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Valuing and representing exogeodiversity: From scientific imagery to artistic imagination

Évaluer et représenter la géodiversité extraterrestre : de l'imagerie scientifique à l'imaginaire artistique

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ABSTRACT

Geodiversity –*i.e.*, the abiotic equivalent of biodiversity– has gained international recognition and usage for more than two decades in the field of geosciences. It now has the theoretical foundations and practical applications of a new paradigm underlying strategies of geoconservation. However, geodiversity has rarely been considered in the context of extraterrestrial environments despite the great geological and geomorphological diversities of celestial bodies revealed by planetary science missions for at least a mid-century. In this paper, we propose to introduce the term "exogeodiversity" to encompass the variety of geological, geomorphological, regolith and hydrological features on all extraterrestrial rocky bodies. Like its terrestrial counterpart, exogeodiversity is endowed with a range of societal values, including cultural, historic, artistic, aesthetic, functional, scientific and educational ones. Given the threats associated with the many projects of human exploration of planetary surfaces, an objective assessment of these values is more than ever required. In the absence of direct (*in situ*) observations with the notable exception of the Moon, the only (indirect) way for a valuation of exogeodiversity is provided by an analysis of the scientific and artistic representations whose historical trajectories are intimately cross-cut. Finally, we stress the potential of the images to promote exogeodiversity in the era of digital technologies, for instance by imagining new forms of virtual exogeotourism.

Keywords: Geodiversity, extraterrestrial landscapes, planetary geomorphology, arts, Mars, Moon, Titan.

RÉSUMÉ

*La géodiversité est un concept désormais admis et reconnu au niveau international dans le domaine des géosciences. Il possède des fondements théoriques et des applications pratiques qui en font un nouveau paradigme sous-tendant l'élaboration des stratégies de conservation de la nature abiotique. Toutefois, la géodiversité a rarement été considérée dans le contexte des environnements extraterrestres, malgré l'exceptionnelle diversité géologique et géomorphologique des autres corps planétaires du système solaire, ainsi que l'ont révélé plusieurs décennies de missions d'exploration spatiale renvoyant des images et des données topographiques à haute résolution. Dans cet article, nous proposons d'introduire le terme d'« exogéodiversité » pour désigner la diversité géologique, géomorphologique, pédologique et hydrologique qui caractérise les corps solides extraterrestres. Comme pour la Terre, la géodiversité extraterrestre possède son propre lot de valeurs sociétales, notamment des valeurs culturelle, historique, artistique, esthétique, fonctionnelle, scientifique et éducative. Compte tenu des menaces qui pèsent sur cette géodiversité en lien avec les nombreux projets de colonisation spatiale qui fleurissent actuellement, une évaluation objective de ces valeurs est plus que jamais nécessaire. En l'absence d'observations directes (*in situ*) à l'exception notable de la Lune, l'analyse de l'imagerie scientifique et des représentations artistiques – dont les trajectoires historiques sont étroitement articulées – semble être la principale voie d'évaluation (indirecte) de cette géodiversité peu ou non accessible. Finalement, nous insistons sur le potentiel de l'image en général pour protéger et valoriser la géodiversité extraterrestre, notamment par l'usage des nouvelles technologies de l'information et de la communication, en imaginant par exemple de nouvelles formes de géotourisme virtuel sur les planètes riches en banques d'images.*

***Mots clés :** Géodiversité, paysages extraterrestres, géomorphologie planétaire, arts, Mars, Lune, Titan.*

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1. Introduction

In the traditional approaches developed since the mid-1990s, the concept of geodiversity – *i.e.,* the variability of abiotic nature– was conventionally limited to the earth surface and its features (Sharples, 1993; Kozlowski, 2004; Zwoliński, 2004; Serrano and Ruiz Flaño, 2007; Gray, 2013). However, at the same time, planetary science missions have revealed a range of geological and geomorphological diversities on all celestial rocky bodies of the solar system, *i.e.,* telluric planets, moons orbiting gas giants, comets and asteroids. One major difficulty arising out of the appreciation and assessment of extraterrestrial geodiversity –that we call "*exogeodiversity*" in this paper– is that such planetary environments remain only accessible by imagery and indirect observations (with the exception of the Moon with the Apollo manned missions and, in a more or less distant future, Mars).

