

INTERIOR LAYERED DEPOSITS
IN CHAOTIC TERRAINS
ON MARS

Mariam Sowe



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Erstgutachter: Prof. Dr. Ralf Jaumann
Freie Universität Berlin
Institut für Geologische Wissenschaften
Fachrichtung Planetologie und Fernerkundung
sowie
Deutsches Zentrum für Luft- und Raumfahrt
Institut für Planetenforschung, Abt. Planetengeologie

Zweitgutachter: Prof. Dr. Gerhard Neukum
Freie Universität Berlin
Institut für Geologische Wissenschaften
Fachrichtung Planetologie und Fernerkundung

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Eidesstattliche Erklärung

Hiermit versichere ich, die vorliegende Arbeit selbständig und nur mit den angegebenen Hilfsmitteln anfertigt, sowie an keiner anderen Hochschule eingereicht habe.

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ABSTRACT

This work describes the investigation of interior layered deposits (ILDs) situated in eastern Valles Marineris and its adjacent chaotic terrains on Mars. It combines various data sets such as high-resolution image, elevation and spectral data in a comparative study of ILDs to study their morphology, albedo, elevation, thickness, consolidation, mineralogy and layering geometry in order to assess possible correlations and deduce adequate formation hypotheses.

The characterisation of ILDs shows that they vary in terms of erosional shape, thickness, elevation, material consolidation and mineralogy, but are mostly comparable concerning their morphologies. On the tops of ILDs, two different morphological types were detected which correlate with respect to their mineralogy. At the same time, they differ in their albedo as well as in their state of weathering and erosion. Oddly enough, there is no correlation with elevation, thickness, or consolidation that could reinforce the above correlation. However, hydrated ILDs are mostly located in protected areas and highly affected by rock break-up whereas non-hydrated ILDs are located in discharge areas and are hardly affected by this process. The different hydration states of sulphates demonstrate post-formation humidity changes. Thus, the presence of water within the ILD could be responsible for their weathering (e.g. frost weathering) resulting in volume changes, jointing and rock fragmentation into boulders. Convolute bedding may also point to dehydration. The former water level –indicated by hydrated minerals – is much higher in Valles Marineris than in chaotic terrain ILDs. Altogether, water was present at the base of some ILDs as well as on their top. ILDs are not always located in the deepest area of the depression and thus could represent eroded material, indicating a much larger extent in the past. Stair-stepped morphologies have been observed suggesting alternating strata of competent and less competent material. Actually, thickly bedded lower units and thinly layered upper units could indicate changes in the depositional process. Moreover, ILD material is highly consolidated, which is confirmed by meter-sized boulders and talus at the base of their steep scarps. The consolidation of ILDs deduced from their thermal inertia indicates both rock and loose material whereas the loose aeolian material mostly covers their tops. Impact craters are rare on ILDs indicating a young Amazonian age. Since erosion on Mars has been more intense in the Hesperian and ILDs are heavily eroded, this age is their erosional rather than their depositional age. Thus ILDs must have formed in the Hesperian and were eroded into the Amazonian.

In this study it is shown that the observations are consistent with criteria of two of the discussed seven hypotheses. ILDs show morphological and mineralogical similarities to spring deposits and lacustrine deposits. Likewise their distribution and geographical position is linked to aqueous processes. Thus ILDs could have formed in closed or partly closed depressions that were fed by water through aquifers or frost layers from the walls or hydrothermal fluids and springs from the subsurface. A combination of these water sources would explain the differences in ILD mineralogy whereas layering is explained by episodic processes and the density contrasts between brine and water, evaporite particles and clastic components. Sulphate formation must have taken place by evaporation and

material that was already in the system (e.g. wall rock, aeolian, volcanic material) was embedded in deposition which might explain the high thicknesses observed for some Valles Marineris ILDs.

