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1 **SUSTAINED FLUVIAL DEPOSITION RECORDED IN MARS' NOACHIAN STRATI-**
2 **GRAPHIC RECORD**

3 **Francesco Salese^{1,2,†*}, William J. McMahon^{1,†}, Matthew R. Balme³, Veronique Ansan⁴,**
4 **Joel M. Davis⁵ and Maarten G. Kleinhans¹**

5 ¹Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands

6 ²International Research School of Planetary Sciences, Università Gabriele D'Annunzio, Pescara, Italy

7 ³Planetary Environments Group, Open University, Walton Hall, Milton Keynes, UK

8 ⁴LPG Nantes, UMR6112, CNRS-Université de Nantes, 2 rue de la Houssinière, BP 92208, 44322, Nantes cédex 3, France

9 ⁵Department of Earth Sciences, Natural History Museum, Cromwell Road, Kensington, London, SW7 5BD, UK.

10 * Corresponding author e-mail f.salese@uu.nl.

11 † These authors contributed equally to this work.

12 **ABSTRACT**

13 Orbital observation has revealed a rich record of fluvial landforms on Mars, with much of this
14 record dating 3.6-3.0 Ga. Despite widespread geomorphic evidence, few analyses of Mars' alluvial
15 sedimentary-stratigraphic record exist, with detailed studies of alluvium largely limited to smaller
16 sand-bodies amenable to study in-situ by rovers. These typically metre-scale outcrop dimensions
17 have prevented interpretation of larger scale channel-morphology and long-term basin evolution,
18 vital for understanding the past martian climate. Here we give an interpretation of a large sedimen-
19 tary succession at Izola mensa within the NW Hellas Basin rim. The succession comprises channel
20 and barform packages which together demonstrate that river deposition was already well estab-
21 lished >3.7 Ga. The deposits mirror terrestrial analogues subject to low-peak discharge variation,
22 implying that river deposition at Izola was subject to sustained, potentially perennial, fluvial flow.
23 Such conditions would require an environment capable of maintaining large volumes of water for
24 extensive time-periods, necessitating a precipitation-driven hydrological cycle.

25

26

27 INTRODUCTION

28 While the present-day martian surface is generally dry and cold, its geomorphic record contains
29 compelling evidence for the former presence of liquid water¹⁻⁷. In addition to this rich geomorphic
30 archive, Mars' increasingly accessible sedimentary rock record provides a repository of infor-
31 mation from which to study how planet-wide patterns in deposition have changed over time. From
32 orbit, martian sedimentary rocks have been observed for more than twenty years⁸⁻¹³, but detailed
33 descriptions of large Noachian alluvial successions have so far been lacking. In fact, unequivocal
34 sedimentary-stratigraphic evidence of alluvium has only been identified in-situ by rover-led stud-
35 ies¹⁴, and whilst rovers provide unprecedented direct access to extraterrestrial strata¹⁵, methodol-
36 ogies are typically limited by accessible outcrop dimensions. For example, the Shaler outcrop, an
37 interpreted Hesperian fluvial deposit identified by Curiosity¹⁶, comprises a single 70-centimetre
38 thick, 20-metre wide sandstone-body. This is a crucial scale difference when compared with orbital
39 investigation: the physical dimensions of most rock outcrops studied on the ground to date are
40 smaller than the dimensions of many geomorphic components of even moderate-sized extant river
41 systems^{17,18}.

42 In this study we use High Resolution Imaging Science Experiment (HiRISE) image (25 cm/pixel)
43 and topographic (1 m/pixel) data to describe the sedimentary-stratigraphic architecture of a far-
44 larger, 1500-metre-wide, 190-metre-thick sedimentary succession. The recently identified Izola
45 outcrop is located in the northwestern rim of the Hellas basin (Fig. 1A), a ~ 2000 km diameter
46 impact structure containing a variety of 3.7 Ga Noachian Fe/Mg phyllosilicate-rich sedimentary
47 intercrater plains, overlain by Hesperian-aged (~3.3 Ga) lava flows¹⁹.

48 These intercrater plains offer erosional windows which expose stratigraphic sections with well-
49 preserved channel-forms, and which must be older than the ~3.7 Ga overlying plains¹⁹. The chan-
50 nel-forms and associated sedimentary packages are interpreted as the product of an actively de-
51 positing fluvial system, with the final sedimentary architecture suggesting that these Noachian-
52 aged rivers were not typified by high-energy episodic floods, but rather perennial or semi-perennial
53 fluvial flow. The scale and completeness of the sedimentary succession offers a so far unique op-
54 portunity to assess the larger-scale morphology of an evolving Noachian-aged fluvial system.

