FACULTY OF SCIENCE AND TECHNOLOGY

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Contents

Introduction

Water is central to life on Earth and how life originated on Earth. The oldest sign of life stems from hydrothermal environments about 3.5 Ga (Chaplin, 2001). Water or indications of water on other planets may be a sign of past or current forms of life. Ramirez (2018) describes the habitable zone or Goldilocks' zone as the distance to a star where conditions are favourable for water on the surface. Solar insolation is a measuring element used to describe whether a planet is in the habitable zone. There are several evidences of water in the geological record of Mars, and these are believed to be from 4.1 Ga to 2.9 Ga. Mars' solar isolation was one-third of Earth's solar isolation 3.5 Ga years ago (Bahcall et al., 2001; Haberle, 1998). Mars' solar insolation was too low to have rivers on the surface because of the combined greenhouse effect of CO_2 and H_2O would be too low (Forget et al., 2013). From satellite data and rover data, evidence indicates hydrological influence on the geology of Mars. A popular hypothesis is that water was present on Mars for intermittent periods of time rather than a continuous presence, and these intermittent periods created the signs of water that are observed today (Ramirez and Craddock, 2018). Stromatolites (3.6 Ga to 3.2 Ga) (Popall et al., 2020) are some of the oldest organisms on Earth, and they arose in shallow aquatic environments with low energy. Lakes or other aquatic environments with low energy are, therefore, potential areas to identify the presence of life on other planets. In the atmosphere of Mars, water is present at about 80 km above the surface (Stone et al., 2020). Mars is arid, and there is confirmed ice on its surface. In total, Mars' atmosphere contains carbon dioxide 95%, nitrogen 2.8%, argon 2%, oxygen 0.174%, carbon monoxide 0.0747%, and water vapor 0.03%. There are two geological time periods that are important for signs of water on Mars, and it is Noachian and Hesperian. Signs of depositional environments on mars have been identified indicating water and this indicate water on Mars(Kite, 2019).

Scientific research has been conducted for more than four hundred years with continually growing amounts of data. There is no central geologic catalogue of fluvial systems for Mars. Such a catalogue would help researchers. There is an overwhelming amount of research that has been done and no one has made a geological catalogue of hydrological data. It was therefore a logical choice to create a geological catalogue of hydrological data. This geological catalogue is based on categories used in the classification of depositional environments and fluvial systems. Collection of data from Mars takes place via remote sensing and field observations are not possible. Therefore, most of the research is focused on geology, which can be easily interpreted and seen in satellite images. An example is a delta or valley networks. These are geological structures that are visible from satellite images and give us information about hydrological data. Several geological structures have been identified on Mars that have to do with hydrology. To gain an understanding of Mars' former global hydrological system, it is important to get an overview, and this can be done via a geological catalogue. Evidence of hydrological systems have also been found elsewhere in the solar system. Pluto has rivers on its surface (Martin and Binzel, 2021), and Titan has a complex hydrological system (Lewis-Merrill et al., 2022).

This thesis aims to contribute to a systematic catalogue of fluvial systems on Mars. The thesis asks:

1. What fluvial systems and depositional environments have been identified on Mars?
2. What geologic attributes should be included in a catalogue?
3. How can a geologic catalogue of Mars be stored and maintained?
4. What does a catalogue for Mars look like?

History of Mars exploration and future

Mars has been observed since antiquity as early as 2300 BCE (Figure 1). It has influenced ancient religions such as Greek, Roman, and Hindu as the god of war. Documentation of Mars observations are shown in Egypt, China, and Greece.

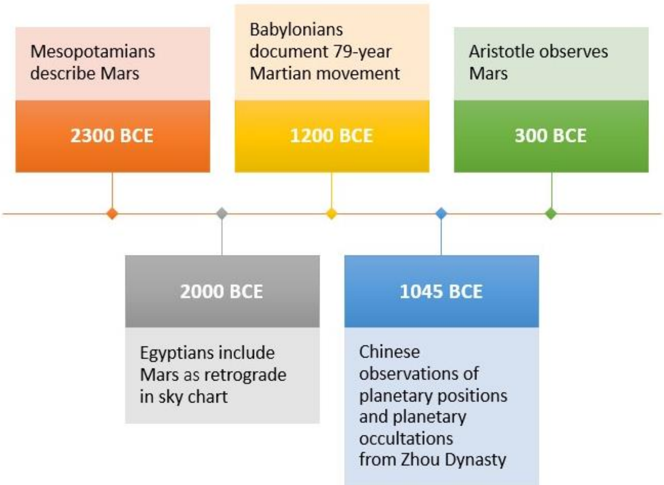


Figure 1. Mars observations from antiquity (Ciyuan, 1988; Esteve, 2017; Novakovic, 2008; Swerdlow, 2014).

Little new knowledge appeared around Mars from antiquity to the 17th century. Between 1600 and 1800, more detailed observations were collected due to the invention and improvement of the telescope. A cultural shift in science saw the start of the scientific method and more consistent and accurate observations were collected (Figure 2).

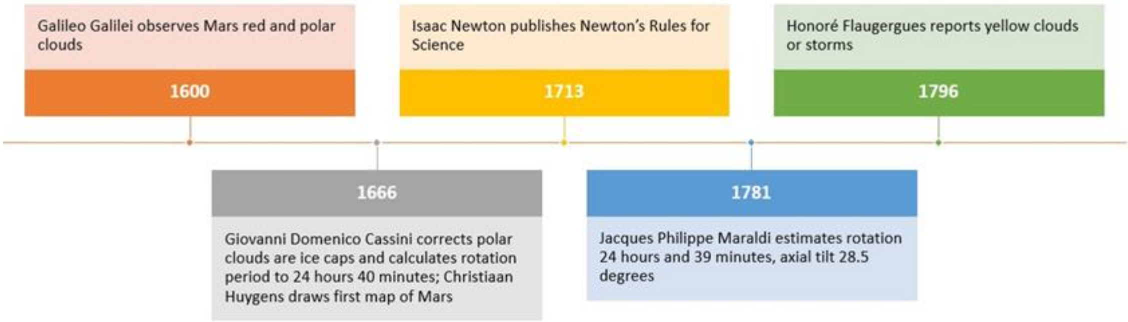


Figure 2. Major events influencing the scientific method and Mars observations between 1600, and 1800. (Capen and Martin, 1971; Harland, 2005; Milner, 2021; Moore, 1984; Newton and Huygens, 1987; Sheehan, 1996; Sheehan and Bell, 2021).

As technology improved, even more observations and measurements were made of Mars during the 1800s and through the mid-1900's at the start of the space race (Figure 3).

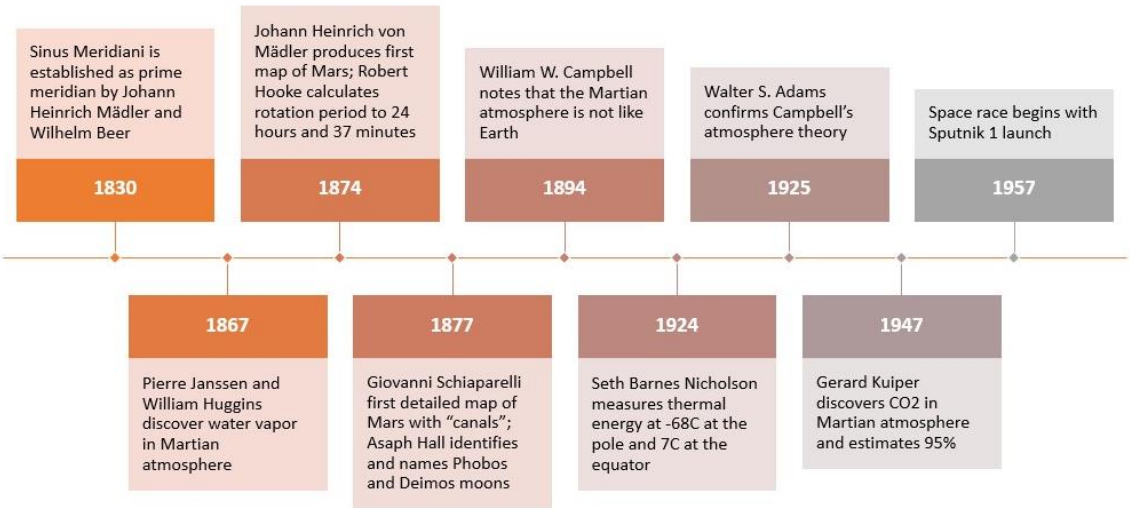


Figure 3.Mars observations increase in detail and accuracy in the 1800 to 1960. (Campbell, 1894; DeVorkin, 1977; Horowitz, 1986; Milone and Wilson, 2008; Moore, 1984; Morton, 2002; Pettit and Nicholson, 1924; Proctor, 1873; Sheehan, 1996).

In the fifties, there was a breakthrough in rocket technology, and the first satellite arrived in 1957 called Sputnik 1 which was from the Soviet Union. Mars 1 was the first attempt made to send a probe to Mars this was also from the Soviet Union. Mars 1 was a failed attempt to send a probe. Throughout the 1960s, the Soviet Union made several attempts to send probes to Mars, but several of the attempts were unsuccessful. They had success with Mars 2, Mars 6, and Mars 7. Partial success with Mars 3, Mars 5, and Phobos 2 (Ouyang and Xiao, 2011) (Figure 4). All these probes were developed under the Mars probe program of the Soviet Union. Mars 6, Mars 7, Phobos 1, and Phobos 2 were the first attempts to send probes to land on Mars. The Phobos probes had many more scientific instruments than the Mars probes. In the US, the Mariner program started in 1962 to 1972. The Mariner program had seven successes out of ten. Mariner Program 7 in 1971 entered orbit around Mars and took the first high-resolution images of Mars. On the images from Mariner Program 9, valley networks were visible (valley networks) on the surface of Mars. Valley networks were first described by Masursky (1973) and have caused much debate about early climate on Mars.

The most important Mars landers include Viking 1 and 2, Mars Pathfinder, Opportunity rover, Spirit rover, Curiosity rover, InSight Mars Lander, and Perseverance rover (Figure 5). These Mars landers have been crucial to Mars research and helped answer questions about the planet (Figure 4).

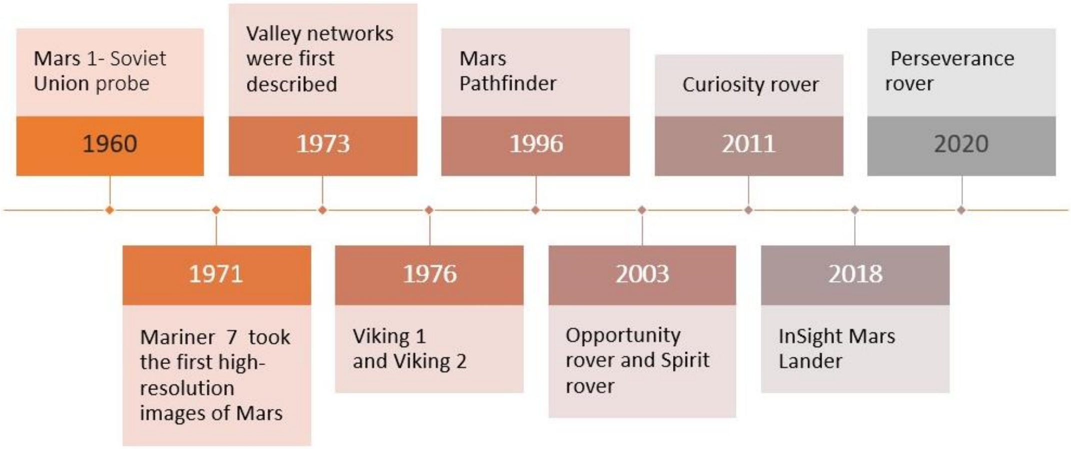


Figure 4: Mars 1960 to 2023. (Liu et al., 2022; Ouyang and Xiao, 2011; Pyle, 2012)

Liu et al. (2022) made an overview of all current spacecraft on (Figure 5; Table 1).

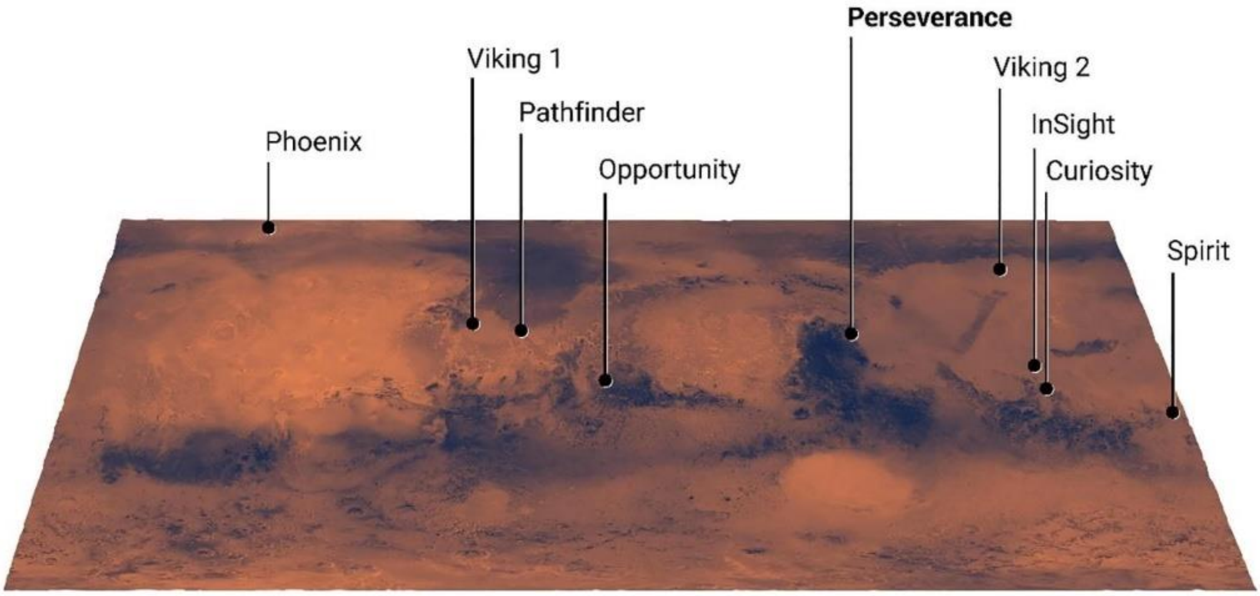


Figure 5: Mars landing sites in history, NASA/JPL-Caltech

Table 1:List of current spacecraft towards Mars from Liu et al. (2022).

Name	**Location**	**Nationality**	**Launched Date**	**Status**
Mars Odyssey	In orbit	United States	2001.04.07	Operational 2001–2025.
Mars Express	In orbit	ESA	2003.06.02	Operational 2003–2026.
Mars Reconnaissance Orbiter	In orbit	United States	2005.08.12	Operational
Mars Science Laboratory Curiosity	Surface	United States	2011.11.26	Operational
Mars Orbiter Mission	In orbit	India	2013.11.05	Operational
MAVEN	In orbit	United States	2013.11.18	Operational
ExoMars Trace Gas Orbiter	In orbit	ESA/Russia	2016.03.14	Operational
InSight	Surface	United States	2018.05.05	Operational
Al-Amal	In orbit	United Arab Emirates	2020.07.20	Operational
Tianwen-1	In orbit	China	2020.07.23	Operational
Perseverance rover	Surface	United States	2020.07.30	Operational

NASA set the following goals in 2010 with the rover program. The goals are to determine whether life ever occurs on Mars, characterize the Martian climate, characterize the geology of Mars, and prepare for human exploration of Mars (National Aeronautics and Space Administration, 2023). It is planned to send samples from the surface collected with the Perseverance rover's drill to Earth for analysis in 2023. The ExoMars program from ESA, and Roscosmos (State Space Corporation) has been postponed indefinitely due to the war in Ukraine. India's ISRO plans to follow up its Mars Orbiter Mission program from 2014.

There are several proposals for missions to Mars. Tianwen 3, and Mars-Grunt are missions that focus on retrieving samples from the surface to Mars. JAXA (Japan Aerospace Exploration Agency) is working on a rover project to look at biosignatures on Mars. NASA plans to send humans to Mars around 2030. The Perseverance rover has collected data on radiation and surface conditions that can be used to plan this mission. SpaceX has future plans to establish human colonies on Mars by 2100; however, there are many issues related to radiation, atmosphere, and resources that must be resolved first.

Geologic history of Mars

The geological history of Mars is divided into four periods. Pre-Noachian is from 4.5 Ga to 4.1 Ga, and most of the geology is believed to have been destroyed due to impacts during the pre-Noachian. A topographic step which is believed to be a sign of a rapidly eroded environment. There are similar environments on Earth on the edge of many countries. No signs of shields and volcanic provinces have been found in this period(Andrews-Hanna and Bottke, 2017). In the Noachian (4.1 Ga - 3.7 Ga), it is assumed that episodic precipitation cycles occurred. These cycles included expected runoff and seepage that contributed to various identified features, such as open-basin lakes fed by valley networks (Carr and Head, 2010; Fassett and Head, 2008; Malin and Edgett, 2003). Deltas or fans have been observed in several of these open-basin lakes (Fassett and Head, 2008). In the Hesperian period (3.7 Ga - 2.9 Ga), fewer valley networks occurred, and there were outflow channels. This led to a decline in groundwater surge events near the end of the period. The exact cause is unknown but likely triggered by a cryosphere event or decreasing tectonic activity (Carr and Head, 2010). The Amazonian period (2.9 Ga to present) can be summed up with low impact cratering, tectonism and volcanism, and low temperature (Carr and Head, 2010). The most common fluvial feature are gullies, but valley networks from this period have been identified in the Valles Marineris area (Malin and Edgett, 2001; Mangold et al., 2004). Mars has had at least four volcanic episodes in this period (Chapman et al., 2010).