Kurzfassung

Diese Arbeit liefert Erkenntnisse über Interior Layered Deposits (ILDs) im östlichen Valles Marineris und den angrenzenden chaotischen Gebieten auf dem Mars. In dieser Arbeit werden verschiedene Datensätze wie hochauflösende Bild-, Höhen- und Spektraldatensätze im Rahmen einer vergleichenden Studie verwendet, um die Morphologie, Albedo, absolute Höhe, Mächtigkeit, Verfestigung, Farbe, Mineralogie und Schichtgeometrie zu untersuchen und vorhandene Korrelation aufzuzeigen und geeignete Bildungshypothesen abzuleiten.

Die Beschreibung der ILDs nach den genannten Parametern zeigt dass Erosionsgestalt, Mächtigkeit, Höhe, Materialverfestigung schwankt und vereinzelt sogar die Mineralogie in jedem Fall aber morphologische Einheiten zwischen den ILDs wieder zu finden sind. Die Oberflächen an den Tops der ILDs unterscheiden sich, was zu einer Einteilung in zwei Klassen führt die mineralogisch korrelieren. Gleichzeitig unterscheiden sich beide Klassen anhand ihrer Albedo, dem Verwitterungszustand und der Erosion. Seltsamerweise tritt keine eindeutige Korrelation mit der Höhe, Mächtigkeit oder Verfestigung auf. Hydratisierte ILDs sind häufig in geschützten Bereichen vorzufinden und ihr Gefüge ist stärker zerrüttet als das der nicht hydratisierten ILDs, die in Durchflussbereichen gelegen sind. Unterschiede im Wasserhaushalt der Sulfate deuten auf Feuchtigkeitsänderungen hin welche vermutlich nach der ILD Bildung auftraten. Das Wasser in den ILDs könnte daher für deren Verwitterung verantwortlich sein (z.B. Frostsprengung) welche zu Volumenänderungen im Gestein sowie Klüftung und Zerstückelung in Blöcke führen kann. Ebenso weisen Strukturen, die zusammengerollter Schichtung ähneln, auf Entwässerung und Änderungen in der Hydratisierung hin. Die Höhe des ursprünglichen Wasserstands – angezeigt durch hydratisierte Minerale- ist viel höher in den Valles Marineris als in den chaotischen Gebieten. Insgesamt war Wasser sowohl an der Basis als auch am Top einiger ILDs vorhanden. Da ILDs nicht immer in den tiefsten Stellen der Depressionen zu finden sind, könnten sie erodierte Reste anzeigen und ihre Ausbreitung wäre somit größer als derzeit beobachtet. Die Schichtstufenmorphologie der ILDs zeigt Unterschiede in der Materialverfestigung an. Vereinzelt werden massige dickbankige Sequenzen unterhalb von feineren dünnbankigen beobachtet welche Änderungen im Ablagerungsprozess anzeigen. ILDs bestehen aus stark verfestigtem Material, was durch metergroße Blöcke und Schutt an der Basis steiler Hänge bestätigt wird. Die Verfestigung der ILDs, die von ihrer thermalen Trägheit abgeleitet wird deutet auf Gesteinsmaterial wie auf Lockermaterial hin, wobei äolisches Lockermaterial meist ihr Top bedeckt. ILDs haben kaum Impaktkrater und zeigen somit ein junges Alter (Amazonium) an. Da die Erosion im Hesperium stärker war und ILDs stark erodiert sind, entspricht dieses Alter eher ihren Erosions- als ihrem Ablagerungsalter.

In dieser Arbeit wird gezeigt, dass die Beobachtungen mit Kriterien von zwei der diskutierten sieben Bildungshypothesen vereinbar sind. ILDs haben morphologische und mineralogische Ähnlichkeiten mit Quell- und Seeablagerungen. Ebenso steht ihre Verteilung und geographische Lage im Zusammenhang mit aquatischen Prozessen. ILDs haben sich vermutlich in geschlossenen bzw. halbgeschlossenen Becken gebildet haben deren Wasserzufluss durch Grundwasserleiter und Frostsichten aus den Wänden oder

hydrothermale Fluide und Quellen aus dem Untergrund gesichert war. Die Verknüpfung dieser Wasserquellen könnte auch die mineralogischen Unterschiede der ILDs erklären wohingegen die Schichtung durch episodische Prozesse und Dichtekontraste zwischen Salzlauge und Wasser, Evaporitpartikeln und klastischen Komponenten gewährleistet wurde. Die Sulfatbildung konnte durch Evaporation erfolgen und Material, das sich schon im System befand (z.B. Wandmaterial, äolisches, vulkanisches Material) wurde bei der Ablagerung miteingebunden wodurch die hohen Mächtigkeiten einiger ILDs im Valles Marineris erklärbar sind.