55

56 **RESULTS AND DISCUSSION**

57 **The Sedimentary Succession**

58 The outcrop exposes layered sedimentary strata which display a variety of large-scale stratal ar-
59 chitectures consistent with an alluvial interpretation. Alluvial sedimentary strata can be subdivided
60 into genetically related three-dimensional packages²⁰⁻²². The aggregate of these packages is re-
61 ferred to as the succession's sedimentary architecture, and is the product of the scale and behavior
62 of the fluvial system over time. The outcrop appears to have undergone little post-depositional
63 deformation, has a gentle dip and large-dimensions, so is suitable for the analysis of sedimentary
64 architecture (Supplementary Figure 5). A hierarchy of bounding surfaces is applied to divide stra-
65 tigraphy, hierarchically ordered to reflect river processes at varying scales (Table 1, Supplemen-
66 tary Figure 1). Two distinct sedimentary packages were recognized in the studied outcrop: 1) chan-
67 nelled packages; and 2) inclined accretionary surfaces. As details of sedimentary facies (usually
68 discriminated by grain size and centimetre to decimetre-scale bedding and sedimentary structure)

69 are unattainable without in-situ investigation on the ground, only the three-dimensional geometry
70 of the sedimentary packages are described, with no details of internal structure attempted.

71 **Channelized Packages**

72 In the observed stratigraphy, packages bound by lower erosional, channel-shaped (fourth-order)
73 surfaces and truncated by flat, erosional (fourth- and fifth-order) surfaces are attributed to channel-
74 fill deposition (Fig. 2, Fig. 3B, Supplementary Figure 2A). They are 5 to 15 metres thick, with
75 observable lateral extents of up to 210 metres (although outcrop limitations restrict observation of
76 the full lateral extent of many channel-forms: Table 2, Supplementary Figure 2). Internally, pack-
77 ages appear succession-dominated²³, comprising multiple aggrading (third-order) surfaces (Fig.
78 3B). Final channel banks and former channel margins coalesce, indicating that the original chan-
79 nels laterally migrated (Fig. 3B, 3D). Some channelized packages have a distinct channel wing
80 (yellow asterisks in Fig. 2B; Supplementary Figure 3-4), which may archive a genetically associ-
81 ated levee or crevasse and thus strengthen the alluvial interpretation. Particular areas of the outcrop
82 show high concentrations of discrete, but partly amalgamated, channelized packages (Fig. 3B). In
83 these areas, smaller channelized packages may be nested inside larger examples (Fig. 3B), imply-
84 ing that periods of net-erosion locally occurred within a dominantly depositional regime. Areas
85 containing clusters of channels are bottomed and topped by laterally extensive (up to 640 metre),
86 low relief, fifth-order surfaces, which suggest a change in the type or location of the dominant
87 depositional process. These surfaces probably reflect channel avulsion, in which the location of
88 the active channel changes abruptly. The sediments enclosed between these fifth-order surfaces
89 were therefore laid down between avulsion events and are thus defined as channel-belts²⁴.

90 **Inclined Accretionary Surfaces**

91 In the observed stratigraphy, wedge-shaped packages comprise gently inclined depositional sur-
92 faces (third and fourth order; Fig. 3D). They are topped and bottomed by flat, erosional surfaces
93 (both fourth order), except on occasions where they can be traced laterally into an associated chan-
94 nelized package (Fig. 3B). Most frequently only erosional remnants are preserved, with deposits
95 often passing laterally into areas of non-exposure (Fig. 3D). Thicknesses range from 1.5 to 14
96 metres, similar to the associated channels. Geometry and internal stacking patterns are suggestive
97 of shifting fluvial barforms. For example, in some instances, bottomsets of fourth order surfaces
98 are downlapped by third order foresets (Fig. 3D), demonstrating discrete intervals of bar-building.
99 The outcrop orientation with respect to paleoflow is not well known, meaning it is not possible to
100 build any unequivocal consensus on the direction of barform accretion with respect to the flow of
101 the original channels (e.g., downstream accretion, lateral accretion). However, the identification
102 of channel-forms in conjunction with the outcrops alignment with the regional slope direction sug-
103 gests a broadly depositional-strike succession.

104 **Alternative Explanations**

105
106 Without in-situ validation of fluvial deposition other alternative possibilities must additionally be
107 considered. In this section we examine two alternative origins for the studied sedimentary succes-
108 sion: aeolian deposition, and deposition within submarine channels.

109 Aeolian: if these deposits are have an aeolian origin, then the working hypothesis is that the chan-
110 nel-forms are in fact localised scour fills formed by migrating aeolian strata, and that this succes-
111 sion records periods of aeolian accumulation punctuated by erosion or stagnation. However, there
112 are disconnects between the stratigraphic architecture described here, and that of large-scale cross-
113 bedding typical of aeolian bedforms described on both Earth^{25,26} and Mars²⁷. No aeolian interpre-

114 tation can explain the observable lateral migration surfaces associated with the discrete channel-
115 ized packages (Fig. 3B). Multiple generations of aeolian dunes would partially erode preceding
116 examples, perceived at outcrop by marked downlapping surfaces not apparent anywhere across the
117 succession. Also, the fill geometry of aeolian dune deposits is often symmetrical and concordant
118 with the trough base, unless the final outcrop is cut obliquely to the original flow direction, in
119 which case planes are perceived to fill asymmetrically and downlap onto the trough base²⁸ (again,
120 an architectural style not recognised here). Finally, multiple possible examples of channel-wings,
121 evident from a distinct inflexion point, are found across the outcrop (Fig. 2B, Supplementary Fig-
122 ure 3,4). Such elements can be variably interpreted as the topmost story of an individual channel
123 or a genetically associated levee or crevasse²³, but do not concur with any aeolian model.