The Perseverance rover landed in Jezero crater which is proven to be a lake about 3.5 Ga. The Jezero crater was considered a good place to look for signs of life. It is uncertain whether Mars has ever had a sea or seas. However, Chan et al. (2018) have evidence of a coastline, but this is controversial. At Jazero crater, there is evidence of a lake that existed for a maximum of 550 years (Salese et al., 2020). This estimate is calculated based on the supply of water that is visible geologically. It is possible that there was water in the past, and there is no trace of it today.

According to Head et al. (2017), Kite (2019), and McKay et al. (2005), Martian temperature between the Noachian to Early Amazonian periods ranged from -4 °C to 7 °C during the warm periods. However, this is a controversial hypothesis, and Bishop et al. (2018) point out that not all of the data supports the hypothesis. Based on the hypothesis by Bishop et al. (2018), Kite (2019) made a summary of Mars' geological history (Figure 6). The reason for the warm periods is given by another hypothesis which says there was an arid climate during the Noachian period and then became semi-arid in the Hesperian. The reason for this was volcanic activity which produced emissions of greenhouse gases (Ramirez and Craddock, 2018).

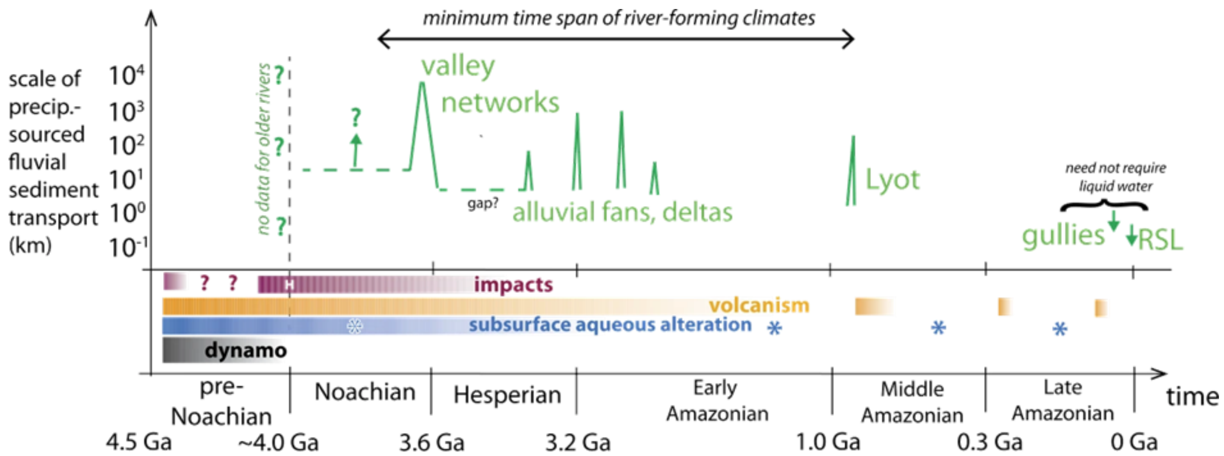
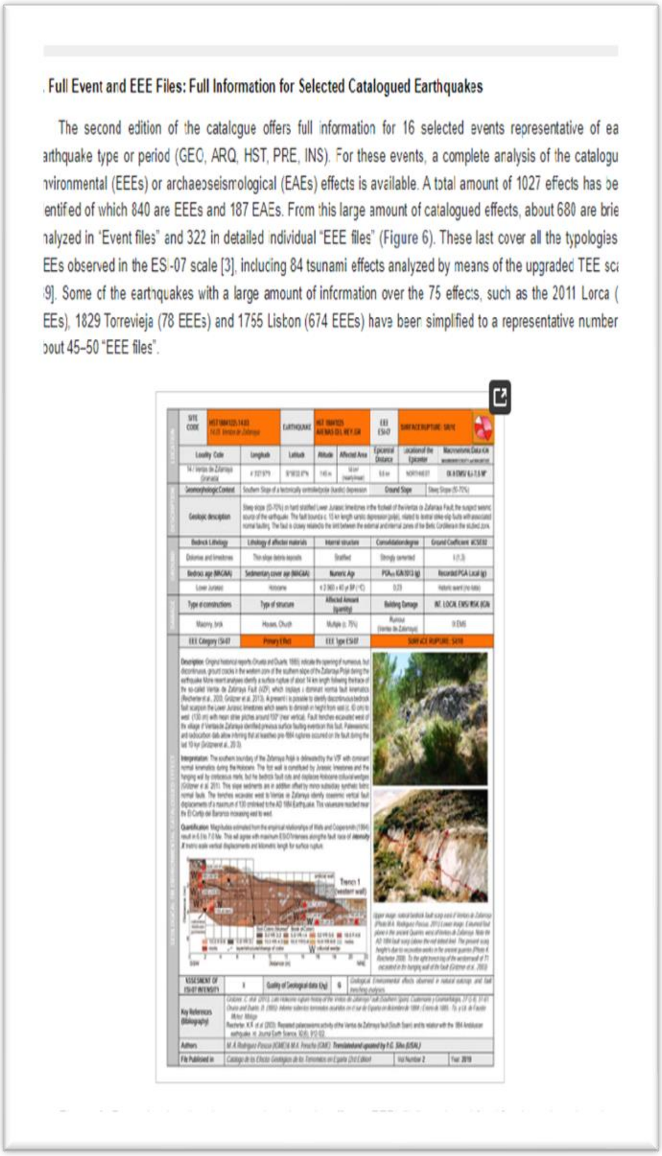


Figure 6. From Kite (2019).

It is more common to look at "what mechanisms best explain the trends, rhythms and aberrations in Early Mars climate that are recorded by Mars' geology" (Carr, 2007), and valley networks are a central part of this research. By explaining the geological processes, a basis for a hypothesis for the climate of early Mars can be created. The hypothesis from Kite (2019) is controversial.

Examples of other geological catalogues

Silva et al. (2019) created a catalogue of earthquake geological effects in Spain, which documents the 51 strongest earthquakes in Spain since the Neolithic period to the present, categorizing them into different types of earthquakes (Figure 7). The catalogue provides various parametric information, quality indexes, and environmental seismic intensity scales based on individual earthquake event.



Full Event and EEE Files: Full Information for Selected Catalogued Earthquakes

The second edition of the catalogue offers full information for 16 selected events representative of ea
arthquake type or period (GEO, ARQ, HST, PRE, INS). For these events, a complete analysis of the catalogu
nvironmental (EEEs) or archaeoseismological (EAEs) effects is available. A total amount of 1027 effects has be
entified of which 840 are EEEs and 187 EAEs. From this large amount of catalogued effects, about 680 are brie
nalyzed in "Event files" and 322 in detailed individual "EEE files" (Figure 6). These last cover all the typologies
EEs observed in the ESI-07 scale [3], including 84 tsunami effects analyzed by means of the upgraded TEE sca
9]. Some of the earthquakes with a large amount of information over the 75 effects, such as the 2011 Lorca (
EEs), 1829 Torrevieja (78 EEEs) and 1755 Lisbon (674 EEEs) have been simplified to a representative number
bout 45–50 "EEE files".

Figure 7. Catalogue of earthquake geological effects in Spain (Silva et al., 2019)

The catalogue from Coleman Jr and Cahan (2012) describes all the basins in the United States with downloadable maps. In the first part, all types of sedimentary basins in the United States are described. The next part consists of a description of the basin by type of basin (Figure 8).

Foreland Basins and Thrust Belts

Cenozoic

Jackson Hole Basin 11

The Jackson Hole Basin is a small foreland basin developed east of the Teton Uplift in western Wyoming. It is bordered on the west by the frontal thrust faults of the Teton Uplift, on the south by the Gros Ventre Uplift, on the east by the westward plunge of the Wind River Uplift and the Washakie Uplift, and on the north by Yellowstone Park Volcanic Area. The boundary for this basin is derived from the basin outline shown in Cohee and others (1962) and Frezon and Finn (1988).

Hanna Basin 5

The Hanna Basin is a small Cenozoic and Mesozoic foreland basin developed south of the Sweetwater Uplift in south central Wyoming. It is bordered on the north by the frontal thrust faults of the Sweetwater Uplift, on the east by a complex of faults separating the Carbon sub-basin of the Laramie Basin and propagating westward from the Laramie Uplift, on the south by the northern extent of the Medicine Bow Uplift, and on the west by the Rawlins Uplift. The boundary for this basin is derived from the basin outline shown in Cohee and others (1962) and Frezon and Finn (1988).

Colville Basin and Foldbelt 138

As used herein, the Colville Basin and Foldbelt is a very large Mesozoic foreland basin and thrust belt that extends across the entire north slope of Alaska from the U.S.–Canadian national boundary to the U.S.–Russian national maritime boundary. Its northern border is a closing structural contour downdip from the crest of the Barrow Arch and its structural extension to the east. Its southern border is the northern thrust fault zone of the main Brooks Range. In the southwest, its border is the boundary between the Hope Basin and the Herald Arch–Lisburne Hills thrusted area. The boundary for this basin is derived from the basin and resource management area outlines shown in Kirschner (1994), the U.S. Geological Survey (1997), and the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) (2010a).

Zuni Basin 24

The Zuni Basin is a small Cenozoic and Mesozoic foreland basin that developed southwest of the Zuni Uplift in west central New Mexico. It is bordered on the northeast by the Zuni Uplift, on the northwest by the Defiance Uplift, and on the southwest, south, and southeast by the White Mountains Volcanic Area and the Datil Volcanic Area. The boundary for this basin is derived from the basin outline shown in Cohee and others (1962) and Frezon and Finn (1988).

Figure 8. Catalogue of the Sedimentary Basins of the United States (Coleman Jr and Cahan, 2012)

Fassett and Head (2008) mapped 210 open-basin lakes and created a catalogue of them (Figure 9). The research article is organized into three parts. The first part is the methodology for identifying valley network-fed lakes and the criteria. The next part consists of the catalogue of 210 open-basin lakes; describes their distribution, morphometry, and mapped connections to other lakes; and the geomorphology of the catalogued lake basins is discussed. The last part consists of exploring the implications of this population of lakes for the atmospheric, surface, and subsurface environment (Fassett and Head, 2008). This catalogue contains a table of relevant attributes with references.

To create the catalogue, previous research was used and new research, where 147 new open-basin lakes were found on Mars, were combined.

Lake #	Lon. (E)	Lat. (N)	Outlet elev.	Lake chain	Area (km²)	Volume (km³)	Reference
1	116.86	1.46	175	*a*	1.68E+02	8.41E+00	
2	151.78	−9.29	−670	*b*	2.37E+02	6.56E+00	Irwin et al. (2007)
3	166.75	−15.20	−1165	*c*	7.40E+01	2.18E+00	
4	−174.86	−14.63	580	*d*	9.43E+02	9.97E+01	Forsythe and Zimbleman (1995)
5	−161.57	−10.32	−1700	*e*	1.60E+02	1.50E+01	Cabrol and Grin, 1999, Cabrol and Grin, 2001
6	152.75	−11.53	540	*f*	4.45E+03	6.16E+02	Irwin et al. (2007)
7	157.12	−12.44	−280	*f*	2.90E+02	2.87E+01	
8	42.19	18.25	−280	*n*	6.57E+03	4.89E+02	
9	59.68	27.47	250	*h*	3.60E+03	4.81E+02	
10	60.94	21.10	500	*h*	9.58E+04	3.10E+04	

Figure 9. Catalogue of 210 open-basin lakes from (Fassett and Head, 2008).

890 alluvial fans and 114 deltas were mapped by Wilson et al. (2021) and are presented on a map of Mars in (Figure 10). This catalogue consists of a description of the method, results, and a discussion of the results. In the supplementary data there is a table of all findings. Sources are included here too, but attributes are different from Fassett and Head (2008). In the table from Wilson et al. (2021) geological time scale was included. The geological time scale of alluvial fans and deltas was estimated using the geological map created by Tanaka et al. (2014).

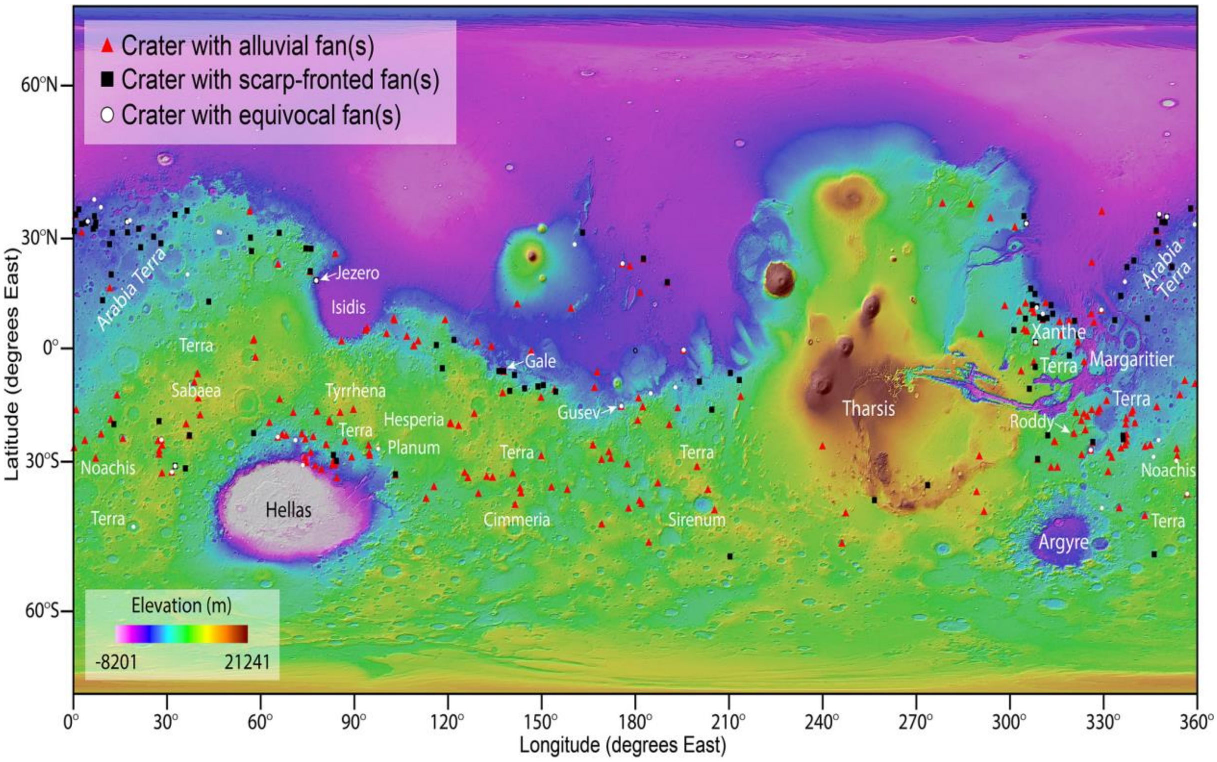


Figure 10. Map of alluvial fans and deltas from Wilson et al. (2021).

In the Mars crater catalogue (Salamunićcar et al., 2012) shown in (Figure 11). With the help of height profile and algorithms 32,843 craters on Mars were mapped, and the catalogue is not presented in the research article. The catalogue can be downloaded from an internet page. The catalogue has also been published as a picture of all craters on Mars.

1	gt_name_id	x	y	r	D[km]	D[range]	p	name	idxs(THM_	idxs(MDIM	idxs(MOC_	depth/diam	depth/diam	depth/diameter (1/512°MOLA, quad_precision=1)
2	S000001B00371R11256C00269T75557Y2005S	2,363280	73,593748	0,15190878	17,976	8	1		144,-4	20,-4	128,-184	0,0527602	0,0544435	0,0545048
3	S000002B00603R10024K20241T75303Y2005S	-170,335936	60,656246	0,14556255	17,225	8	1		84,-8	-4,0	108,-284	0,0369035	0,0417018	0,0421485
4	S000003B01099R06820K20279T75084Y2005S	-108,886714	60,167967	0,18314351	21,672	8	1		84,0	12,-4	108,-284	0,0386081	0,0405678	0,0407643
5	S000004B01803R05240C00134K20533T74496Y2005S	-37,417967	56,761718	0,22585347	26,726	9	1		0,0	4,8	120,-308	0,0519520	0,0559768	0,0562391
6	S000005B02753R13896K20444T74775Y2005S	37,992187	58,617187	0,10686049	12,645	7	1		0,0	4,-4	104,-292	0,0091344	0,0095356	0,0094021
7	S000006B04456R19225C00762K20395T74879Y2005S	112,425777	58,675777	0,07320978	8,663	6	1		0,0	0,0	108,-296	0,0225139	0,0259019	0,0264905
8	S000007B05742R15282C00513K23109T60916Y2005S	-178,480467	27,593748	0,10132925	11,991	7	1		0,0	12,0	100,-276	0,0098248	0,0135726	0,0139762
9	S000008B00700R09967T61918Y2005S	-142,742184	34,015620	0,13697523	16,209	8	1		0,0	4,0	112,-308	0,0480275	0,0539806	0,0550168
10	S000009B06120R12987T63269Y2005S	-106,992187	24,382812	0,12040401	14,248	7	1		0,0	12,12	104,-272	0,0577143	0,0615417	0,0629299
11	S000010B01311R08872K22792T65176Y2005S	-72,957029	31,027342	0,16288336	19,275	8	1		0,0	20,0	104,-304	0,0605954	0,0643529	0,0647320
12	S000011B07886R03253C00080K23201T69396Y2005S	-38,640623	26,460937	0,29131256	34,472	10	1		0,0	12,4	100,-276	0,0400317	0,0396350	0,0395467

Figure 11 Crater catalogue MA130301GT (Salamunićcar et al., 2012)

De Toffoli et al. (2021) made an updated version of the catalogue from Wilson et al. (2021) that describes 161 deltas on Mars. The catalogue from De Toffoli et al. (2021) was created using context cameras and digital elevation models.