In this context, all available images –both scientific and artistic– depicting extraterrestrial environments appear as essential tools for valuing exogeodiversity, especially for geoconservation purposes (Fewer, 2007; Matthews and MacMahon, 2018). Indeed, the anticipated human exploration of Moon, Mars and other rocky bodies (*e.g.,* asteroids) in the next decades implies an objective assessment of exogeodiversity to be made in order to protect the most valuables features –from scientific, cultural, historic, aesthetic and/or artistic viewpoints– against a range of anthropogenic threats, prior to the selection of future landing sites. Such threats also demand efforts of intellectual and practical reflection on how conserving and promoting exogeodiversity in the best way, as a support to future international agreements on this subject (Matthews and MacMahon, 2018). In this paper, we assume that the image could be an appropriate mediator in order to value, to protect and to promote exogeodiversity.

The aims of this exploratory paper are threefold: *(i)* defining the new term "*exogeodiversity*", that involves a semantic extension of commonly used definitions on geodiversity, and analysing its societal values on non-Earth environments; *(ii)* depicting the cross-cutting trajectories of scientific and artistic representations of exogeodiversity in a historical perspective, with empirical observations and discoveries from planetary sciences as a source of artistic inspiration and reciprocally; *(iii)* exploring the potential of the image, particularly through the use of new digital technologies and artist views, as an indirect way to protect and to promote the most valuable features of exogeodiversity.

2. Defining and valuing exogeodiversity

2.1. Exogeodiversity: extending geodiversity to extraterrestrial bodies

The field of "*geodiversity studies*" is traditionally concerned with describing and quantifying the abiotic diversity of Earth features and systems, mainly in their geological, geomorphological, pedological and hydrological components (Sharples, 1993; Kozlowski, 2004; Gray, 2013). More holistic definitions exist in the vast literature dedicated to geodiversity (Bétard, 2017): it may include "the link between people, landscapes and culture" (Stanley, 2001) and it may also concern poorly accessible environments or invisible features such as the ocean depths (Serrano and Ruiz Flaño, 2007). Because abiotic variability also characterizes the planetary surfaces of other rocky bodies in the solar system, as revealed by the numerous spacecraft missions for a mid-century, we propose to expand the scientific contours and acceptance of geodiversity to extraterrestrial bodies, by introducing the new term "*exogeodiversity*". This neologism –meaning "geodiversity outside of Earth"– is itself inspired by the recent introduction of the term "*exogeoconservation*", as an extension of geoconservation principles and practices in the field of planetary sciences, to qualify "*the identification of scientific, historic, aesthetic, ecological or cultural value in celestial bodies and in their component geological and geomorphological features, and the protection of such bodies and features*" (Matthews and MacMahon, 2018). As stressed by those authors, the "*exo-*" prefix expresses the extraterrestrial scope of geoconservation –just as in the term "exobiology" aiming to study extraterrestrial life– and could be applied as well to other associated terms such as "*exogeosites*" and "*exogeoheritage*". In this paper, as an extension and adaptation of the commonly used definition of geodiversity proposed by Gray (2013), we define "*exogeodiversity*" as: "*the natural range (diversity) of geological (structures, rocks, minerals), geomorphological (landforms, processes), soil (regolith) and hydrological features on extraterrestrial rocky bodies, including their assemblages, relationships, properties and systems*". Compared to Earth's abiotic diversity, it comprises some peculiarities such as the absence of proven fossils in rocks and of organic matter in soils, and a hydrosphere possibly composed of other fluids than water, *e.g.,* hydrocarbon lakes and rivers on Titan (Mitri et al., 2007; Neish et al., 2016).

Like its terrestrial counterpart, exogeodiversity applies at various scales, from the global scale of planets and satellites, to the elemental scale of atoms and ions, going through the "*myriadic*" landscape scale. For instance, a global exogeodiversity is easily detectable on a geological map of Mars (fig. 1) on which are represented the major structural features of the planetary surface: large impact basins (*e.g.,* Hellas Basin), volcanic provinces and chains (*e.g.,* Tharsis Montes), tectonically-controlled canyon systems (*e.g.,* Valles Marineris). All these large-scale features give the planet a variety of forms and structures in which smaller-scale geodiversity features are imbricated, down to microforms and elementary particles. The semantic expansion of geodiversity toward extraterrestrial environments is also justified by the variety and analogy of Earth-like planetary landscapes and landforms, as revealed by a pluri-decade geomorphological analysis of extraterrestrial environments (Baker, 1993; Peulvast and Vanney, 2001, 2002; Baker et al., 2015; Burr and Howard, 2015).