124 Submarine channels: certain depositional structures are found in both submarine and alluvial en-
125 vironments (e.g., channel wings), but several architectural characteristics in these deposits favour
126 alluvial interpretation and suggest against a submarine origin. Evidence of lateral migration is
127 widespread across the outcrop (i.e., inclined accretionary surfaces). Such an architectural style is
128 more typical of alluvial settings, with submarine slope architectures more regularly dominated by
129 vertical accretion²⁹. Some inclined accretion surfaces additionally have distinct foreset and bot-
130 tomset elements (Fig. 3D), consistent with those of fluvial barforms which scale to bankfull water-
131 depth. Furthermore, most described submarine slope channels on Earth are at least an order of
132 magnitude greater in size than the channels identified in this study³⁰, which have dimensions con-
133 sistent with many other geomorphic fluvial channels identified across the martian surface³¹. Fi-
134 nally, regional observations of paleolakes occupying the Hellas basin at various stages in its evo-
135 lution³² are compatible with an alluvial interpretation for these deposits.

136 Although a degree of ambiguity exists in any interpretation of ancient sedimentary strata, whether
137 on Earth or Mars, and disputes between subaqueous and subaerial interpretations are commonplace
138 on both planets^{10,33,34}, considering the discussion herein, we argue that outcrop evidence strongly
139 favours a fluvial origin for the described Izola architecture.

140 **Depositional Environment**

141 From outcrop measurements, the channel and barform thicknesses are up to 13 and 14 metres
142 respectively. This provides minimum constraints for bankfull water-depths at the time of deposi-
143 tion. Numerical models demonstrate that preserved sand-body thickness is on average 30% of the
144 original channel depth³⁵, so this approximation is almost certainly an underestimate. These hy-
145 pothesized water depths would be comparable with those of modern, mature fluvial systems on
146 Earth draining extensive basins³⁶, suggesting these Noachian-aged rivers had similar drainage ca-
147 pacities.

148 Channels and barforms account for the entire observable stratigraphy. The evidence for channels
149 being succession dominated (Fig. 3B) implies that entrenchment was quickly followed by bed
150 aggradation²³. The occurrence of distinct channel clusters is consistent with channel belts with
151 relatively stable banks and limited lateral mobility³⁷. The internal structure of the identified bar-
152 forms comprises remnants of numerous phases of bar-building activity (Fig. 3D). On Earth, de-
153 posits of rivers with low peak discharge variability preserve macroform structure, enabling the
154 reconstruction of barform morphology^{35,38}. The similar preserved architectural style seen here, of
155 relatively intact barforms and channels, implies that the depositing Izola rivers were also charac-
156 terized by low peak discharge variability. Episodic flooding events may not have been responsible
157 for deposition, but rather long-term, potentially perennial fluvial flow. This conclusion also indi-
158 cates that the Izola rivers were not the product of meltwater flowing from a glacial front, as these

159 environments are more widely associated with fluctuating, high discharges, and so would be un-
160 likely to leave a stratigraphic record comprising relatively intact channels and bars.

161 **Siliciclastic Deposition On An Unvegetated Planet**

162 Depositional models are largely based on sedimentary environments on Earth, where physical form
163 and process is near ubiquitously influenced by biology³⁹. Comparisons between the terrestrial and
164 martian sedimentary record therefore require careful consideration before application. For in-
165 stance, copious observations demonstrate the various ways extant vegetation modifies fluvial pro-
166 cesses and landforms^{40,41}. Most important from an astrobiological standpoint is the likelihood of
167 alluvial mud becoming preserved on an unvegetated planet. In addition to increasing mud produc-
168 tion through chemical weathering⁴², terrestrial vegetation promotes mud retention on the conti-
169 nents through above-ground baffling and below-ground stabilization^{41,43,44}. Through these com-
170 bined processes, an upsurge in mudstone abundance within alluvial stratigraphy is observed in
171 stratigraphic alignment with evolving land plants⁴⁵. Before this time terrestrial alluvium is pre-
172 dominantly sand-grade or coarser with few preserved muddy floodplain facies^{45,46}. Direct compar-
173 ison between the pre-vegetation Earth and unvegetated martian record might therefore imply that
174 the studied Izola alluvium might also be lacking in preserved mudstone. Such tangible character-
175 istics of the terrestrial pre-vegetation alluvial record have been previously used as supportive evi-
176 dence for environmental interpretations elsewhere on Mars: for example, the scarcity of pre-veg-
177 etation terrestrial floodplain mudstones was used to recommend a lacustrine, not floodplain, origin
178 of the Sheepbed mudstone at Gale crater¹⁶. The abundance of mudstone in the studied outcrop here
179 is not known or speculated upon, as their intrinsic fine-grained components require rover-based
180 observations. However, the preserved channel-belt architecture, comprising relatively intact chan-
181 nels and barforms, suggests some degree of original channel belt stability, with naturally shear-