A	B	C	D	E	F	G	H	I	J	K	L
id	Reference	Lat	Long	Front Elevation	Channel Length	Basin	Flow Direction	Channel Type	Region	Delta Morphology	Additional Info
1	Hauber et al., 2013; Wilson et al., 2021	14.559	-51.85	-2500	242.33	C	13	Valley Network	Amazonis Lunae Palus	Incised	
2	Wilson et al., 2021	31.599	-13.146	-4510	21.91	C	130	Single Valley	Arabia Mare Acidaliu	Stepped	
3	Wilson et al., 2021	-21.662	57.313	-77	155.23	OL	100	Valley Network	Syrtis Major	Incised	
4		-24.666	71.691	-2960	12.14	C	180	Single Valley	Hellas lapygia	Incised	
5		-23.373	70.944	-2155	90	OL	136	Valley Network	Hellas lapygia	Prograding	
6		-35.816	-179.346	80	52.92	OL	110	Single Valley	Phaethontis	Prograding	
7		-29.984	77.523	-4250	78.71	C	198	Valley Network	Hellas	Prograding	
8		31.603	-15.168	-3941	39.57	O	0	Single Valley	Arabia Mare Acidaliu	Prograding	
9	Wilson et al., 2021	33.443	-10.095	-3660	68.95	OL	315	Single Valley	Arabia Mare Acidaliu	Incised	

Figure 12. Catalogue of deltas (De Toffoli et al., 2021)

71 pristine fluvial valley networks, located between 18.08N and 55.08S, were mapped by Cabrol and Grin (2001)(Figure 13). Viking orbiter photomosaics were used to create this catalogue.

No.	MC	Latitude	Longitude	Area (km^2)	Perimeter (km)	Length (km)
(a)						
1	10SE	+18	54	3200	240	400
2	10SE	+15	53	9200	460	560
3	10SE	+15	51	6000	300	310
4	12SE	+09	319	6400	320	430
5	12SE	+12	317.5	6400	440	770
6	13SE	+03	277.5	2400	260	240
7	13SE	+02	270.1	4000	350	460
8	13SW	+7.5	313.5	5600	420	700
9	13SW	+7.5	311.5	7200	520	500
10	13SW	+14.2	311.5	800	460	1000
11	16NW	−11.8	178	3800	320	430
12	16SW	−17	180	4800	300	500

Figure 13. Pristine fluvial valley networks between 18.08N and 55.08S catalogue (Cabrol and Grin, 2001).

Birch et al. (2016) found 82 (Figure 14) alluvial fans across the surface of Titan using Cassini RADAR and made a catalogue of alluvial fans. Titan has methane as liquid on the surface and has complex fluid processes (Hayes et al., 2018; Lewis-Merrill et al., 2022; Lunine and Atreya, 2008; Newman et al., 2016).

Number	Latitude (°)	Longitude[a] (°)	Fan area (km^2)	Fan length (km)	Fan width (km)
1	78.5	−89.3	735	27	17
2	78	−104.4	291	14	6
3	77.8	−105.5	165	11	5
4	77.6	−6.7	360	21	6.5
5	77.5	−104.6	377	15	10
6	68.8	73.8	1993	37	45
7	68.5	74.4	2398	59	30
8[b]	51.3	−80.2	505–647	39	15
9[c]	50.7	−79.6	348–407	31	16
10	25.4	−9.4	37	10	5
11[d]	21.2	−77.4	$2.26–2.66 \times 10^4$	207	190
12	−28.2	105.1	1100	57	73

Figure 14. Catalogue of alluvial fans on Titan (Birch et al., 2016)

Geohydrological features on Mars and how to classify them

On Mars, signs of depositional environments and fluvial systems have been identified through several years of research and expeditions with rovers. Valley networks (Figure 15) superficially resemble terrestrial river drainage basins on Mars (Carr, 2007). Valley networks were first seen by Mariner 9 and the geological results were described by Masursky (1973). Milton (1973) proposed a theory that some large channels on Mars show features like notably bars and braiding which may indicate an origin by the action of running water, and smaller channels on steep slopes may have been produced by runoff of precipitation. Valley networks (Figure 15) can be compared to rivers, but Mars only had liquid water on the surface for periods. As a product of valley networks, it is common to find lakes, deltas, flood deposits, alluvial fans, and channel deposits.

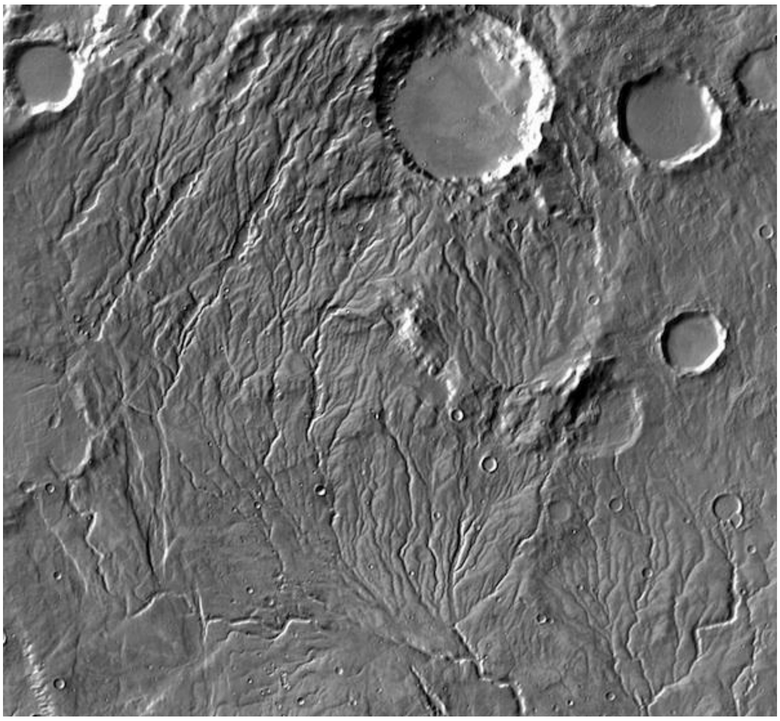


Figure 15. Valley Networks of Warrego Valles (NASA/JPL-Caltech/Arizona State University)

Valley networks and channel deposits.

Valley networks (Figure 15) on Mars can be compared to rivers on Earth, but it is uncertain whether the rivers were created by runoff. With current research, this explanation seems that it is runoff. On Earth, rivers are made by weather and erosion over longer periods of time. On Mars, it is controversial whether the early climate supported a climate with rain (Carr and Head, 2010; Kite, 2019). Some valley networks are inverted (Figure 16). It happens when sediments in the river are more resistant than sediments next to the river. The residue becomes a form of a river that lies above the other sediments.

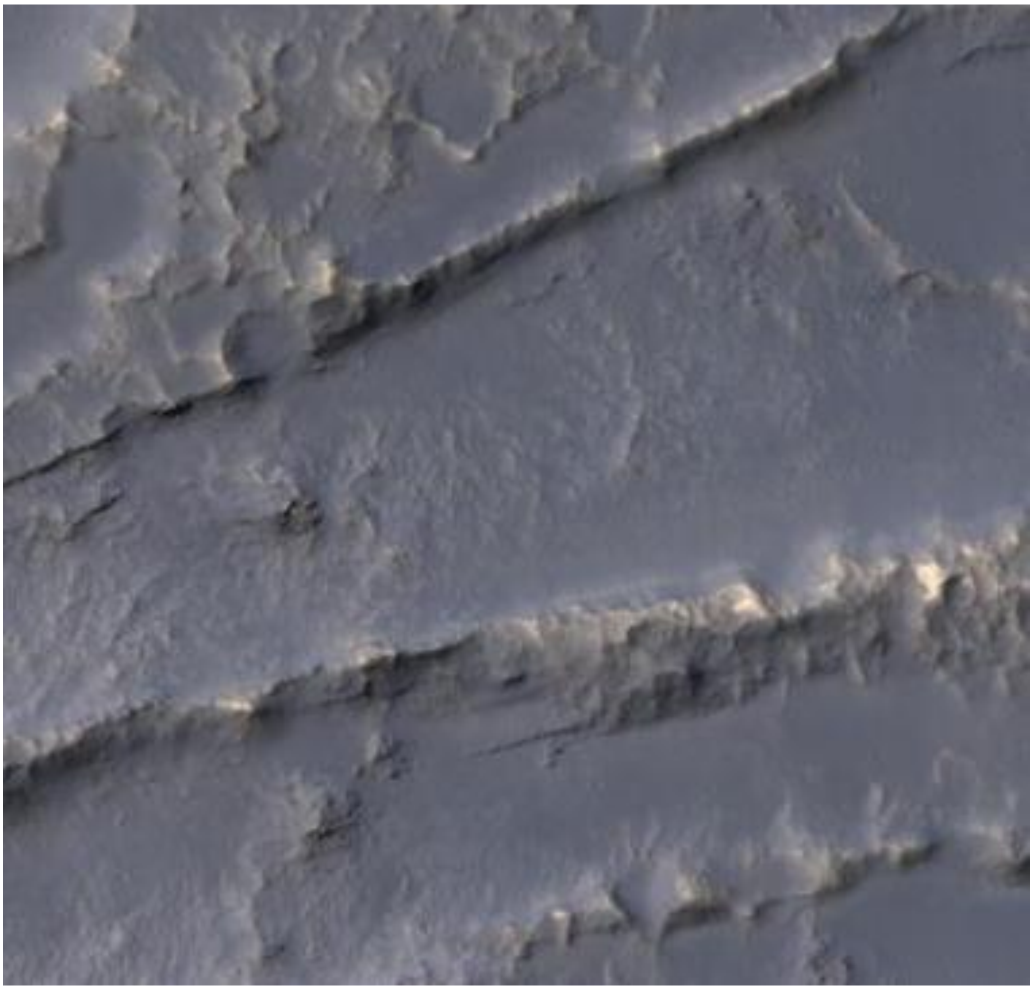


Figure 16. Inverted valley networks. ESP_042198_1560_COLOR /Arizona State University.

Valley networks (Figure 15) are easy to recognize from satellite images and look like meandering rivers. In some places, braided rivers can also be seen, but meandering rivers are more common. Meandering rivers have a point bar and a cutbank. The river burrows in at the cutbank and deposits sediments at the point bar (Figure 17) (Schon et al., 2012).

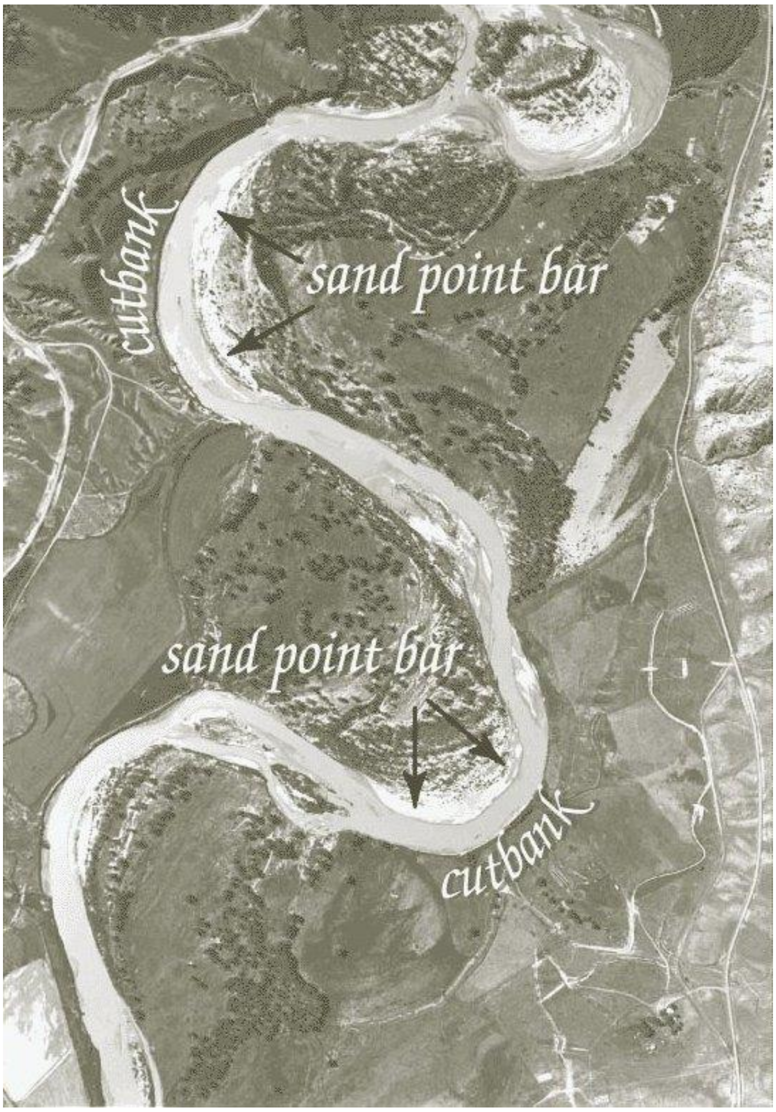


Figure 17. River in Montana. United States Geological Survey

By drawing the structures in the landscape from satellite images, point bars and cutbanks can be recognised (Figure 18) (Schon et al., 2012) . This method from was used by Goudge et al. (2017a) to identify point bars in Jezero Crater with stereo-derived digital elevation models.

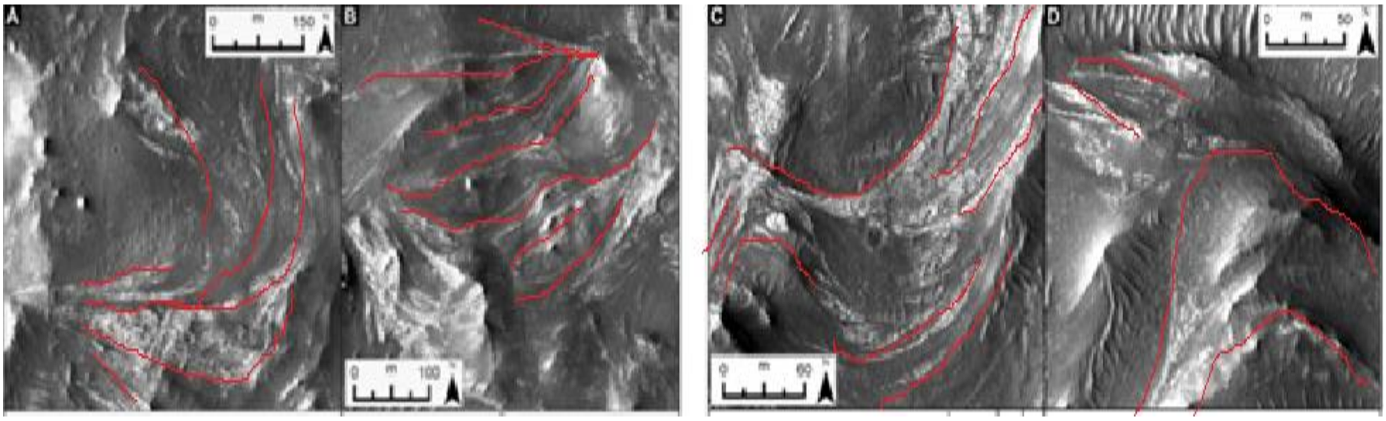


Figure 18. In the picture, the edges of the river are marked in red, and point bars can be identified from that. Modified from (Schon et al., 2012).

Deltas

On Mars, it is common to find Gilbert deltas which are river-dominated deltas. This is a steep-fronted sediment body that occurs when sediments are deposited in a relatively deep basin (Budai et al., 2021). Galloway (1975) recognized three major factors for the delta's sedimentary structure. These are river, waves, and tide. No tide-dominated or wave-dominated deltas have been found on Mars. Galloway (1975) created a classification scheme for deltas; deltas are divided into three categories for classification. Deltas change according to which processes are active (Galloway and Hobday, 1996). The Galloway and Hobday (1996) delta classification scheme can be used to classify deltas on Mars. Based on available information, river-dominated deltas are applicable to Mars. River–denominated delta classification is marked in red in (Figure 19).