Such exogeodiversity features include:

(i) a range of tectonic structures and associated landforms, such as fault scarps (*e.g.,* Rupes Recta on the Moon) (fig. 2A) and large-scale canyon systems controlled by strike-slip and normal faults (Valles Marineris, Mars) (fig. 2B); it also includes original structures and landforms with no equivalent on Earth, such as "*lobate*" scarps on Mercury, interpreted as the surface manifestation of thrust faults in response to the accommodation of horizontal shortening of Mercury's lithosphere (Banks et al., 2015), or evidence for plate tectonics mounts controlled by original subduction process on the icy surface of Europa, one of the Jupiter's moons (Johnson et al., 2017a).

(ii) a diversity of volcanoes and volcanic structures: it includes, for the biggest ones, 500 to 600 km-wide shield volcanoes (Olympus Mons, Mars; Sapas Mons, Venus) (fig. 2C) as well as smaller volcanic landforms and features such as stratovolcanoes and cinder cones with associated lava flows (Biblis Patera, Mars) (fig. 2D), explosive features like calderas and maars or, at the opposite, evidence of effusive activity with lava channels flowing towards impact basins (Angkor Vallis, Mercury) (fig. 2E) and contributing to their "resurfacing" (see the recent or ongoing processes of volcanic resurfacing of Venusian and Io's craters (Peulvast and Vanney, 2002).

(iii) a high variability of fluvial-like landforms and processes (Baker et al., 2015): morphological evidence for ancient