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LIST OF ABBREVIATIONS

ASCII	American Standard Code for Information Interchange
ASU	Arizona State University
BT	Brightness Temperature
cf.	confer
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
DEM/ DTM	Digital Elevation Model/ Digital Terrain Model
DLR	German Aerospace Center, <i>Deutsches Zentrum für Luft- und Raumfahrt e. V.</i>
ENVI	Environment for Visualising Images
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
Fig.	Figure
FUB	Freie Universität Berlin
GIS	Geographic Information System
HCP	High Calcium Pyroxene (comparable to clinopyroxene)
HiRISE	High Resolution Imaging Science Experiment
HRSC	High Resolution Stereo Camera
IDL	Interactive Data Language
ILD(s)	Interior Layered Deposit(s)
ISIS	Integrated Software for Imaging Spectrometers
LCP	Low Calcium Pyroxene (comparable to orthopyroxene)
MER	Mars Exploration Rovers
MEX	Mars Express
MGS	Mars Global Surveyor
MO	Mars Odyssey
MOC (NA)	Mars Orbiter Camera (narrow angle)
MOLA	Mars Orbiter Laser Altimeter
MRO	Mars Reconnaissance Orbiter
MSSS	Malin Space Science Systems
NASA	National Aeronautics and Space Administration
NIR	Near-Infrared
OMEGA	Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité
PHS	Polyhydrated sulphates
Sect.	Section
SI	Système International d'Unités
TES	Thermal Emission Spectrometer
THEMIS	Thermal Emission Imaging Spectrometer
TI	Thermal Inertia
TIR	Thermal Infrared
USGS	United States Geological Survey
VICAR	Video Image Communication Retrieval
VNIR	Visible-Near Infrared

CHAPTER 1 INTRODUCTION AND MOTIVATION

Mars is a terrestrial and the most Earth-like planet, which makes it important for comparative planetology. Since 1996, several successful orbiters and landers especially of ESA and NASA have explored its surface providing excellent imaging as well as spectral and elevation data [*Malin et al.*, 1992; *Christensen et al.*, 1999; *Christensen et al.*, 2001a; *Squyres et al.*, 2003; *Bibring et al.*, 2004; *Jaumann et al.*, 2007; *McEwen et al.*, 2007; *Murchie et al.*, 2007]. Although, the Mars currently appears very cold and dry, its surface exhibits many features such as fluvial morphologies [*Sharp and Malin*, 1975] indicating the presence of water in the Noachian and Hesperian period and thus warmer and wetter conditions. The analysis of water-related surface features in turn is essential for understanding the climatic and atmospheric conditions with time and thus reconstructs the geologic evolution.

Dominantly, the Martian surface looks reddish due to iron oxide but in several regions, light-toned, layered deposits are exposed [*McCauley*, 1978]. These are called Interior Layered Deposits (ILDs) and are associated with depressions, i.e. chasmata, and craters that are linked to chaotic terrain. These are present throughout the whole Valles Marineris in several chasmata as well as in the adjacent eastern chaotic terrains, which occur mainly in Noachian-aged impact craters and lead into the Late Hesperian-aged outflow channels [*Scott and Tanaka*, 1986].

ILDs stand out from the surrounding terrain because of their distinct layering, high albedo, morphology and high nighttime TI and brightness-temperature [e.g. *Catling et al.*, 2006, *Sowe et al.*, 2008]. Their surface composition of sulphates and haematite [*Gendrin et al.*, 2005; *Glotch and Christensen*, 2005] indicates aquatic conditions prevailing during their formation. Sulphates and haematite in turn are supposed to have formed successively after the Martian climate changed due to ceasing volcanic activity in the Late Noachian/Early Hesperian [*Bibring et al.*, 2006]. Groundwater upwelling and evaporation must have dominantly contributed to the alteration of rocks [*Andrews-Hanna et al.*, 2007b].