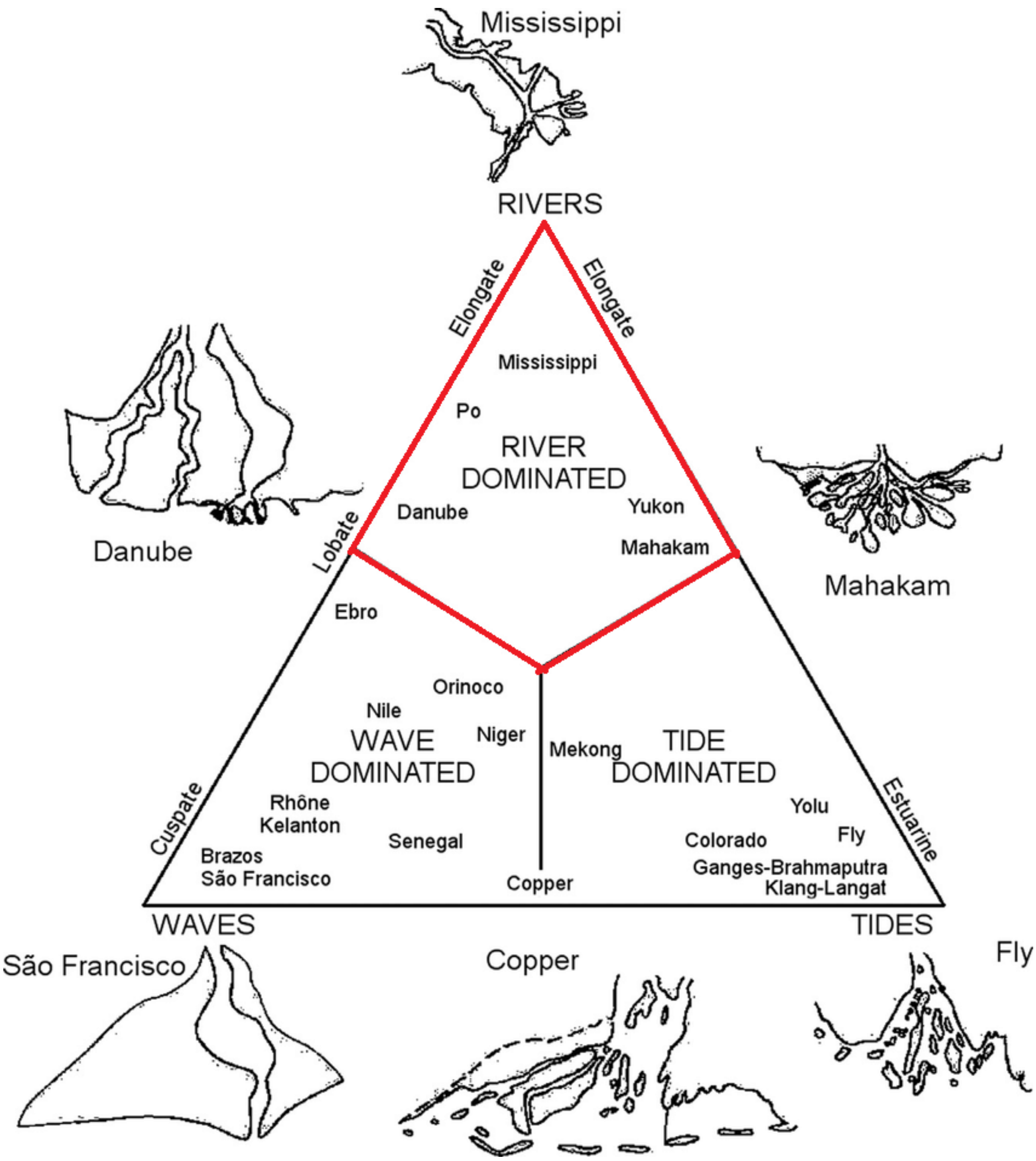


Figure 19. The whole classification scheme from Galloway (1975).

A delta was described in Goudge et al. (2018) and their conclusion was “The Jezero crater western delta is a well-exposed example of fluvial stratigraphy formed during the era of valley network activity on Mars” (Figure 16). The Perseverance rover found evidence for a delta-lake system and flood deposits, and this was described in Mangold et al. (2021).

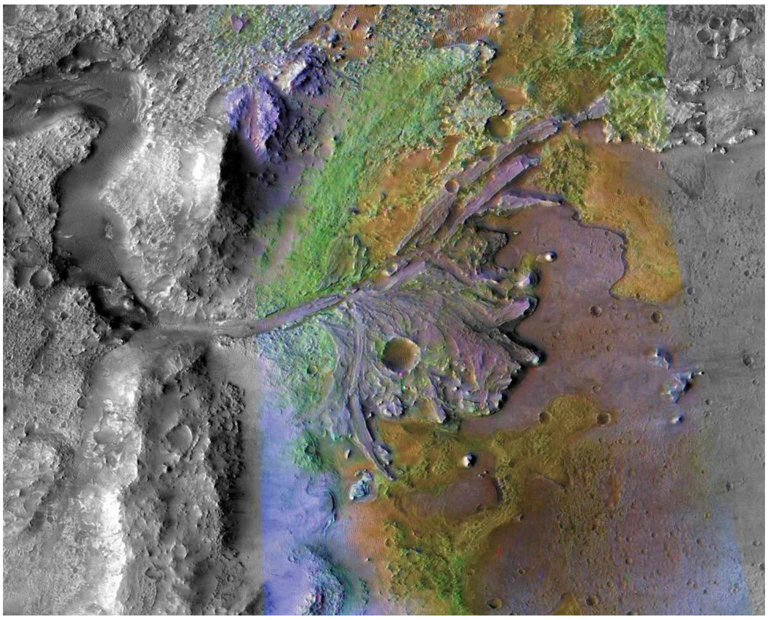


Figure 20. The Jezero crater western delta. NASA/JPL-Caltech/ASU.

Lacustrine environments and lakes

Most evidence has been found for lakes, but it has been suggested that there may be coastline by studying possible ancient sea level markers (Chan et al., 2018). Lacustrine environments are a controversial subject since there was no liquid water for extended periods of time (Figure 4). Lacustrine environments are central to mapping the former global hydrological system on Mars and whether it is based on runoff or there was a sea on Mars. At 3.24 Ga, Earth was a water world (Johnson and Wing, 2020), and the oldest sign of life is from 3.5 Ga. At Jezero crater there has been done an estimated minimum life span of the Jezero fluvial delta is between 6.55 and 27.36 years depending on the channel width. The minimum lake delta formation timescale for 90–150 years with a channel 190 m wide to 330–550 years for a channel 50 m wide (Salese et al., 2020). It is possible the lake was there before this. (Salese et al., 2020). Lacustrine environments are an environment that must be studied to find signs of life, since early life on Earth arose in lacustrine environments. As mentioned earlier, there is uncertainty as to whether there were seas on Mars, this is also supported in Kite (2019).There is a possibility for microorganisms in lacustrine environments, although these lacustrine environments may only have been there for a few hundred years at most.

By looking at the height profile, lakes can be interpreted from and by using descriptions from Bradley (1925) ,Olsen (1990) and Carroll and Bohacs (1999). Based on this, a diagram was made by Schon et al. (2012) (Figure 17). The sediments in the lake will be deposited from the inlet to the lake. If there is a lot of water coming in, it will overflow, and the sediments will be deposited as inclined. If a basin has little supply of water and it never overflows, the sediments lie horizontally (Figure 21).

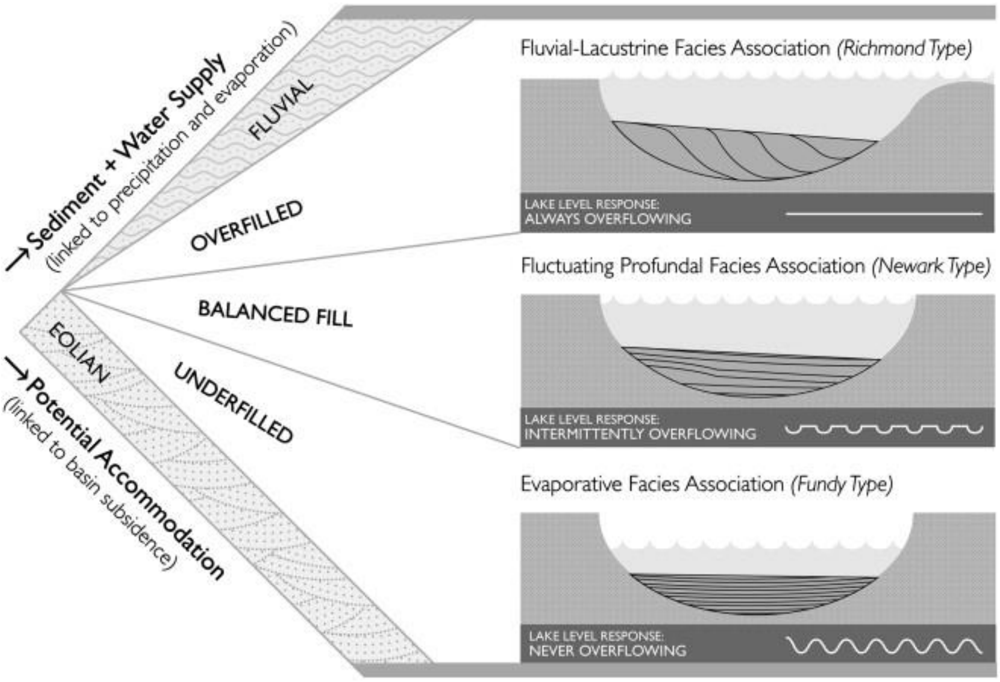


Figure 21. Describes how sediments are deposited. From (Schon et al., 2012)

In the Jezero crater, there has an intake and an outlet from the lake (Figure 18). It was described by Goudge et al. (2018). The delta identification was done by interpreting elevation profiles and satellite images. The white area is the delta in Jezero crater (Figure 22).

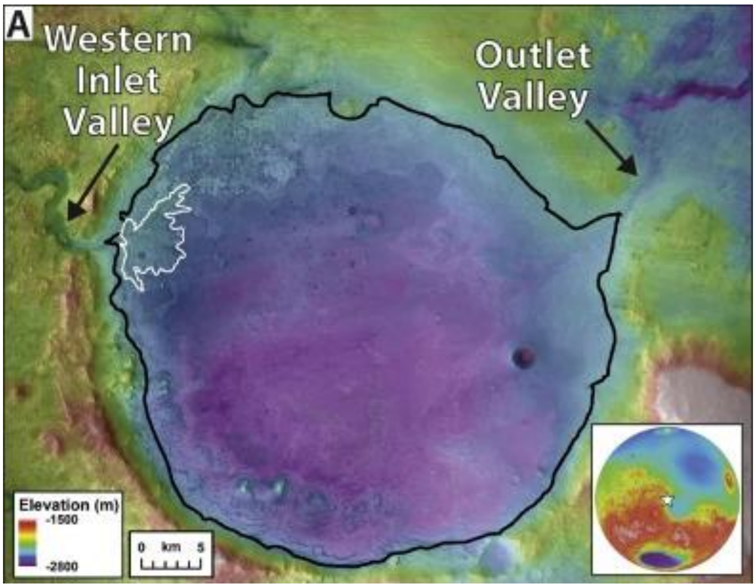


Figure 22. Lake in Jezero crater (Goudge et al., 2018). The white area is Jezero crater western delta.

Alluvial fans

Alluvial fans are formed when streams lose energy and the result is a sedimentary structure that looks like a fan (Bull, 1977; Harvey, 1978). In Figure 19, the alluvial fan is marked in red. Alluvial fans can be easily seen from satellite images, but interpretation from a cross section becomes difficult without images from the surface. Figure 19 shows an alluvial fan at 22s 292W and described by Williams et al. (2011). Williams et al. (2011) found 890 alluvial fans on Mars in 314 craters.

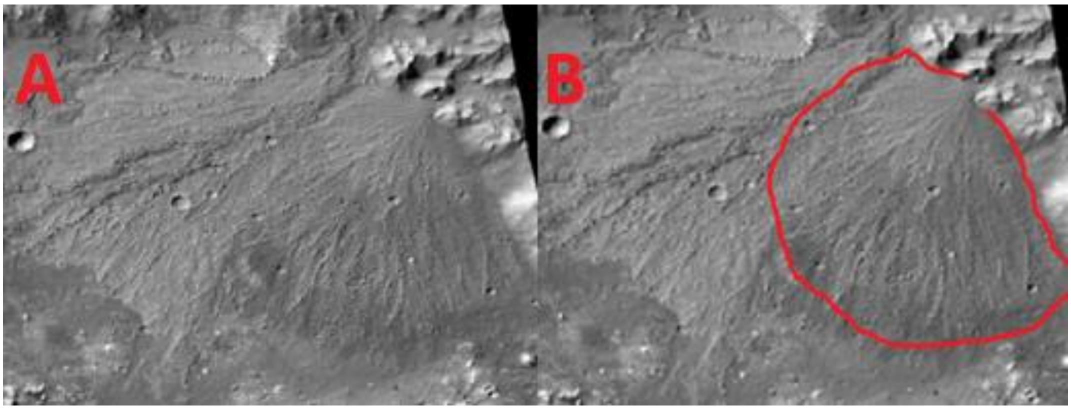


Figure 23. A is a picture without the alluvial fan marked. In picture B, the alluvial fan is marked in red. MRO Context Camera G02_019160_1580_XN_22S292W, NASA/JPL/Arizona State University.

Additional classification attributes

Sedimentary structure.

Most of the research on sedimentary structures are from Gale crater and Jezero crater (Figure 24). This research is based on rover images from the surface which are used for the interpretation of sedimentary structures. From satellite images, sand dunes can be seen. Data on sedimentary structures and depositional environments are mostly from rovers.

Figure 24. Picture shows sedimentary structures in Jezero crater. Jezero crater, NASA/JPL-Caltech/ASU

Strata

Strata analysis is most common from rover images and from these images the strata can be described. Strata can also be interpreted based on height profile. Strata are important for understanding the lithology on Mars and the geology of the area under study. It was therefore included as a subcategory.

Grain size

By looking at sizes of pixels, grain size can be interpreted. Information on grain size is rarely found in publications. From mineralogy, additional information such as formation environments, bio mineralogy, and mineral ecology can be interpreted.

Mineralogy

With a spectrometer, information about minerals can be obtained. This is done from a satellite or rover.

Flood deposit

Because of Mars' geological history, it is common to find flood deposits. It can be seen in connection with volcanic activity and seasonal runoff. Flood deposits are sediments from rivers or other sources of water. Usually flood deposits are composed of clay, gravel, sand, and silt, but boulders can also be present (Kovács, 2013). Figure 25 shows a flood deposit in Jezero crater that was described by Mangold et al. (2021).

Figure 25. Jezero crater flood deposit. NASA/JPL-Caltech/ASU/MSSS

Organize, store, and maintain the catalogue

The geological information in the geological catalogue must have a standard and requirements for what can be added to the catalogue. This geological catalogue contains information about hydrology on Mars. Therefore, it is not relevant to add information about geological structures that are not made by water. The main attributes may change over time, but should stick to hydrology, and not go beyond this topic. A great deal of research is done annually within this topic. It is, therefore, best if researchers are given access to the geological catalogue, and this is on a cloud service. In geology, it is common to use a database management system (DBMS)(McHugh et al., 1997). Microsoft Access, FileMaker, and SQL are examples of DBMS that can be used. Through the University of Stavanger's cooperation with other universities, it can be ensured that geologists, researchers, and other interested parties have access. With such collaboration, it can also be ensured that the catalogue is up to date by constantly adding new data. The implementation of a collaborative catalogue, however, is outside the scope of this thesis.

Catalogue

Based on earlier catalogues as a template, there are several ways to present the catalogue. In this catalogue, earlier research is classified according to content and stylized like an encyclopaedic entry.

The catalogue is divided into five categories with five subcategories. Subcategories are in the main category. The catalogue is put in boxes, where geo hydrological features are the main categories. Additional classification attributes are added where relevant in main categories. Examples such as mineralogy, stratigraphy, and grain size can be used to explain the geological depositional environment. It is more appropriate to have subcategories than for example stratigraphy to be a separate category. The categories are valley networks, lacustrine environments, deltas, alluvial fans, and area of research. Subcategories are flood deposits, channel deposits, sedimentary structure, strata, mineralogy. Area of research uses all subcategories; this is so that the user can get information about everything that is relevant. This gives an overview of all the content of a research report in an area.

This section provides an example entry for each of the catalogue categories.. An example of relevant information within a category is given. Images from satellites use a reference code, and with this code, it is possible to search for the original image. The reference code has been included when known. The reference code can be searched here: http://viewer.mars.asu.edu/viewer. Appendix I contains larger resolution images of those included in figures 22, 26, and 27. In Appendix II, other sources are listed by category.