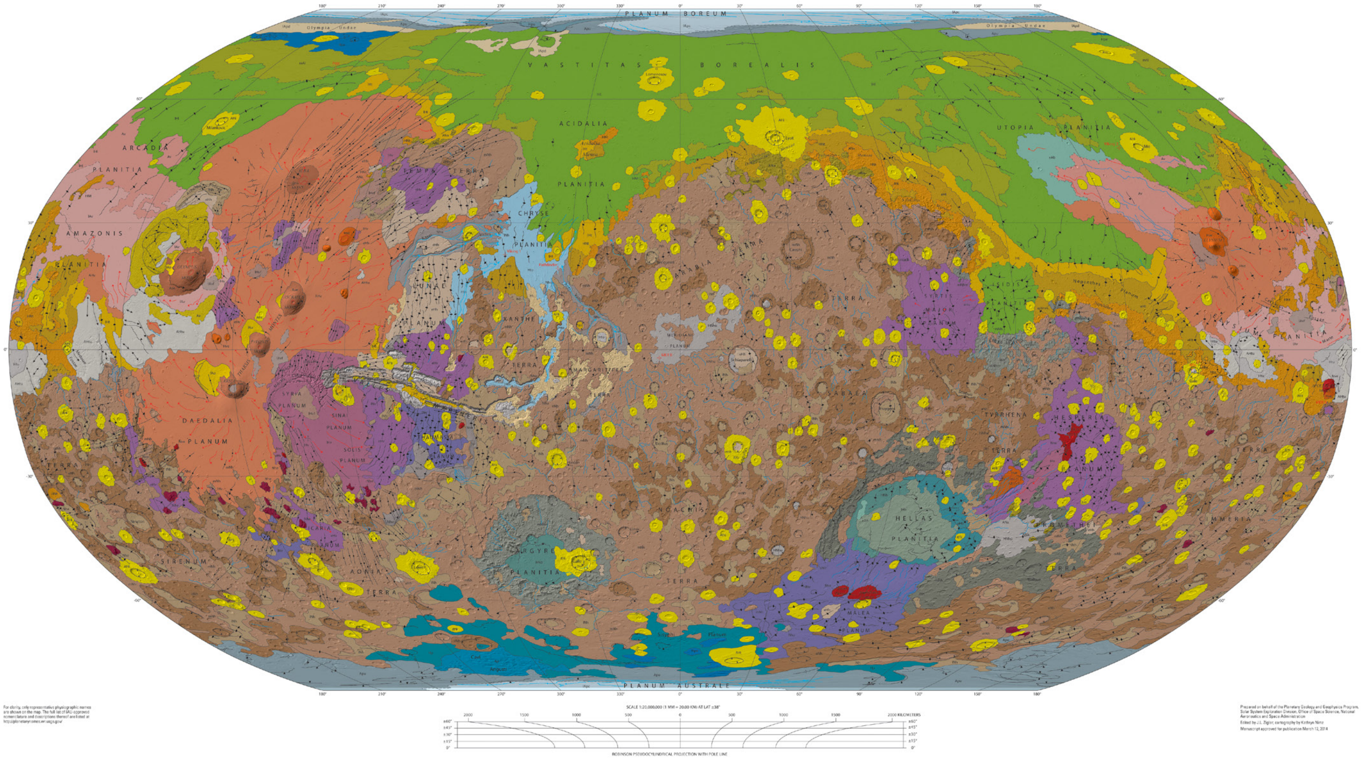

Fig. 1 – Geologic map of Mars (Tanaka et al., 2014).

This cartographic product records the diversity and distribution of geologic units and landforms on the planet's surface through time, and is based on a great variety of remotely sensed data acquired since the Viking Orbiters. These data have provided topographic, morphologic, spectral, thermophysical, radar sounding, and other indirect observations for integration, analysis, and interpretation in support of geologic mapping. Source: USGS. Detailed legend and complete map (accessible at: https://pubs.usgs.gov/sim/3292/pdf/sim3292_map.pdf) need to be consulted to get a proper understanding of this document.

Fig. 1 – Carte géologique de la planète Mars (Tanaka et al., 2014).

La carte, qui montre la diversité et la répartition des unités géologiques et des grands ensembles du relief, est basée sur une grande variété de données acquises depuis les missions Viking. Ces données ont fourni des informations topographiques, morphologiques, spectrales, thermophysiques, ainsi que des données radar et autres observations indirectes qui ont servi à la cartographie géologique. Source : USGS. Légende complète et détaillée à consulter sur https://pubs.usgs.gov/sim/3292/pdf/sim3292_map.pdf pour une compréhension globale du document.

channelized flows (dendritic river systems and associated valley networks, braided channels, deltas and alluvial fans, gully systems) (fig. 2F) mainly exist on the surfaces of Mars and Titan where the fluid flows are not volcanic lava (water for Mars; methane for Titan) (fig. 2G). In the N_2-rich atmosphere of Titan, the global methane cycle generates clouds, rainfall and fluvial features connected to shallow lakes and seas of liquid CH_4 in the near-polar regions (fig. 2G).

(iv) A set of mass wasting processes and gravitational landforms, most of which have been observed in the high scarps and crater rims of Mars (fig. 2B,F). Viking Orbiter images have provided a first basis to identify and quantify the volumes involved in the large-scale landslides, rock avalanches and debris flows affecting the Valles Marineris wallslopes (Lucchitta, 1979, 1987; McEwen, 1989; Peulvast et al., 2001), according to gravitationally driven processes possibly triggered by seismotectonic activity and/or melting of near-surface ground ice (Costard et al., 2002; De Blasio, 2011).

(v) a variety of extra-terrestrial dunes, wind erosion features and aeolian deposits: sand dune fields and systems with various morphologies have been described on Mars (fig. 2H), Venus and Titan (Greeley and Iversen, 1987; Bourke et al., 2010; Rodriguez et al., 2014). Sand dunes and dust deposits are also affected by smaller-scale features and bedforms (*e.g.,* impact and granule ripples). Aeolian abrasion also acts as an efficient erosional process on Mars and Venus at various scales, from the shaping of ventifacts to the sculpture of yardangs (Zimbelman and Griffin, 2010).

(vi) a complex assemblage of glacial and periglacial landscapes and landforms, well studied and inventoried on Mars: it includes the two permanent ice caps of the Martian poles, high-latitude cold-based mountain glaciers (Head and Marchant, 2003) as well as high-altitude tropical mountain ones (Fastook et al., 2008), debris-covered valley glaciers and their moraine-like ridges and deposits (fig. 2I). Traces of ancient glaciations on Mars are represented as well by a range of typical glacial landforms (U-shaped and hanging valleys, glacial cirques) (Kargel and Strom, 1992; Conway et al., 2018; Bouquety et al., 2019). Finally, Martian permafrost features are reported for a long time ago (*e.g.,* Carr and Schaber, 1977), with a various set of periglacial processes and landforms: cryoturbation processes and small-scale polygonal features (sorted stone circles, patterned grounds and pingo-like forms: Mellon, 1997; Mangold, 2005; Balme and Gallagher, 2009), thermokarst processes and landforms along alluvial terraces and channels (Costard and Baker, 2001), etc.