Thus, analysing ILDs is an excellent possibility to get insights to the Martian climatic conditions at the time when the sulphates and haematite were formed, which directly indicate water availability for longer time periods. Both mineral groups reveal certain temperatures and eh /pH-conditions they require for their formation [*Matthes*, 2001] that are essential to constrain the physical and chemical surface and subsurface conditions at that time.

The exact age of the ILDs is uncertain, as there are hardly any impact craters on their surface. This fact could be explained by the heavily eroded nature and aeolian coverage of ILDs. However, a relative stratigraphic age is deduced from the location of the exposure [*Komatsu et al.*, 1993] e.g. on chaotic terrain. Based on the fact of relative stratigraphy, ILD formation can be incorporated into the Martian chronology [*Tanaka*, 1986; *Hartmann and Neukum*, 2001]. However, few crater countings were performed to constrain erosional surface ages of ILDs. For Valles Marineris a Late Hesperian up to Amazonian age is estimated [*Lucchitta*, 1999]. Contrary for Juventae Chasma a young age of Late Amazonian was dated by *Neukum et al.* (2007). Referring to *Rossi et al.* (2008), ILDs in

chaotic terrains show an erosional age of the Late Amazonian.

ILDs have been known and analysed for many decades but their origin is still unknown and intensely debated. The following hypotheses are being discussed at the moment:

- ILDs are ancient deposits (glacial, lacustrine or aeolian) that are exposed by erosion [*Malin and Edgett, 2000*] and formed prior to the formation of Valles Marineris;
- ILDs are made of volcanic material generated by subaeric pyroclastic volcanism [*Peterson, 1981; Chapman and Tanaka, 2002; Hynek et al., 2002*], sub-glacial volcanism [*Chapman and Tanaka, 2001*] or volcanic flows [*Lucchitta, 1981; Lucchitta et al., 1992; Lane and Christensen, 1998*] during and after the formation of Valles Marineris;
- ILDs were deposited in a lacustrine environment [*McCauley, 1978; Nedell et al., 1987; McKay and Nedell, 1988*] after the formation of Valles Marineris;
- by spring deposits [*Rossi et al., 2007; 2008*], or formed by
- salt diapirism [*Milliken et al., 2007*] after the formation of Valles Marineris.

Furthermore, a combination of different processes is conceivable emanating from the volcano-tectonic setting of the Valles Marineris [*Lucchitta et al., 1992*] in which ILDs are located and in addition aeolian processes that are still active on Mars [*Greeley et al., 1992*].

The objective of this study is to characterise ILDs by their morphology, albedo, elevation, thickness, material consolidation, colour, mineralogy, and layering geometry in order to perform a comparative study and discuss their formation processes. The study area (18°S/309°E to 5°N/343°E) is located near the equator -between Ganges Chasma in the west and Iani Chaos in the east. The key aspect of this thesis is to determine whether there is a common stratigraphic level in order to assess possible correlations between ILDs. Correlations between ILDs could potentially indicate a corresponding mode of formation for it is still unknown whether all ILDs were formed similarly. Consequently, ILDs will be analysed on the basis of high-resolution image- and elevation data, and spectral data.

Altogether, this comprehensive evaluation of different data sets adds fresh insights to modelling ILD formation. For the first time the named parameters were studied statistically. Thus, the main objective of this study is to characterise ILDs geologically, mineralogically and statistically with respect to their distribution and correlations in order to constrain climatic conditions and formation processes.

First, the history, atmosphere, climate, and geology of the planet Mars will be outlined to provide an impression of the planet itself and the surface processes that are taking place there. Afterwards the relationship between ILDs on the one hand and the Valles Marineris and chaotic terrains on the other will be described, together with morphological terrestrial analogies.

Datasets and methodology are presented in the following section to describe the content and accuracies of the data.

The major part of the investigation consists of mapping, geomorphological, geological, and mineralogical analysis, and comparisons of ILDs. Differences and similarities will be

discussed in order to identify possible formation processes. Finally, the formation of the units is discussed based on observations and their analyses.