Area of research

Most of the research that has been done focuses on the whole of Mars. However, areas such as Gale Crater, Jezero crater, and Nili Fossae region are areas of particular interest. Box 1 presents an example entry for Jezero crater. Images from the rover are used here, and they do not contain a reference code

Box 1

Area of research: Jezero crater

Region: Nili Fossae region

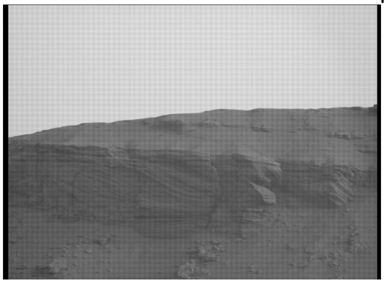
Coordinates to work area: 18.38°N 77.58°E

Reference to photos:

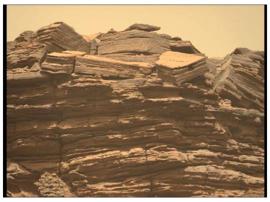
Ref code A: ORB_036600_036699
Ref Code B: ESP_036618_1985
Ref Code C: D14_032794_1989_XN_18N282W
Ref Code D: ORB_003700_003799
Ref Code E: PSP_003798_1985
Ref Code F:D15_033216_1989
Ref Code G:B02_010272_2009
Ref Code H:B06_011841_2005
Ref Code I: P04_002664_1988

Sedimentary structures: cross-stratification, horizontal lamination, wave ripples

Cross stratification: Jezero crater April 22, 2022 (Sol 416) NASA/JPL-Caltech/ASU



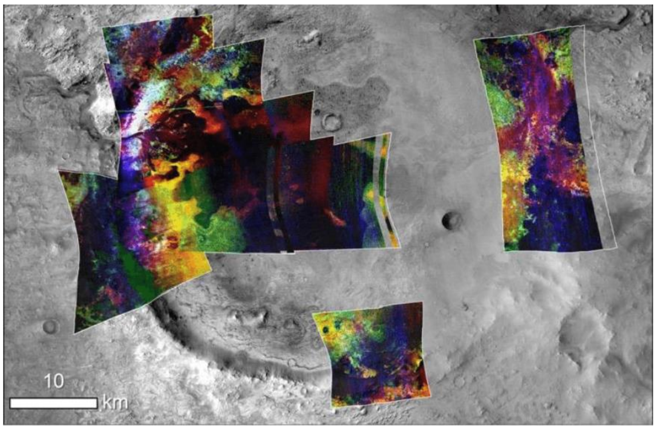
Horizontal lamination: Jezero crater July 24, 2022 (Sol 507) NASA/JPL-Caltech/ASU



Wave ripples: Jezero crater NASA/JPL-Caltech/MSSS

Mineralogy: Mg-rich carbonate, olivine, Fe/Mg-smectite (nontronite or saponite)

CRISM image HRL000040FF Spectral diversity in carbonate, modified from (Horgan et al., 2020), Red: Olivine, Yellow/white: Strong olivine and carbonate signatures, Cyan/blue: Strong carbonates with weaker olivine, Green indicates : Fe/Mg possibly



Delta, and alluvial fans: Gilbert delta

Flood deposit: Flood deposits have been found in Jezero crater. Boulder conglomerates indicate repeated floods (Figure 21).

Keywords: Delta-lake system, Jezero crater, Flood deposits, Gilbert-type deltas, Strata.

Geologic Map: Map of Jezero Crater and the Nili Planum Region https://pubs.er.usgs.gov/publication/sim3464 (Sun and Stack, 2020)

Sources : (Goudge et al., 2016; Goudge et al., 2017b; Goudge et al., 2018; Goudge et al., 2015; Holm-Alwmark et al., 2021; Horgan et al., 2020; Mangold et al., 2021; Sun and Stack, 2020)

Valley networks

Valley networks (Figure 26) were the first sign of water to be found and are a river system. Much research has been done on this topic and is important for understanding the hydrologic system on Mars. Box 2 shows an example entry.

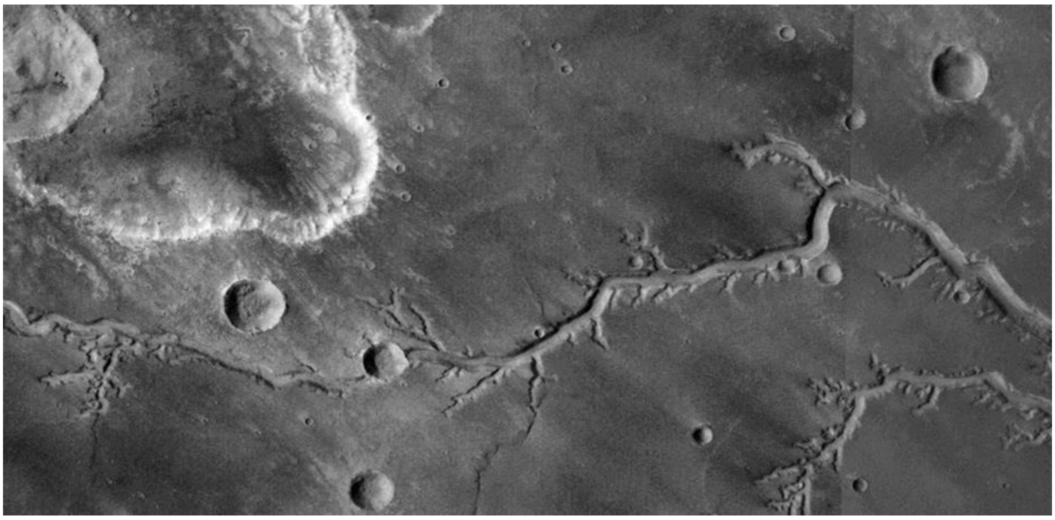


Figure 26. Valley networks. HRSC image h6442_0000, NASA/JPL/Arizona State University.

Box 2

Position	Aera	Width and length	Description	Ref code
Lat 18.83° Lon 78.64°	Jezero	Width 1 km and length 53 km eastward	Channel deposit is visible. Noachian	P02_001965_1988_XN_18N281W
Lat −23.72° Lon 34.78°	Terra Sabaea	Width unknown and length 91 km	Inverted channel. Late Noachian–Early Hesperian	CTX global mosaic

Sources: (Boatwright and Head, 2023; Molloy and Stepinski, 2007; Schon et al., 2012)

Lacustrine environments

Lakes (Figure 27) and possible coastlines have been extensively researched and are an important topic for further research. To understand lacustrine environments, and the formation of the environment, a lot of information is needed. It is therefore important to thoroughly document what information is available. In Fassett and Head (2008) open-basin lakes are categorized by lake chain or whether the lake was not part of a lake chain. This can be used in further work to define the entire hydrological system the lake is part of. Box 3 shows an example entry.

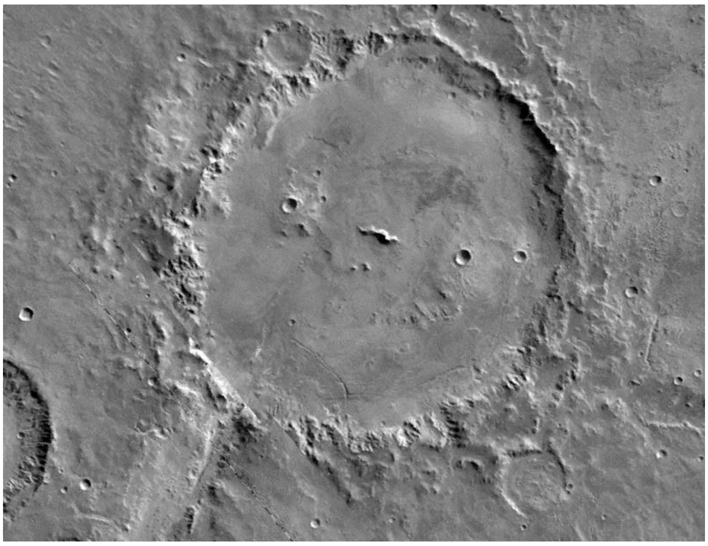


Figure 27. Lake in Holden crater, Viking Orbiter Mosaic, U.S. Geological Survey.

Box 3

Name of region area: Nili Fossae region

Name of area of research: Jezero crater

Coordinates to work area: 18.4°N, 77.7°E

Reference to pictures:

Ref Code A: P04_002664_1988
Ref Code B: P06_003376_1987,
Ref Code C: P06_003521_1971
Ref Code D: P15_007068_1971
Ref Code E: P04_002664_1988

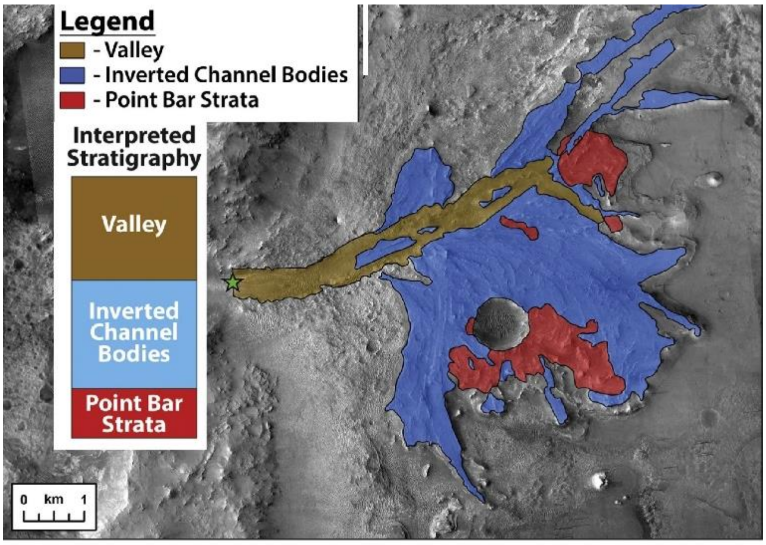
Geological period: Middle-to-Early Noachian

Watershed area: 30,700 km2

Lake area: 45 km diameter

Strata: valley, channel bodies, point bar

Strata at Jezero crater, modified from (Goudge et al., 2018) Goudge et al. (2018)



Mineralogy: Mg-rich carbonate, olivine, Fe/Mg-smectite (nontronite or saponite)

Delta, and alluvial fans: Gilbert delta

Sedimentary structure: Cross stratification, horizontal, wave ripples.

Sources: (Fassett and Head Iii, 2005; Fassett and Head, 2008; Goudge et al., 2018; Goudge et al., 2015; Schon et al., 2012)

Delta and alluvial Fans

On Mars, several deltas have been found, and deltas are visible from satellite imagery. With the interpretation of the height profile and images from a rover, a good analysis can be made of a delta. *Delta Deposits on Mars: A Global Perspective* (De Toffoli et al., 2021) can be used as a basis for information that should be included. Alluvial fans are a common geological structure on Mars, and a lot of research has been done in this area. 890 alluvial fans and 114 deltas have been mapped (Wilson et al., 2021). Box 4 shows an example entry.

Box 4

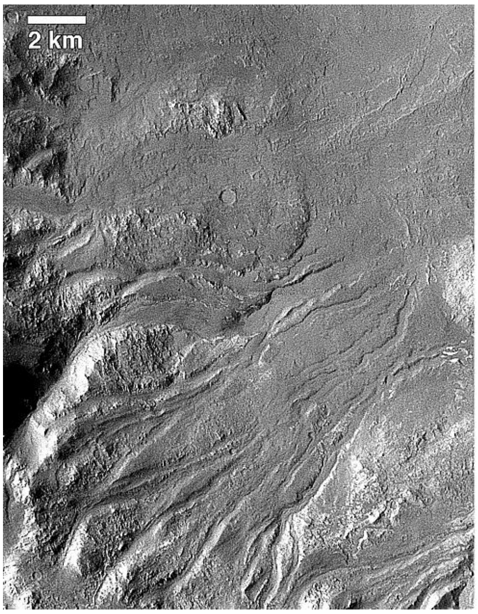
Name of area: Holden crater

Alluvial Fans Holden crater

Alluvial Fans	Coordinates	Flow direction
1	-26.04°S -34.02°W	152.66°
2	-26.04°S -34.02°W	152.66°
3	-26.04°S -34.02°W	152.66°
4	-26.04°S -34.02°W	152.66°
5	-26.04°S -34.02°W	152.66°
6	-26.04°S -34.02°W	152.66°
7	-26.04°S -34.02°W	152.66°
8	-26.04°S -34.02°W	152.66°
9	-26.04°S -34.02°W	152.66°
10	-26.04°S -34.02°W	152.66°
11	-26.04°S -34.02°W	152.66°
12	-26.04°S -34.02°W	152.66°
13	-26.04°S -34.02°W	152.66°
14	-26.04°S -34.02°W	152.66°
15	-26.04°S -34.02°W	152.66°
16	-26.04°S -34.02°W	152.66°

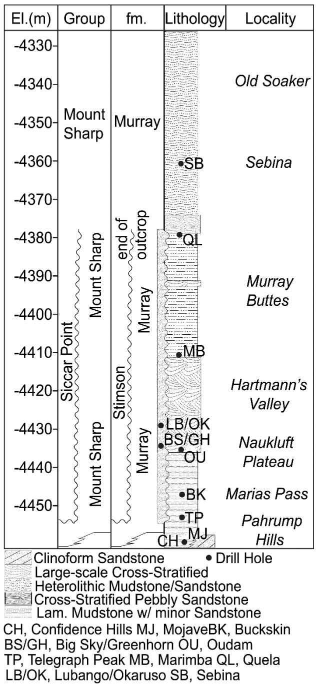
Box 4cont'd:

Reference to picture: THEMIS VIS image V01762003, centered 26.49°S, 34.97°W modified from (Moore and Howard, 2005)



Geological period: Amazonian and Hesperian

Strata: Stratigraphic column at Gale crater from (Stein et al., 2018)



Sources: (Buz et al., 2017; Moore and Howard, 2005; Stein et al., 2018; Yen et al., 2017)

Discussion

Based on other geological catalogues, a basis has been provided, and categories for the geological catalogue can be selected based on previous research into hydrological systems on Mars. The work done here is not a definitive answer to a geological catalogue of hydrological systems on Mars. The catalogue will change when more information becomes available, and information in the categories will change according to what creators or contributors interpret as essential information.

The category “area of research” contains all available information about an area. This gives an overview of the area and what research has been done there. The information will vary from area to area. It is because some areas such as Jezero crater have been extensively researched. While other areas, such as the Chryse basin, it is difficult to find published information.

Lacustrine environments are categories chosen that are relevant to lakes. If in the future a sea is found on Mars, lacustrine environments must be split up. Here, the emphasis is on a joint catalogue of lakes with information that matches each other. This is done so that lakes can be compared. A sea has a different depositional environment than a lake. In the case of a sea, there are possible depositional environments such as lagoon, shallow marine, reef, beach, etc. A lake does not have these depositional environments, and therefore it makes sense to separate them.

Valley networks information is added to a table so that they can be easily compared. It was difficult to find a reference image of the valley network that was described. Most publications do not include a photo of the described valley network. It is common for several valley networks in an area to be given in a table and where the author mentions the source of the images that were used in the analysis as CTX global mosaic. CTX global mosaic is a set of images showing the entire surface of Mars and is a collection of 125,000 images (Robbins et al., 2023). When referring to the CTX global mosaic, it becomes difficult to find the valley network which is described again by the reader. This therefore becomes a weakness in a geological catalogue of valley networks when images are not readily available, and descriptions of the valley network cannot be confirmed by others.

Delta and alluvial fans are given with a table, a picture of the area, and a description of the strata. In Holden crater, there were 16 alluvial fans, and strata data was available due to rovers. Information about strata is not available in all areas, but a geological map (Tanaka et al., 2014) of Mars can be used to find the age of strata in the area. Alluvial fans in Jampur crater were first described by Wilson et al. (2012) who list 7 alluvial fans in the area. It is difficult to find information and photos from Jampur crater showing alluvial fans in the area. This means that if the alluvial fans in Jampur crater are added to the geological catalogue, there will be a lack of information and a picture will be missing. Information may be added later when it becomes available. With a lack of information, it becomes problematic to compare, for example, Holden and Jampur craters.

Almost all the geological catalogues given as examples use tables to convey information. There are two catalogues that do not use tables: Coleman Jr and Cahan (2012) and Silva et al. (2019). A table is appropriate in certain cases such as deltas or alluvial fans. When describing an area, it is better to use text or images.

In some publications, not all data is available, or it is unknown where the data is from. Not all information given in publications can be used for the catalogue creation. The information may be specific to the research that was carried out, and the information is not provided in other publications. This geological catalogue emphasizes attributes that is repeated in several publications. An example is valley networks, where most publications have length and width. By standardizing information that should be included within a research area such as valley networks, it becomes easier to interpret the information and see differences between geographical areas.

Mars' geological history is controversial and will change as more research is done. This has affected the geological catalogue according to what information is relevant. There is evidence for a coastline, but not a sea. Therefore, it was to appropriate to include seas in the geological catalogue. If solid evidence is found for a sea on Mars, the geological history will have to be changed, which means that the geological catalogue will have to be changed. If fossils or bacteria are found in lakes, this must also be included in the catalogue. While carbonates are documented in Jezero crater, they are not differentiated between organic or chemical carbonates. Carbonate types should be documented in the catalogue. At the present time, it is not documented what type of carbonates are at Jezero crater, and therefore it is not classified in the catalogue.
Inspiration has been taken from other catalogues. An example of that is valley networks. By studying other catalogues and using their.