Given the high (non-exhaustive) diversity of extraterrestrial landscapes described above, the question of its valuation can be put forward, in the same terms as for the Earth's abiotic diversity (Gray, 2013) but with two specificities: *(i)* the absence of direct (*in situ*) observations by humans (with the notable exception of the

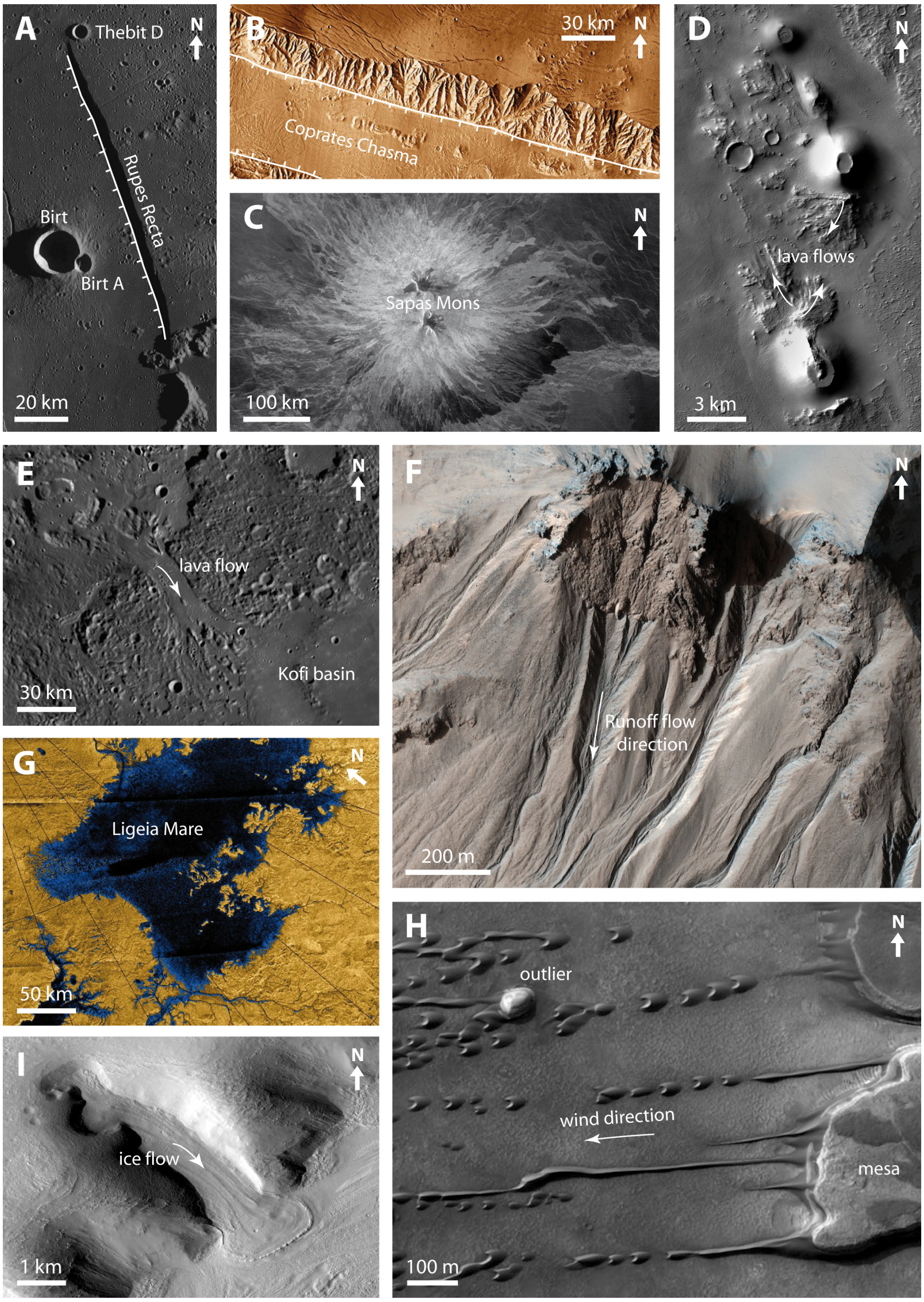

Fig. 2 – Some relevant exogeodiversity features at various scales on Earth-like planetary surfaces.