182 resistant sediment such as mud a possible candidate^{47,48}. With regard to channel and barform fa-
183 cies, evidence of relatively stable, deep-channeled drainage on pre-vegetation Earth is increasingly
184 reported³⁷. Such findings are helping to dispel notions that pre-vegetation rivers were ubiquitously
185 wide and shallow⁴⁹, an observation that can now be extended to Mars (Fig. 2).

186 **Preservation Of Time And Implications For Early Mars Climate**

187 Disentangling the total duration recorded from any sedimentary outcrop is difficult, as stratigraphic
188 records are highly fragmentary, incomplete chronicles of time^{50,51}. Despite uncertainty, broad ap-
189 proximations from the studied outcrop can be made which can inform ongoing debates about the
190 early martian climate⁵². The outcrop comprises at least four possible channel belts (Fig. 2), discrete
191 packages of strata bound by laterally extensive (fifth order) surfaces and, on Earth, channel belts
192 of this scale can require up to $\sim 10^4$ - 10^5 terrestrial years to deposit⁵² (though we recognize that this
193 approximation may differ under Mars' distinct boundary conditions). However, the amount of ad-
194 ditional time hidden within the bounding fifth order surfaces between individual channel-belts is
195 unknown (and unknowable)⁵³. If a channel-belt interpretation is correct, the laterally extensive
196 surfaces developed after the active channel-belt was transposed through avulsion. During this time,
197 deposition was likely occurring elsewhere in the basin, and the region covered by our sedimentary
198 outcrop was undergoing intervals of net erosion or stasis⁵⁴. In other words, hiatuses in deposition
199 in the studied outcrop were accompanied by deposition elsewhere in the basin. This implies that
200 the time recorded in the 190-metre thick succession represents only a fraction of the total time
201 fluvial deposition was ongoing in this region. The majority of strata and time will have either been
202 lost to erosion, or preserved in outcrops as of yet undiscovered, or currently buried and not ame-
203 nable to study. While we are only beginning to understand the chronostratigraphic exactness of

204 sedimentary rock outcrops on Earth^{53,55,56}, let alone Mars, it appears likely that the period of dep-
205 osition in the northwestern rim of the Hellas basin exceeded 10^5 terrestrial years. Furthermore, the
206 preservation of relatively intact channel-margins and barforms advocates that throughout this pro-
207 tracted period fluvial deposition was a relatively constant phenomena³⁸.

208 The architectural interpretation of this so far unique sedimentary succession feeds into ongoing
209 debates about the early martian climate. Our interpretation of long-lived, deep, perennial or semi-
210 perennial rivers necessitates a climate in which active water-conduits were maintained for 10^5
211 years or longer. For the first time, orbital data has allowed us to examine, through detailed high-
212 resolution architectural analysis, a large (1500 metre by 190 metre) pre-late Noachian outcrop, and
213 draw reliable paleoenvironmental interpretations based on sedimentary-stratigraphic evidence.
214 Our observations and analysis favour steady water discharges that are most consistent with a pre-
215 cipitation-driven hydrological cycle. This conclusion aligns with previous arguments for the pro-
216 longed presence of water on the early martian surface drawn from alternative geomorphologi-
217 cal^{2,6,14,19} and mineralogical^{57,58} observations.

218

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222 Reconnaissance Orbiter and HiRISE teams and USGS/IAU for having named the studied outcrop
223 and the nearby crater in honour of the Slovenian town of Izola.

224 **Author contributions** F.S. conceptualized the study; F.S. and W.J.M. devised the methodology,
225 analyzed the data and wrote the paper; M.R.B., V.A., J.M.D., M.G.K. revised the paper and con-
226 tributed to the discussion; J.M.D. processed the HiRISE stereo pairs and built the digital elevation
227 model; F.S. and M.K. acquired funding.

228 **Competing interests** The authors declare no competing interests.

229 **Data Availability Statement** The HiRISE data that support the findings of this study were ob-
230 tained freely from the Planetary Data System (PDS) and are publicly available online at
231 <https://pds.nasa.gov/index.shtml>. Satellite imagery and the Extended Data were generated with
232 ISIS 3 (Integrated Software for Imagers and Spectrometers) available online at [https://isis.astro-](https://isis.astro-geology.usgs.gov)
233 [geology.usgs.gov](https://isis.astro-geology.usgs.gov). All these data were integrated into ArcMap 10.6 project. The DTM was pro-
234 duced using the USGS Integrated Software for Imagers and Spectrometers (ISIS 3) software and
235 the BAE photogrammetric package SOCET SET with a post spacing of 1 m/pixel.