The catalogue builds on previous geological catalogues such as De Toffoli et al. (2021), Fassett and Head (2008), Salamunićcar et al. (2012), Wilson et al. (2021). These publications form the basis of this geological library, but not all publications contain information that they should contain. An example of that is the watershed area, or lake area. Much research has been done about the lake at Jezero crater or the lake at Gale Crater. In these publications, it is not usual to describe the watershed area or lake area. Another example is images taken with rovers such as in Mangold et al. (2021). In Mangold et al. (2021), the raw image is given as a reference (https://mars.nasa.gov/mars2020/multimedia/raw-images/) to the images taken with the rover. By searching for raw images from 2021 to 2022, which is the period this research article is from, the result is approximately 140,000 images. The search is limited to only searching images from mastcam-Z-Left, and mastcam-Z-Right with which the images were taken from. If another researcher is to confirm the results in the research report, it is problematic to look through 140,000 images.

With rover images, distance is also problematic if the number of pixels is not known and the length per pixel is not known. The method for calculating the length per pixel is often not specified nor the number of pixels in the image. It will be difficult to confirm results without this information.

If the scientific method is to be followed, the hypothesis must be confirmed with new experiments. These experiments should also be confirmed by other researchers, which means that all data should be available to everyone. Academic freedom says that everyone should be able to research what they want without hindrance, but it becomes difficult when not all information is available. This concept is described as FAIR data, which stands for findability, accessibility, interoperability, and reusability (Figure 28).

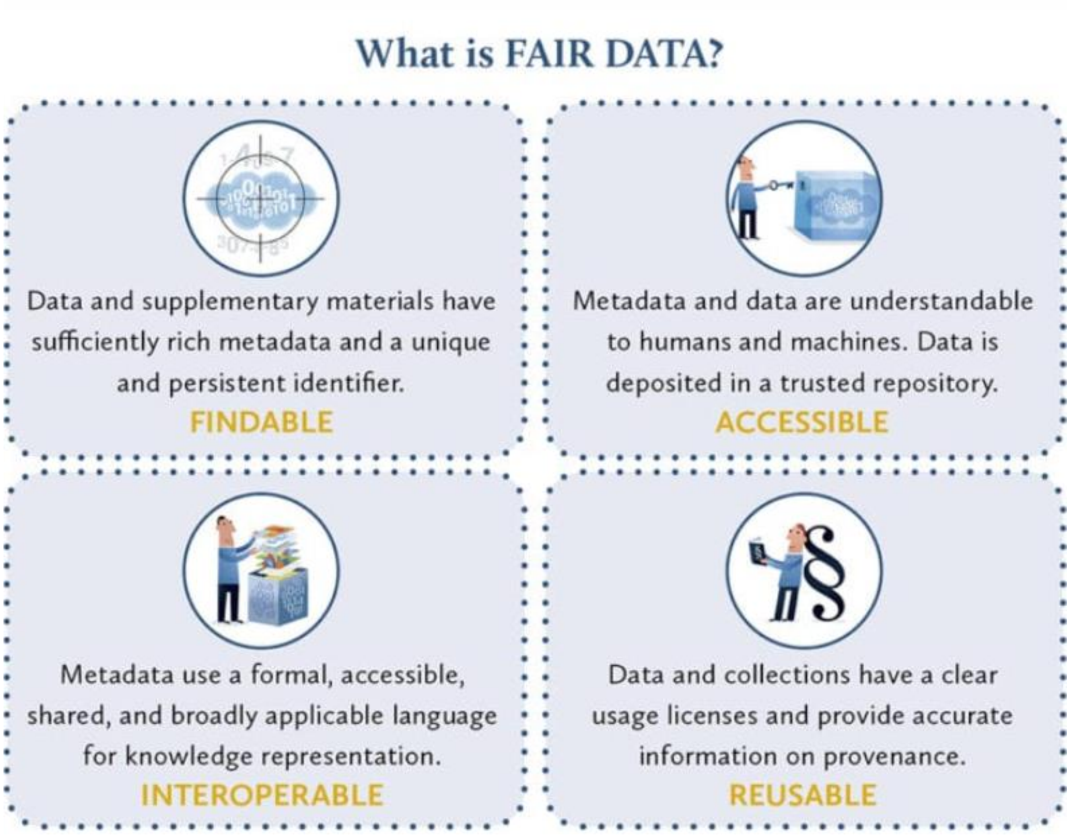


Figure 28. Description of FAIR data from (LIBER, 2018).

This geological catalogue can be used as a basis for what information should be included in a research area. How the hydrological systems on Mars are documented can be used as a template for documentation on Pluto and Titan. By standardizing the documentation of hydrological systems, the various planets can be compared, and differences in the geology can be documented. On Titan, the liquid on the surface is menthane, and on Earth, Pluto, and Mars, it is water. How this affects the geology with methane as a liquid has not been researched, but a geological catalogue can contribute to this research. Pluto, and Titan have documented hydrological systems, and a geological catalog can be used here. The geological catalogue for Mars can as a basis for cataloguing hydrological systems on Pluto, and Titan. The difference is that Titan has methane as liquid on the surface and not water. Titan is believed to have a complex fluid processes (Figure 29). In (Birch et al., 2016) it was found 82 alluvial fans and fan-like features on Titan and a geological catalogue of alluvial fans and fan-like features. When more research is done on Titan a catalogue of cataloguing hydrological systems can be made. A mission to Titan is planned in 2026 called Dragonfly which will arrive in 2034. To document the geological information in 2036, a geological catalogue can be used.

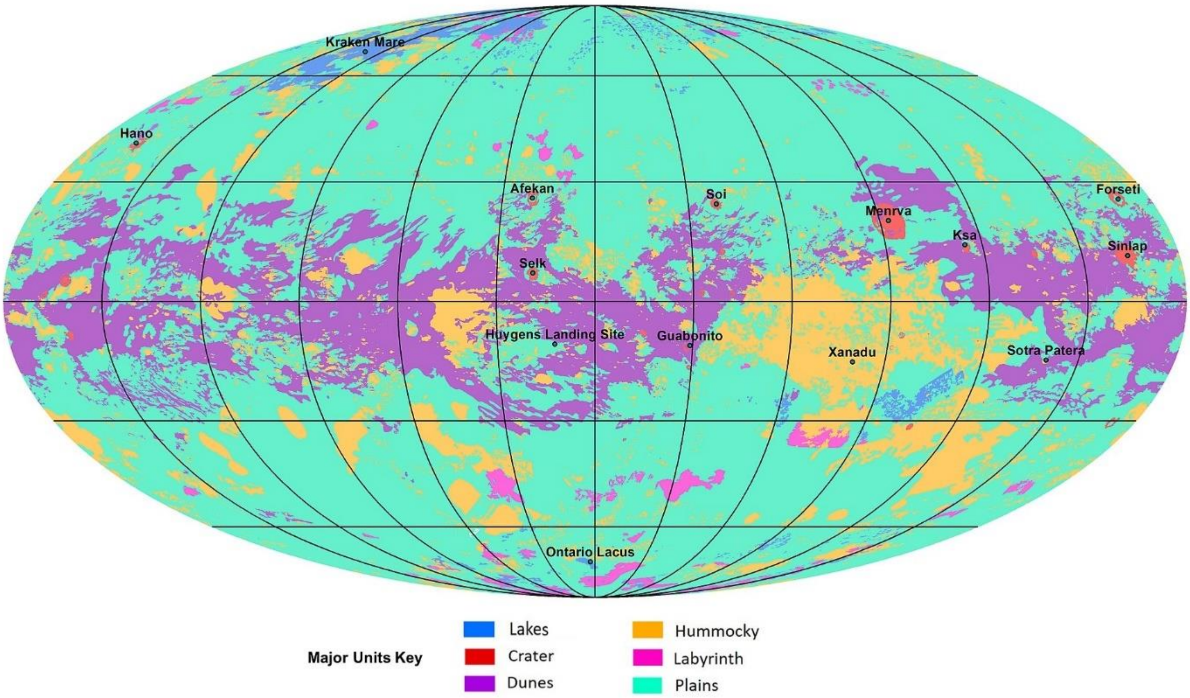


Figure 29. Figure 29: Global geologic map of Titan, NASA/JPL-Caltech/ASU

Evidence of rivers has been found on Pluto. With ammonia water, the freezing point of water is lowered, and it is possible to have water on the surface even above minus 200 °C (Martin and Binzel, 2021). When more information about Pluto becomes available, a geological catalog can be used.

Conclusions

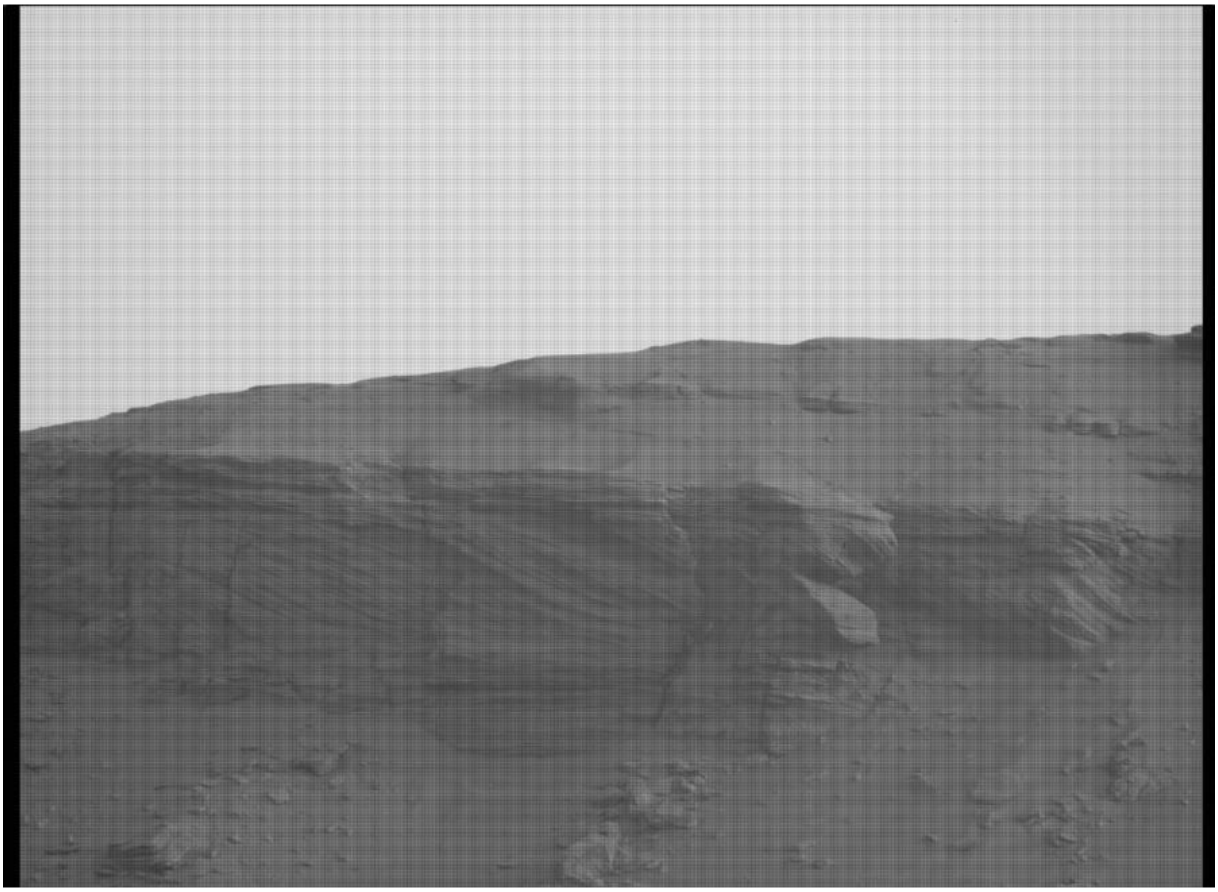
On Mars, signs of fluvial systems and depositional environments such as lakes, valley networks, deltas, and alluvial fans have been found. A format for a geologic catalogue has been proposed focused on hydrologic features on Mars in this bachelor's thesis. A hydrologic catalogue of Mars may be stored and maintained using several methods, but it is important that it is done in accordance with FAIR principles. The hydrological geological catalogue for Mars should contain information that is relevant and will be updated after new research. The geological catalogue in this bachelor's thesis can be used as a template, creating a basis for further work either for Mars, Titan, or Pluto. This bachelor's thesis contributes to further work on Mars, and how the information can be collected in a geological catalogue.

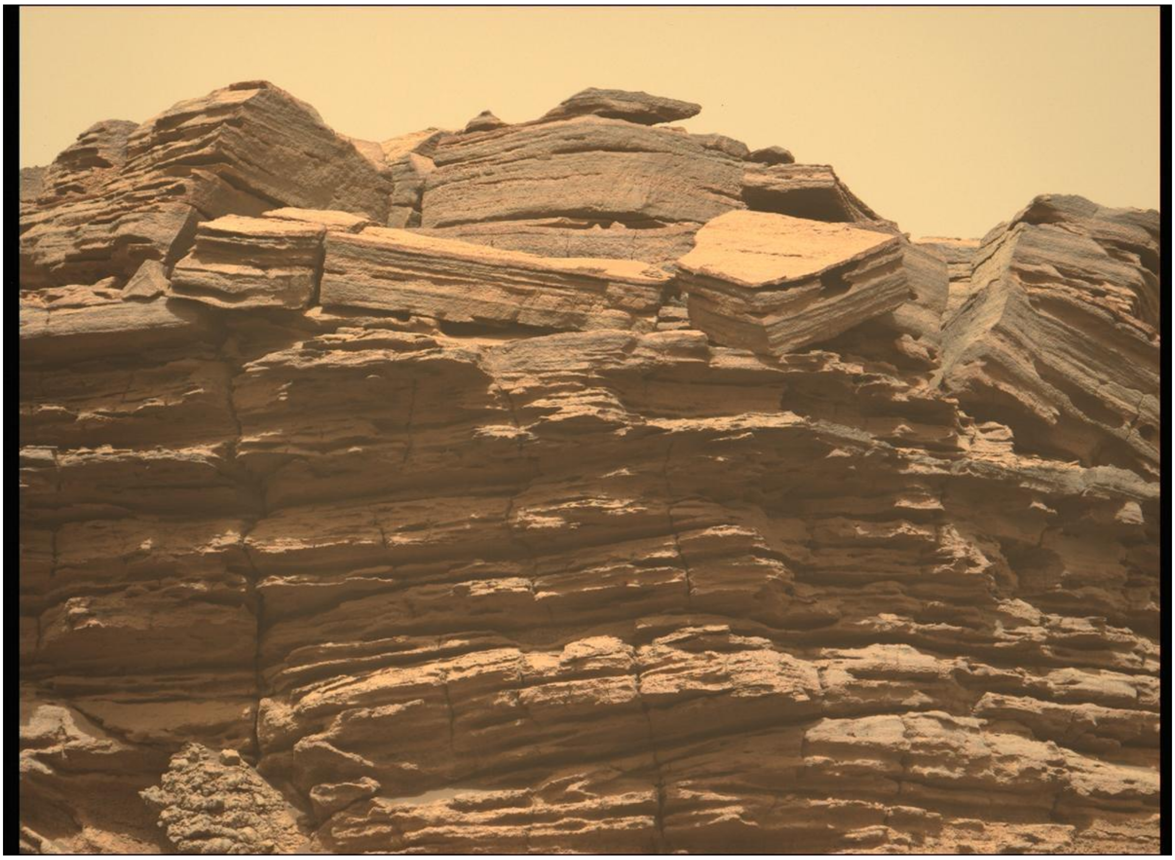
Appendix I

Catalogue images

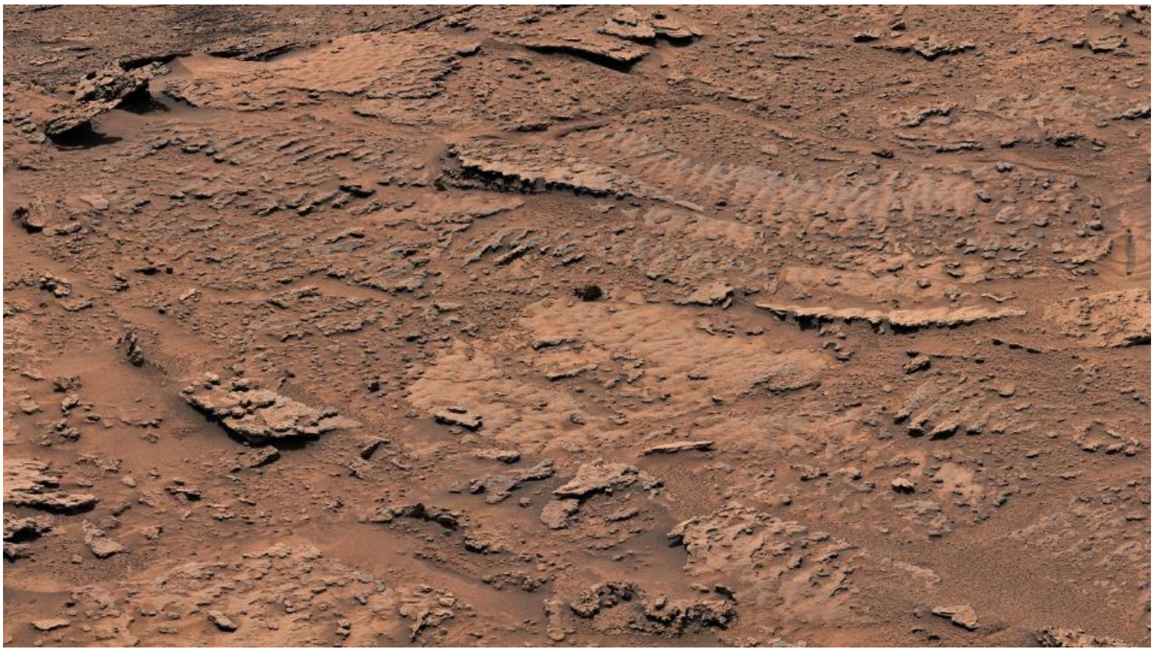
Area of research: Jezero crater

Cross stratification: Jezero crater April 22, 2022 (Sol 416) NASA/JPL-Caltech/ASU