A: Rupes Recta (or Straight Wall), a 110 km-long and 300 m-high normal fault scarp in the southeastern part of the Mare Nubium, Moon (Lunar Reconnaissance Orbiter Camera); note the presence of the twin impact craters Birt and Birt A to the West. B: Coprates Chasma, a large graben bounded by normal fault high scarps, as part of the Valles Marineris canyon system, Mars (THEMIS infrared image, Mars Odyssey); note the scalloped contours of the fault scarp ridge, affected by gullying and large landslides together with boulder falls probably triggered by sismotectonic activity. C: Sapas Mons, a 600 km diameter shield volcano located on the flanks of the Atla Rise, Venus (Magellan radar image); note the complex, multi-generational system of lava flows extending all around the volcano. D: Cinder cone field and associated lava flows near Biblis Patera, Mars (CTX image, Mars Reconnaissance Orbiter); note that the association of cinder cones and lava flows is rarely observed on Mars, that is a factor of high extrinsic exogeodiversity. E: Angkor Vallis, a lava channel flowing towards the flooded impact crater Kofi, Mercury (Mercury Dual Imaging System, MESSENGER); note the presence of “kipukas”, or residual hills streamlined in a direction parallel to the channel’s long axis. F: Near-parallel system of gullies in the inside rim of the Hale Crater, Mars (HiRISE false-color image); note that the coarse material of the rim’s edge suggests a high disposition to debris-flows. G: Ligeia Mare, a shallow lake of liquid methane in the north polar region of Titan (colorized SAR image, Cassini/Huygens); note the well-organized fluvial dissection network connected to the lake, and the numerous islands whose scalloped contours reflect the flooding of an entrenched drainage system. H: Barchan and linear lee dunes shaped downwind of layered mesas in the Hellespontus region, Mars (HiRISE image); note the breakdown of the rectilinear lee dunes into barchans with distance from the flow obstruction, the winds blowing from west to east. I: Debris-covered valley glacier alimented from a cirque-like alcove in the Protonilus Mensae region, Mars (CTX image, Mars Reconnaissance Orbiter); note the apparent flow-parallel lineations and the moraine-like ridge that bounds the glacier front. Image credits © Courtesy NASA/JPL/University of Arizona.

Fig. 2 – Quelques traits caractéristiques de la géodiversité extraterrestre sur des surfaces planétaires semblables à celle de la Terre.

A : Rupes Recta, appelé également « l’épée dans la Lune », un escarpement de faille primitif situé dans la partie sud-est de Mare Nubium, Lune (Lunar Reconnaissance Orbiter Camera) ; noter la présence des cratères d’impact jumeaux Birt et Birt A à l’Ouest. B : Coprates Chasma, un large graben délimité par des hauts escarpements de faille s’intégrant dans le vaste système de canyons de Valles Marineris, Mars (image infrarouge THEMIS, Mars Odyssey) ; noter les contours festonnés de l’escarpement, affecté par d’immenses ravins et de grands glissements de terrain possiblement déclenchés par l’activité sismotectonique. C : Sapa Mons, un volcan-bouclier de 600 km de diamètre situé sur les flancs de l’Atla Regio, Vénus (image radar Magellan) ; noter le système complexe et multi-phasé de coulées de lave autour du volcan. D : Cônes de scories et coulées de lave associées dans le secteur de Biblis Patera, Mars (image CTX, Mars Reconnaissance Orbiter) ; noter que l’association entre cônes de scories et coulées de lave est rarement observé sur Mars, ce qui est un facteur de forte géodiversité extrinsèque. E : Angkor Vallis, un couloir de laves coulant vers le cratère d’impact Kofi, Mercure (Mercury Dual Imaging System, MESSENGER) ; noter la présence de « kipukas », îlots rocheux entourés de lave, alignés dans l’axe de la coulée. F : Système de ravins parallèles sur le rebord interne de Hale Crater, Mars (image fausse-couleur HiRISE) ; noter l’abondance de matériel grossier au sommet du rempart, suggérant une forte prédisposition aux coulées de débris. G : Ligeia Mare, un immense lac de méthane liquide situé près du pôle nord de Titan (image SAR colorisée, Cassini/Huygens) ; noter l’existence d’un réseau hiérarchisé de dissection fluviale connecté au lac, et les nombreuses îles dont les contours reflètent l’ennoiement d’un ancien système de vallées. H : Barkhanes et dunes d’abri façonnées sous le vent de mésas stratifiées dans la région d’Hellespontus, Mars (image HiRISE) ; noter le passage progressif des dunes d’abri rectilignes aux dunes barkhanoïdes à une certaine distance du relief-obstacle, le vent soufflant d’Ouest en Est. I : Glacier noir de vallée alimenté à partir d’un bassin d’accumulation de type cirque dans la région de Protonilus Mensae, Mars (image CTX, Mars Reconnaissance Orbiter) ; noter les linéations parallèles à l’écoulement glaciaire et le bourrelet de type morainique situé au front de la langue glaciaire. Crédits image © Avec la permission de NASA/JPL/University of Arizona.