236 **Correspondence and requests for materials** should be addressed to Francesco Salese
237 (f.salese@uu.nl)

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246 **METHODS**

247 **Dtm Construction**

248 High Resolution Imaging Science Experiment⁵⁹ image ESP_055357_1540 acquired in May 2018
249 along with HiRISE image PSP_003799_1540 (acquired in 2007) enabled the construction of a
250 centimetre scale DTM. Both images have 25.6 cm/pixel (with 1 x 1 binning) resolution so objects
251 down to 77 cm can be resolved. A digital elevation model (DEM) was produced from the HiRISE
252 images ESP_055357_1540 and PSP_003799_1540 using the USGS Integrated Software for Im-
253 agers and Spectrometers (ISIS) software and the BAE photogrammetric package SOCET SET
254 according to a previously used methodology⁶⁰. Tie points were automatically populated in SOCET
255 SET between the two images. We ran a series of bundle adjustments, removing erroneous tie points
256 until the remaining points had an RMS pixel matching error of ≤ 0.6 pixels. The resultant DEM
257 was then tied to Mars Orbital Laser Altimeter⁶¹ topography and exported with a horizontal post
258 spacing of 1 m/pixel and a vertical precision of ~ 1 m.

259 **Calculation Of Sedimentary Package Dimensions**

260 The acquired HiRISE DTM of the Hellas outcrop was of sufficient resolution to enable accurate
261 tracing of beds and plotting of architectural elements (Figure 2). Channels depths were obtained
262 measuring the exact elevation of the channel top and the exact elevation of the channel base using
263 ArcMap 10.6 elevation tools. Channel widths were measured by tracing an edge-to-edge topo-
264 graphic channel profile using the HiRISE DEM. This allowed calculation of true thickness, given
265 that they are bound by laterally-extensive fifth-order surfaces, which are almost flat lying (Sup-
266 plementary Figure 5).

267

268 **Architectural Analysis**

269 Line drawings were only attempted at areas where stratigraphy is clearly visible. Outcrop orienta-
270 tion with respect to paleoflow is not known, so no architectural elements with distinct directional
271 components (e.g., downstream accretion, lateral accretion) were assigned. Sediment grain size is
272 also unknown, thereby prohibiting the distinction between active and abandoned channel-fill de-
273 posits. The completed architectural panel enabled the various sediment stacking patterns and lat-
274 eral relationships assessed.

275 **Bounding Surface Hierarchy**

276 A hierarchy of bounding surfaces was used to describe partitions of fluvial strata at outcrop, with
277 different order surfaces reflecting river processes at varying scales⁶² (Table 1, Supplementary Fig-
278 ure 1). The principles of the hierarchical division applied here follows that detailed in previous
279 papers^{22,62}. Succinctly, zeroth, first, and second order surfaces relate to foreset, set and coset
280 boundaries respectively, and are not observable from HiRISE imagery. Third and fourth order
281 surfaces indicate the presence of macroforms (e.g., a barform deposit) or a channel. Fourth order
282 surfaces represent the upper and lower boundaries of the macroform or channel, whereas third
283 order surfaces relate to internal growth increments (indicating flow fluctuation, but no significant
284 changes in predominant fluvial style). Fifth order surfaces are the highest order observed at the
285 studied outcrop and bind major depositional packages (e.g., channel-belts). More fifth order sur-
286 faces are likely present in the studied outcrop than highlighted on Figure 2. This is simply because
287 their confident recognition depends on an understanding of their relationship with lower order

288 surfaces, and in some instances the vagaries of outcrop exposure (particularly towards the bottom
289 of the section) prevent this.

290 **Estimation Of Outcrop Age**

291 The age of the intercrater plains, which form the planform cover of the studied sedimentary-strat-
292 igraphic succession, has been estimated in a previous work¹⁹ using various crater count techniques.
293 They date $3.70 \pm 0.03/-0.04$ Ga (Noachian). The latter represents the age of the surface at the top
294 of the outcrop studied in this work, which lies in the S1 unit (Figure 18¹⁹). Crater counts were
295 performed on Context Camera (CTX; 5–6m/pixel) data using Crater Tools. Crater statistics and
296 crater model ages were analyzed with Craterstats2 software. For more details and references see a
297 previous study¹⁹.