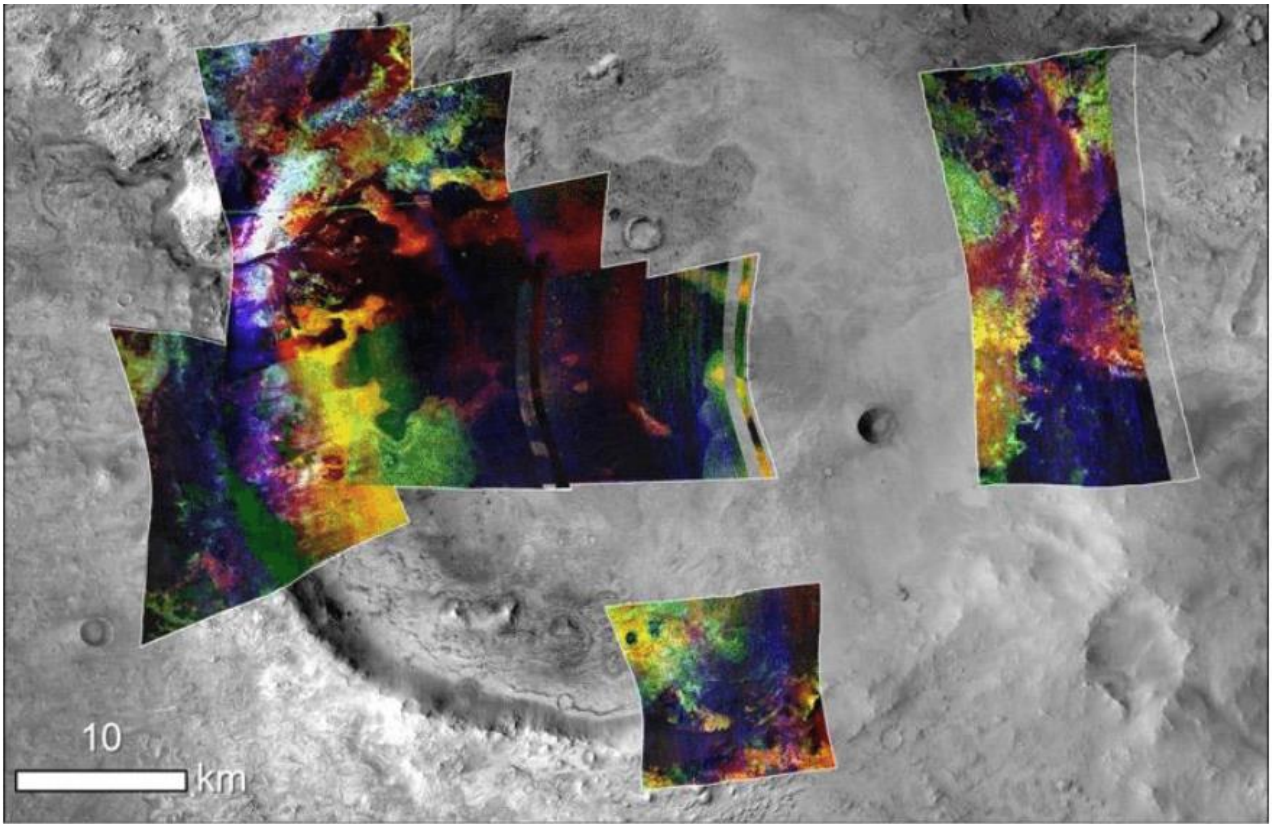




Horizontal lamination: Jezero crater July 24, 2022 (Sol 507) NASA/JPL-Caltech/ASU

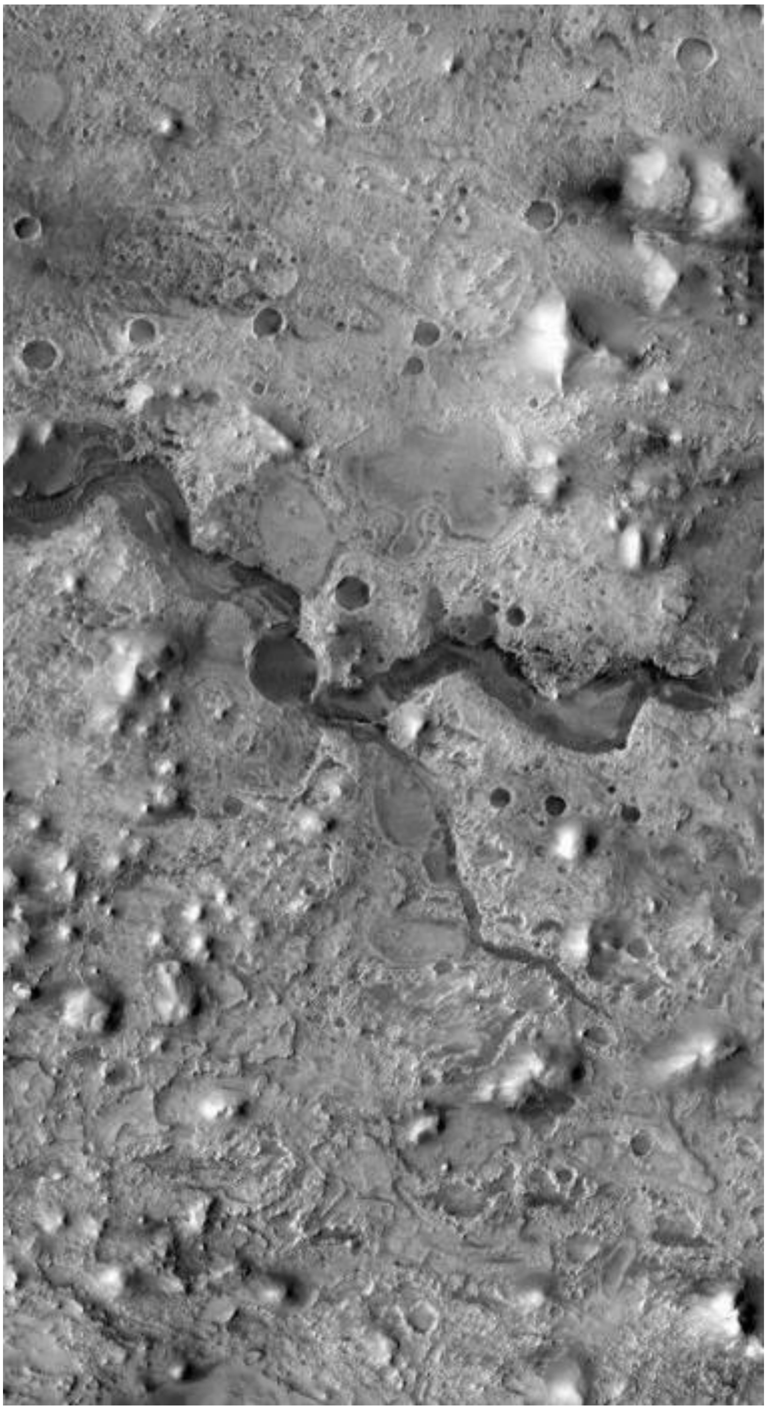


Wave ripples: Jezero crater NASA/JPL-Caltech/MSSS



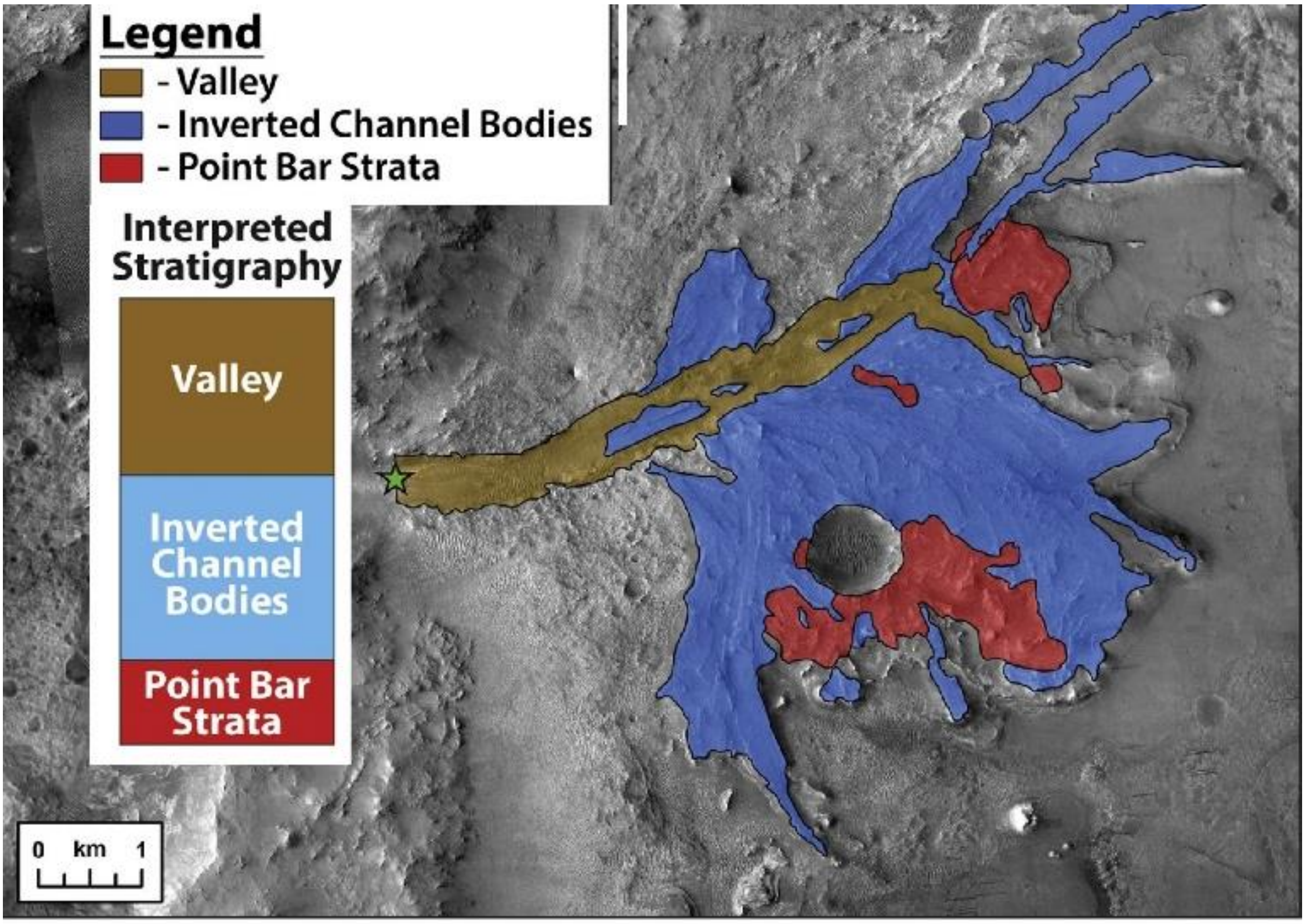
CRISM image HRL000040FF Spectral diversity in carbonate, modified from (Horgan et al., 2020), Red: Olivine, Yellow/white: Strong olivine and carbonate signatures, Cyan/blue: Strong carbonates with weaker olivine, Green indicates: Fe/Mg possibly

Valley networks



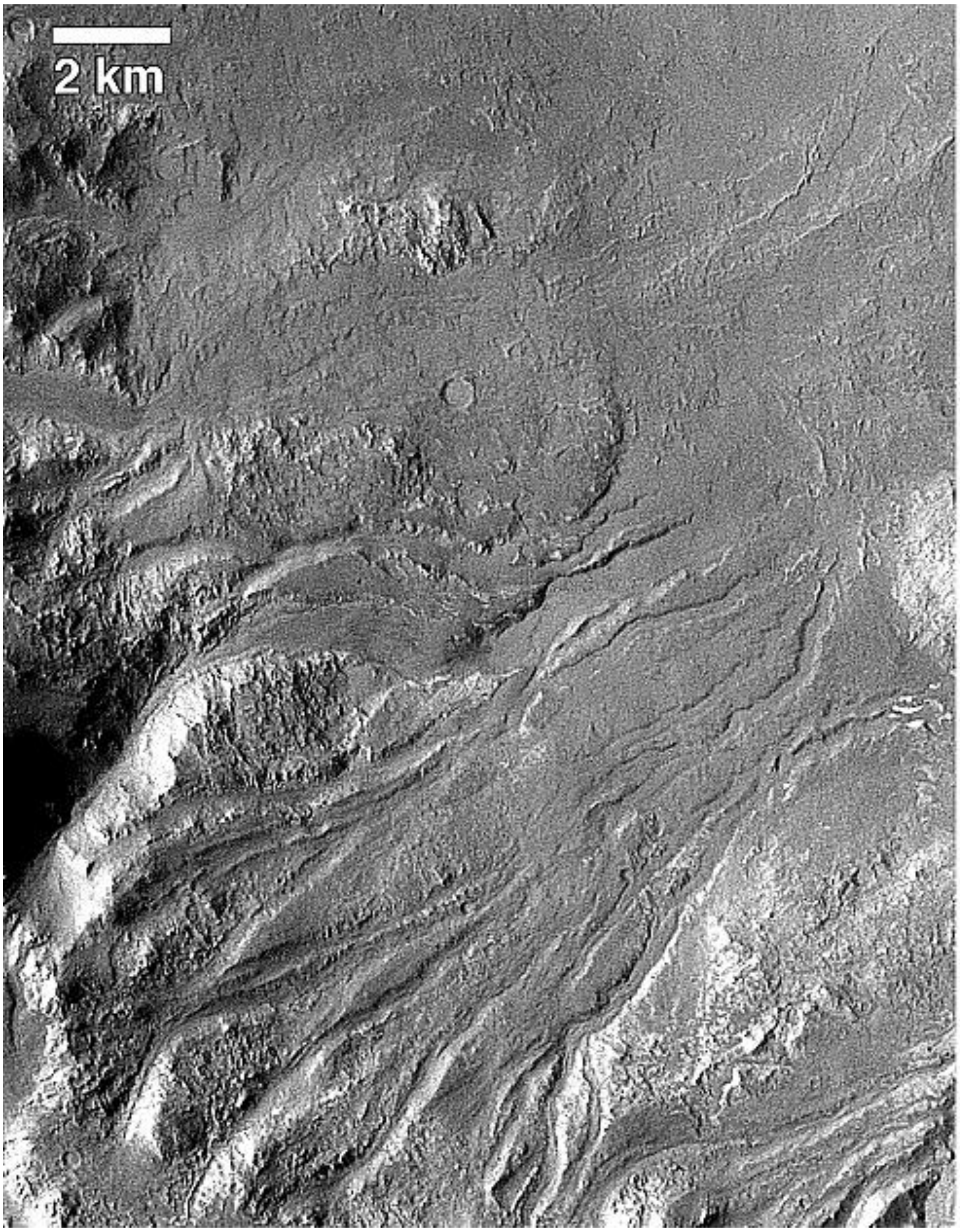
P02_001965_1988_XN_18N281W

Lacustrine environments

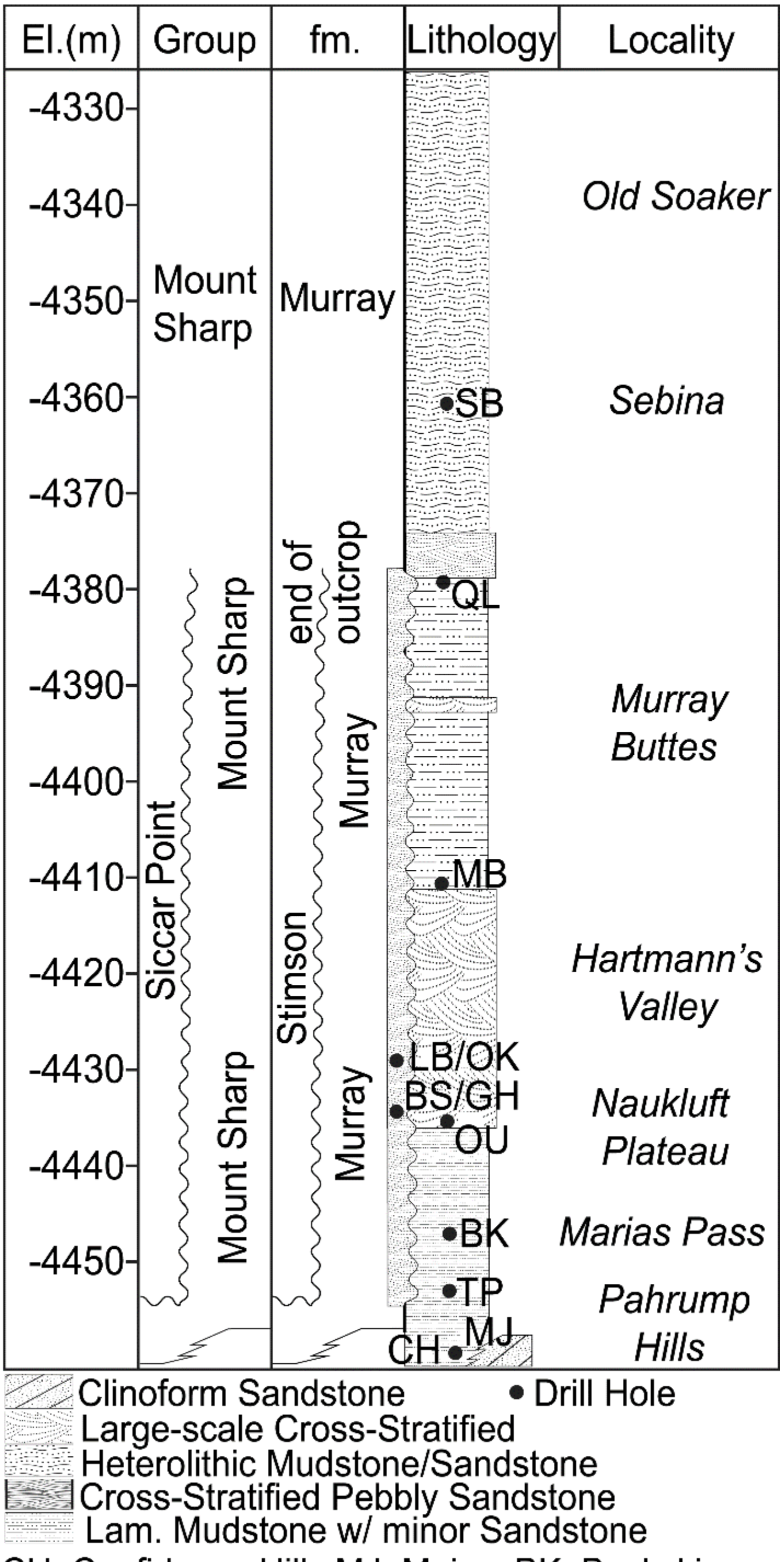


Strata at Jezero crater, modified from (Goudge et al., 2018)

