atmosphere. A wetter and warmer climate during early Mars implies a denser CO_2 atmosphere (between >100 mbar and <2 bar) than today [21]. A widespread reservoir of carbonates on the surface or in the subsurface would have been a natural sink for this past atmospheric CO_2 but they are only rarely observed at the surface. Several explanations have been proposed for the apparent lack of carbonates but the debate is still ongoing. Recently, some authors proposed that carbonate-bearing rocks are maybe abundant but poorly exposed [17]. Based on MAVEN results, others indicate that as much as 0.8 bar of CO_2 might have been lost to space, rather than sequestered in the form of carbonates on the surface [22].

Ocean or not ocean? The question is pending since the observation of possible shorelines in the northern plains [23]. Studies based on radar data show that the northern plains have low values of dielectric constant which is consistent with the presence of low-density sedimentary deposits, massive deposits of ground-ice, or a combination of the two which would support the hypothesis of a putative late Hesperian ocean [24]. Possible tsunami deposits would also be consistent with an Hesperian ocean [25].

Exploration of Mars from orbit and with the future Mars 2020 and ExoMars rovers definitely will keep improving our knowledge of this fascinating geologic history of Mars.

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