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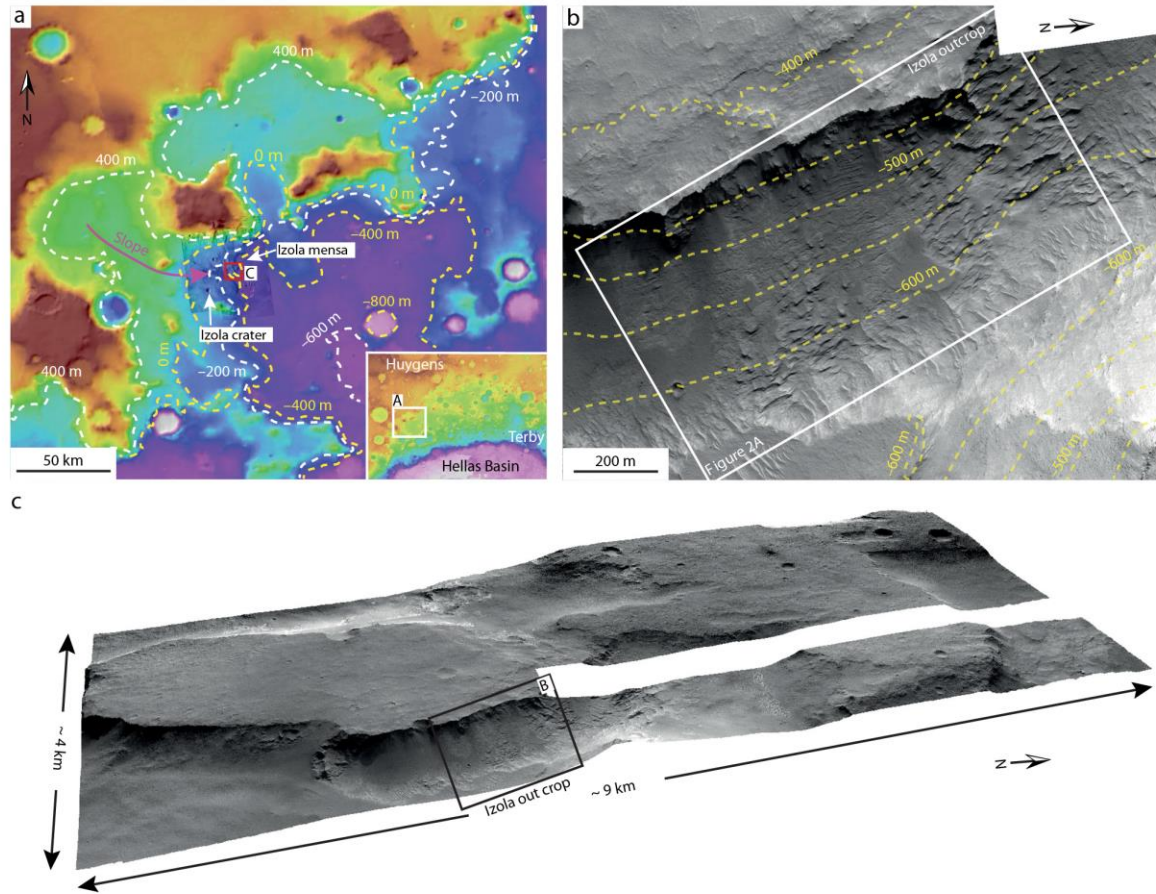


Fig. 1 General context of study location at Izola mensa. a Mars Orbiter Laser Altimeter (MOLA) topographic map centred on the NW rim of the Hellas basin, showing a depression (blue/violet) in the centre-lower right corner, the cratered highlands (brown-orange) in the upper left corner and the location of the studied outcrop within the red box. The magenta arrow indicates the slope direction of the modern surface. The identified macroforms suggest that the outcrop is broadly cut in the depositional-strike direction, in alignment with regional slope. The topographic elevation spans from 1500 m (brown) to -1350 m (white). Bottom right inset shows the regional context. Mars Orbiter Laser Altimeter (MOLA) topographic map centred on the northwestern shoulder of the Hellas basin. Study area indicated by white box. The topographic elevation spans from 4319 m (brown) to 8194 m (white). b High-resolution imaging science experiment (HiRISE) contour lines from HiRISE digital elevation model (1 m/pixel) (HiRISE stereo pairs ESP_055357_1540; PSP_003799_1540) over HiRISE visible image (25 cm/pixel). The Izola outcrop is located at 25.88°S and 54.29°E and faces almost N-S. c 3D view without vertical exaggeration of the Izola outcrop shown in b. HiRISE ESP_055357_1540 (25 cm/pixel) draped on HiRISE digital elevation model (1 m/pixel).