Delta and alluvial fans



THEMIS VIS image V01762003, centered 26.49°S, 34.97°W modified from (Moore and Howard, 2005)



CH, Confidence Hills MJ, MojaveBK, Buckskin
BS/GH, Big Sky/Greenhorn OU, Oudam
TP, Telegraph Peak MB, Marimba QL, Quela
LB/OK, Lubango/Okaruso SB, Sebina

Strata: Stratigraphic column at Gale crater from (Stein et al., 2018)

Appendix II

Other sources for the catalogue

Area of research list

Mars

- Geologic history of Mars: Earth and Planetary Science Letters (Carr and Head, 2010)
- The Geology of Mars: Evidence from Earth-Based Analogs (Chapman, 2007)
- The Sedimentary Cycle on Early Mars (McLennan et al., 2019)
- Water in the history of Mars: An assessment (Rickman et al., 2019)
- Origin of the valley networks on Mars: a hydrological perspective (Gulick, 2001)
- Revisiting subglacial hydrology as an origin for Mars' valley networks (Buffo et al., 2022)
- Automatic mapping of valley networks on Mars (Molloy and Stepinski, 2007)
- River Confluences, Tributaries and the Fluvial Network (Roy et al., 2008)
- Impact craters and the observability of ancient Martian shorelines (Baum et al., 2022)
- Groundwater-controlled valley networks and the decline of surface runoff on early Mars(Harrison and Grimm, 2005)
- Hydrology of early Mars: Valley network incision (Matsubara et al., 2013)
- Valley network-fed, open-basin lakes on Mars: Distribution and implications for Noachian surface and subsurface hydrology (Fassett and Head, 2008)
- Updated global map of Martian valley networks and implications for climate and hydrologic processes (Hynek et al., 2010)
- Basal melting of snow on early Mars: A possible origin of some valley networks (Carr and Head Iii, 2003)
- Interior channels in Martian valley networks: Discharge and runoff production(Irwin et al., 2005)
- Lakes on Mars (Cabrol and Grin, 2010)
- Branching geometry of valley networks on Mars and Earth and its implications for early Martian climate (Seybold et al.)
- Paleolakes on Mars (Wharton et al., 1995)
- Geologic Constraints on Early Mars Climate (Kite, 2019)
- New Evidence of an Ancient Martian Ocean From the Global Distribution of Valley Networks (Chan et al., 2018)
- The Global Distribution of Craters With Alluvial Fans and Deltas on Mars (Wilson et al., 2021)
- Asynchronous formation of Hesperian and Amazonian-aged deltas on Mars and implications for climate (Hauber et al., 2013)
- Experimental delta formation in crater lakes and implications for interpretation of Martian deltas (de Villiers et al., 2013)
- Delta Deposits on Mars: A Global Perspective (De Toffoli et al., 2021)
- Martian stepped-delta formation by rapid water release (Kraal et al., 2008)
- Composition of Deltas and Alluvial Fans on Mars (Carter et al., 2012)
- Large alluvial fans on Mars (Moore and Howard, 2005)

- Geological diversity and microbiological potential of lakes on Mars (Michalski et al., 2022)

Jezero crater

- Perseverance rover reveals an ancient delta-lake system and flood deposits at Jezero crater, Mars (Mangold et al., 2021)
- Stratigraphy and paleohydrology of delta channel deposits, Jezero crater, Mars (Goudge et al., 2018)
- Estimated Minimum Life Span of the Jezero Fluvial Delta (Salese et al., 2020)
- Assessing the mineralogy of the watershed and fan deposits of the Jezero crater paleolake system, Mars (Goudge et al., 2015)
- Photogeologic Map of the Perseverance Rover Field Site in Jezero Crater Constructed by the Mars 2020 Science Team (Stack et al., 2020)
- Sedimentological evidence for a deltaic origin of the western fan deposit in Jezero crater, Mars and implications for future exploration (Goudge et al., 2017b)
- Geologic map of Jezero crater and the Nili Planum region, Mars (Sun and Stack, 2020)

Nili Fossae region

- Fluvial sedimentary deposits on Mars: Ancient deltas in a crater lake in the Nili Fossae region (Fassett and Head, 2005)
- Geologic map of Jezero crater and the Nili Planum region, Mars (Sun and Stack, 2020)

Gale Crater

- Multiple stages of aqueous alteration along fractures in mudstone and sandstone strata in Gale Crater, Mars (Yen et al., 2017)
- Desiccation cracks provide evidence of lake drying on Mars, Sutton Island member, Murray formation, Gale Crater (Stein et al., 2018)
- Mineralogy and stratigraphy of the Gale crater rim, wall, and floor units (Buz et al., 2017).
- Alternating wet and dry depositional environments recorded in the stratigraphy of Mount Sharp at Gale crater, Mars (Rapin et al., 2021).
- Redox stratification of an ancient lake in Gale crater, Mars (Hurowitz et al., 2017).
- Do Deltas Along the Crustal Dichotomy Boundary of Mars in the Gale Crater Region Record a Northern Ocean? (Rivera-Hernández and Palucis, 2019)

Terra Sabaea

- Inverted fluvial channels in Terra Sabaea, Mars: Geomorphic evidence for proglacial paleolakes and widespread highlands glaciation in the Late Noachian–Early Hesperian (Boatwright and Head, 2023)

Sinton crater

- Sinton crater, Mars: Evidence for impact into a plateau icefield and melting to produce valley networks at the Hesperian–Amazonian boundary (Morgan and Head, 2009)

Northern lowlands

- Ancient ocean on Mars supported by global distribution of deltas and valleys (Di Achille and Hynek, 2010)

Margaritifer Sinus region

- Hypsometric analysis of Margaritifer Sinus and origin of valley networks(Luo, 2002)

Western Memnonia

- Terraces and Gilbert-type deltas in crater lakes in Ismenius Lacus and Memnonia (Ori et al., 2000)

Ismenius Lacus

- Terraces and Gilbert-type deltas in crater lakes in Ismenius Lacus and Memnon (Ori et al., 2000)
- Outflow channels with deltaic deposits in Ismenius Lacus, Mars (Mangold and Howard, 2013)

Eberswalde crater

- Evolution and depositional environments of the Eberswalde fan delta, Mars(Pondrelli et al., 2008)
- The origin and timing of fluvial activity at Eberswalde crater, Mars (Mangold et al., 2012)
- Mars: The Morphological Evidences of Late Amazonian Water Activity in Shalbatana Vallis (Kuzmin et al., 2002)

Chryse basin

- Hypotheses for the origin of the Hypanis fan-shaped deposit at the edge of the Chryse escarpment, Mars: Is it a delta? (Adler et al., 2019)

Shalbatana Vallis

- Positive identification of lake strandlines in Shalbatana Vallis, Mars (Di Achille et al., 2009)
- Evidence for late Hesperian lacustrine activity in Shalbatana Vallis, Mars (Di Achille et al., 2007)
- Matching shorelines and fan-delta fronts indicate young (Early Amazonian) lacustrine activity in Shalbatana Vallis, Mars (Di Achille, 2006)

Holden Crater

- Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars (Malin and Edgett, 2003)
- HiRISE imaging of impact megabreccia and sub-meter aqueous strata in Holden Crater, Mars (Grant et al., 2008)
- Dynamic river channels suggest a long-lived Noachian crater lake on Mars (Bhattacharya et al., 2005)

Tharsis region

- Subglacial catastrophic-flood origin of linear and curvilinear flat-rimmed pit chains on Mars: Evidence from geomorphological mapping and detailed landsystem analysis (Kakaria and Yin, 2023).

Valley networks List

- An overview of geological results from Mariner 9 (Masursky, 1973)
- The Geology of Mars: Evidence from Earth-Based Analogs (Chapman, 2007)
- Stratigraphy and paleohydrology of delta channel deposits, Jezero crater, Mars (Goudge et al., 2018)
- Origin of the valley networks on Mars: a hydrological perspective (Gulick, 2001)
- Morphological and hydrological analysis of volcanic flank valleys – Evidence for a volcanic origin (Bahia, 2022)

- Terrestrial martian analogues from the Indian subcontinent: Implications for hydrological activity on Mars (Chavan et al., 2022)
- Revisiting subglacial hydrology as an origin for Mars' valley networks (Buffo et al., 2022)
- Automatic mapping of valley networks on Mars (Molloy and Stepinski, 2007)
- River Confluences, Tributaries and the Fluvial Network (Roy et al., 2008)
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- Lakes on Mars (Cabrol and Grin, 2010)
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Lacustrine environments

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- Geological diversity and microbiological potential of lakes on Mars (Michalski et al., 2022)

Delta

- Perseverance rover reveals an ancient delta-lake system and flood deposits at Jezero crater, Mars (Mangold et al., 2021)
- The Geology of Mars: Evidence from Earth-Based Analogs (Chapman, 2007)
- Lakes on Mars (Cabrol and Grin, 2010)
- Ancient ocean on Mars supported by global distribution of deltas and valleys
- Geologic Constraints on Early Mars Climate (Kite, 2019)
- The Global Distribution of Craters With Alluvial Fans and Deltas on Mars (Wilson et al., 2021)
- Asynchronous formation of Hesperian and Amazonian-aged deltas on Mars and implications for climate (Hauber et al., 2013)
- Palaeoflow reconstruction from fan delta morphology on Mars (Kleinhans et al., 2010)
- Fluvial sedimentary deposits on Mars: Ancient deltas in a crater lake in the Nili Fossae region (Fassett and Head, 2005)
- Terraces and Gilbert-type deltas in crater lakes in Ismenius Lacus and Memnon (Ori et al., 2000)
- Experimental delta formation in crater lakes and implications for interpretation of Martian deltas (de Villiers et al., 2013)
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- Martian stepped-delta formation by rapid water release (Kraal et al., 2008)
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- Hypotheses for the origin of the Hypanis fan-shaped deposit at the edge of the Chryse escarpment, Mars: Is it a delta? (Adler et al., 2019)
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- Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars (Malin and Edgett, 2003)

- Assessing the mineralogy of the watershed and fan deposits of the Jezero crater paleolake system, Mars (Goudge et al., 2015)
- Photogeologic Map of the Perseverance Rover Field Site in Jezero Crater Constructed by the Mars 2020 Science Team (Stack et al., 2020)
- Sedimentological evidence for a deltaic origin of the western fan deposit in Jezero crater, Mars and implications for future exploration (Goudge et al., 2017b)

Channel deposit

- Outflow channels with deltaic deposits in Ismenius Lacus, Mars (Mangold and Howard, 2013)
- Stratigraphy and paleohydrology of delta channel deposits, Jezero crater (Goudge et al., 2018)
- An overfilled lacustrine system and progradational delta in Jezero crater, Mars: Implications for Noachian climate (Schon et al., 2012)
- Resolving the era of river-forming climates on Mars using stratigraphic logs of river-deposit dimensions(Kite et al., 2015)

- The Geology of Mars: Evidence from Earth-Based Analogs (Chapman, 2007)
- Stratigraphy and paleohydrology of delta channel deposits, Jezero crater, Mars (Goudge et al., 2018)
- Outflow channels with deltaic deposits in Ismenius Lacus, Mars (Mangold and Howard, 2013)

Flood deposit

- Paleohydrology of Eberswalde crater, Mars (Irwin et al., 2015)

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- Outflow channels with deltaic deposits in Ismenius Lacus, Mars (Mangold and Howard, 2013)
- Subglacial catastrophic-flood origin of linear and curvilinear flat-rimmed pit chains on Mars: Evidence from geomorphological mapping and detailed landsystem analysis (Kakaria and Yin, 2023)

Alluvial Fans

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- Geologic Constraints on Early Mars Climate (Kite, 2019)
- The Global Distribution of Craters With Alluvial Fans and Deltas on Mars (Wilson et al., 2021)

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- Evidence for Persistent Flow and Aqueous Sedimentation on Early Mars (Malin and Edgett, 2003)
- Large alluvial fans on Mars (Moore and Howard, 2005)

Sedimentary structure

- Perseverance rover reveals an ancient delta-lake system and flood deposits at Jezero crater, Mars (Mangold et al., 2021).
- Desiccation cracks provide evidence of lake drying on Mars, Sutton Island member, Murray formation, Gale Crater (Stein et al., 2018).
- Mineralogy and stratigraphy of the Gale crater rim, wall, and floor units (Buz et al., 2017)
- The Sedimentary Cycle on Early Mars (McLennan et al., 2019)
- Multiple stages of aqueous alteration along fractures in mudstone and sandstone strata in Gale Crater, Mars (Yen et al., 2017)
- Stratigraphy and paleohydrology of delta channel deposits, Jezero crater, Mars (Goudge et al., 2018)
- Alternating wet and dry depositional environments recorded in the stratigraphy of Mount Sharp at Gale crater, Mars (Rapin et al., 2021).

Strata

- Perseverance rover reveals an ancient delta-lake system and flood deposits at Jezero crater, Mars (Mangold et al., 2021)
- Multiple stages of aqueous alteration along fractures in mudstone and sandstone strata in Gale Crater, Mars (Yen et al., 2017)
- Desiccation cracks provide evidence of lake drying on Mars, Sutton Island member, Murray formation, Gale Crater (Stein et al., 2018).
- Alternating wet and dry depositional environments recorded in the stratigraphy of Mount Sharp at Gale crater, Mars (Rapin et al., 2021).
- The Sedimentary Cycle on Early Mars (McLennan et al., 2019)
- Mineralogy and stratigraphy of the Gale crater rim, wall, and floor units (Buz et al., 2017)
- Stratigraphy and paleohydrology of delta channel deposits, Jezero crater, Mars (Goudge et al., 2018)
- Redox stratification of an ancient lake in Gale crater, Mars (Hurowitz et al., 2017)
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- Sedimentological evidence for a deltaic origin of the western fan deposit in Jezero crater, Mars and implications for future exploration (Goudge et al., 2017b)

- Geologic map of Jezero crater and the Nili Planum region, Mars (Sun and Stack, 2020)
- HiRISE imaging of impact megabreccia and sub-meter aqueous strata in Holden Crater, Mars (Grant et al., 2008)

Grain size

- Desiccation cracks provide evidence of lake drying on Mars, Sutton Island member, Murray formation, Gale Crater (Stein et al., 2018)

Mineralogy

- Mineralogy and stratigraphy of the Gale crater rim, wall, and floor units (Buz et al., 2017)
- Redox stratification of an ancient lake in Gale crater, Mars (Hurowitz et al., 2017)

- Assessing the mineralogy of the watershed and fan deposits of the Jezero crater paleolake system, Mars (Goudge et al., 2015)
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- Sedimentological evidence for a deltaic origin of the western fan deposit in Jezero crater, Mars and implications for future exploration (Goudge et al., 2017b)

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