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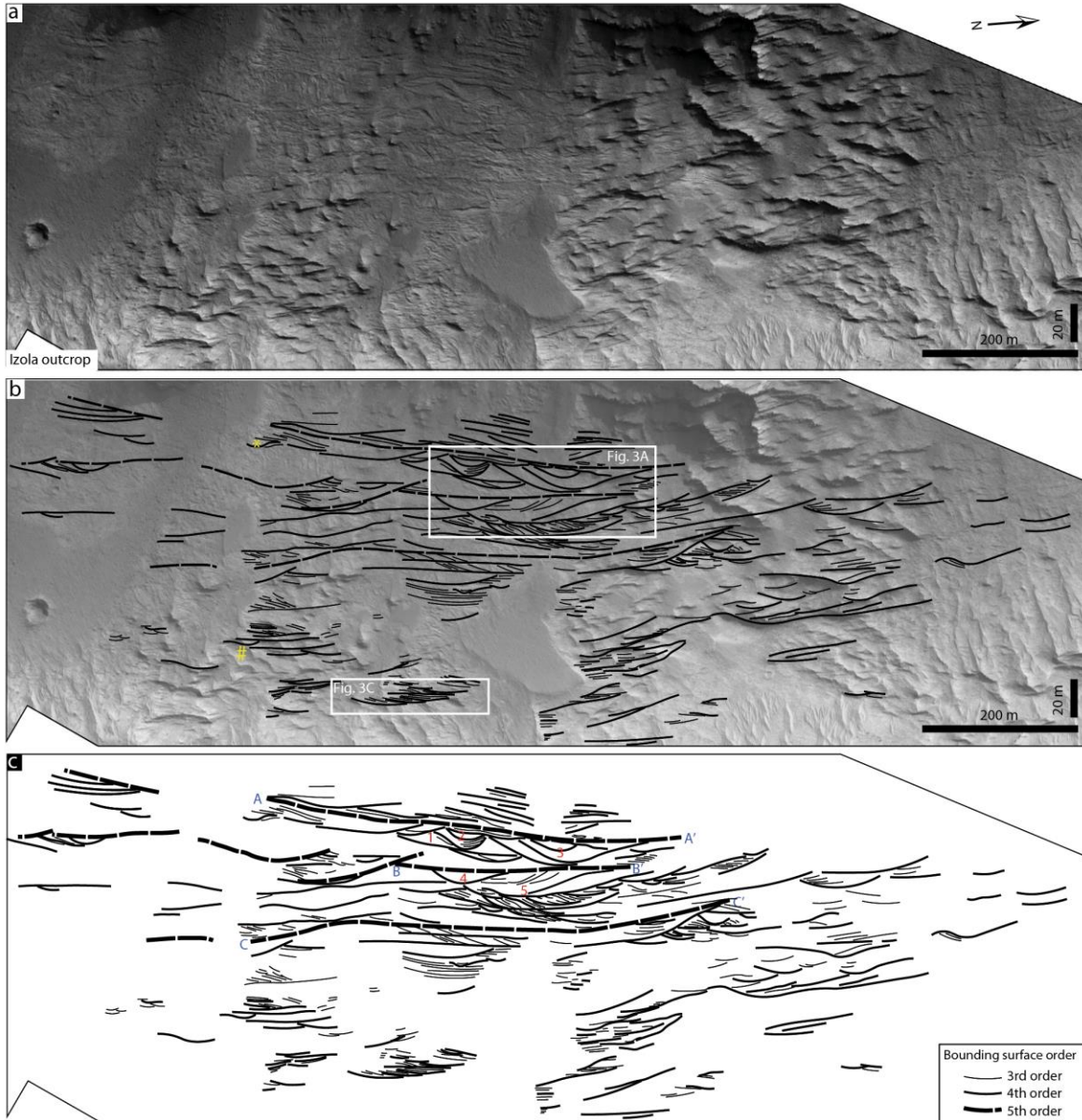


Fig. 2 Architectural analysis of Martian channel forms and inclined accretionary surfaces at the Izola outcrop. a High-resolution imaging science experiment (HiRISE) image of the studied outcrop (ESP_055357_1540; 25 cm/pixel resolution). Objects down to 77 cm can be resolved. The outcrop is 1500-m-wide and 190-m-thick. Note the different scale between the vertical and horizontal axis (vertically exaggerated) b Line drawing of (a) to illustrate an architectural interpretation, displayed in black. Line drawings were only attempted in areas where stratigraphy was clearly visible (no lines were joined across areas on non-exposure). The yellow asterisk and hashtag link to Supplementary Figs. S3 and S4, both possible examples of channel wings. Identified fifth-order surfaces are labelled with letters and surface dimensions and listed in Table 2. The well-exposed channels are labelled with numbers and their parameters reported in Table 2.

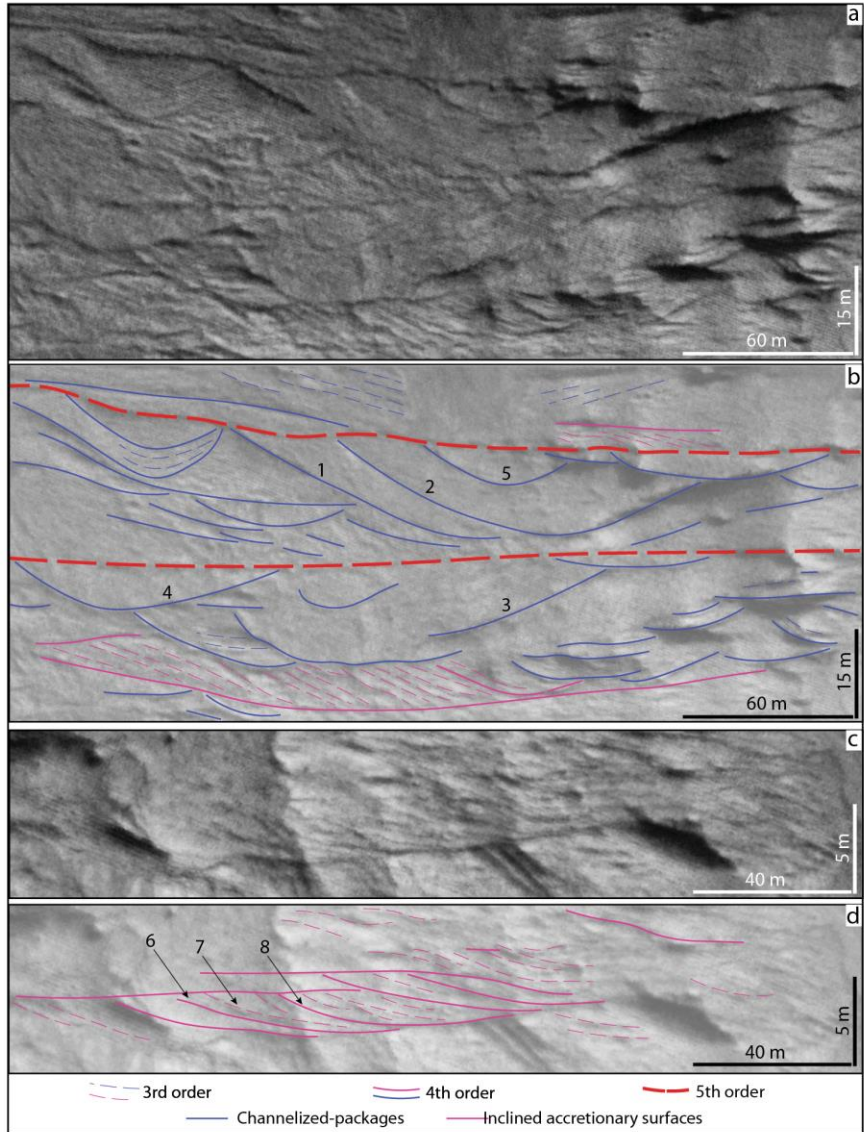


Fig. 3 Example channelised packages and inclined accretionary surfaces. a Close up of white box indicated in Fig2b. b Architectural interpretation of a displaying a number of channels (blue lines). Some examples preserve former channel margins, strong evidence for original channel lateral migration. Channelised packages have associated inclined accretion surfaces (orange lines), with all packages topped and floored by more extensive fifth-order surfaces (red lines). Fifth-order surfaces possibly archive avulsion events. A previous channel margin (1+ 3) laterally coalesces with the final channel margin (2+ 4) indicating that the original active channel migrated laterally. A nested channel-cut (5) is present within a larger channelised package. c Close up of white box indicated in Fig2b. d Examples of inclined accretion surfaces with distinct foreset and bottomset elements (topsets truncated by overlying strata). Downlapping of internal, third-order surfaces suggest multiple accretion phases. Note that line drawings are not attempted in areas where exposure is poor. A third-order surface (7) downlaps the bottomset of an underlying fourth-order surface (6) indicating bar migration. A subsequent fourth-order surface (8) truncates the previous fourth-order surface (7) indicating multiple phases of bar-building activity.

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Bounding surface order	Maximum lateral extent	Bounded units	Sedimentary process
Fifth	640 metres	Channel belts	Switch between dominant depositional process (e.g., channel-belt avulsion)
Fourth	210 metres	Channel fills, fluvial barforms	Termination of accretion or reworking of a discrete macroform
Third	180 metres	Macroforms	Accretion of a discrete macroform
Second	Not observable (rover only)	Cosets	Accretion and reworking of mesoforms
First	Not observable (rover only)	Sets	Ripple or dune migration
Zeroth	Not observable (rover only)	Laminae	Burst-sweep cycle

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458 **Table 1 Hierarchical division of bounding surfaces applied in this study. Surface ranking and process interpretations**
459 **adopted from previous studies^{22,62}.**

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4th order ID	Depth (m)	Width (m)	Width/Depth Ratio
1	8	150	18
2	11	110	10
3	15	210	14
4	7	110	15
5	15	170	11

5th order ID

A-A'	undefined	570	n/a
B-B'	21	345	n/a
C-C'	30	640	n/a

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Table 2. 4th and 5th order observed bounding surface dimensions. The ID locations of these surfaces are reported in Figure 2C.

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