Apollo manned missions on the Moon), that needs to proceed with indirect observations (imagery) for its valuation; *(ii)* the absence of direct connection and interaction with human and non-human life until present, given rise to an original set of societal values.

2.2. The values of exogeodiversity

Valuing exogeodiversity has an interest as it falls into the scope of (exo)geoconservation (Matthews and MacMahon, 2018), that can be simplified using the following formula:

Values of exogeodiversity x Threats = Need for exogeoconservation

This coupling between values and threats is central in the longstanding debates on environmental ethics and conservation about our own planet, where human pressure seriously threatens both living and non-living features of Earth's diversity in the Anthropocene times (Hudson and Inbar, 2012; Johnson et al., 2017b). If exogeodiversity does not appear directly threatened because extraterrestrial environments remain uninhabited up today, this situation is likely to change rapidly in the next decades given the many projects of human exploration and settlement, with the Moon and Mars topping the list. For these reasons, we propose to draw a special attention to the values, making possible to transform exogeodiversity features into exogeoheritage, so the necessity for human societies to conserve or manage exogeosites for the next generations. Table 1 gives a summary of the main recognizable values of exogeodiversity with some representative examples.

Intrinsic or *existence values* are those potentially associated with natural or extraterrestrial objects simply for their own sake rather than for their utilitarian function or direct use by humans (Gray, 2013). This is a large philosophical and ethical debate in which we will not take part in this paper. More relevant are the societal values that can be attributed to geodiversity, sometimes referred to as "*geosystem services*" or "*abiotic ecosystem services*" by some authors in the vein of the Millenium Ecosystem Assessment (Gray, 2011, 2012; Alahuhta et al., 2018). However, this instrumental vision is not free from criticism because it does not reflect the diversity of potential relationships that human societies have with abiotic nature, whether terrestrial or extraterrestrial. Since the geodiversity of celestial bodies should be considered more than a basic provider of goods and services, we prefer to conserve an approach by the "*values*":

(i) cultural values may originate from folklore associated to popular astrology, mythology and legends about the Moon,

Tab. 1 – Exogeodiversity values and some related examples.

Tab. 1 – Valeurs de la géodiversité extraterrestre et quelques exemples associés

General value	Specific value	Examples
Intrinsic value	1. Intrinsic value	Exogeodiversity free of human valuations
Cultural value	2. Folklore	Popular astrology, mythology and legends about the Moon, Mars and other planets
	3. Archeological/historical value	Landing site of Apollo 11 mission in 1969 – Tranquility Base (Moon)
	4. Spiritural/religious value	Universe and planets as a divine creation
	5. Artistic inspiration	Literature (Verne), science-fiction movies (Kubrick), comics (Hergé), paintings (Bonnestell)
Aesthetic value	6. Aesthetic value	Impressive landscapes of Valles Marineris (Mars)
Economic value	7. Energy	Space exploration for the exploitation of energy resources (e.g., helium-3 on the Moon)
	8. Metallic minerals	Projects of asteroid mining for raw materials and precious metals (iron, gold, silver, platinium…)
	9. Tourism and leisure	Space tourism, virtual geotourism (Google Moon, Access Mars)
Functional value	10. Platforms	Projects of lunar habitat bases and infrastructure construction
	11. Storage and recycling	Storage of hydrogen and human wastes
	12. Ecosystem functions	Potential habitat for exobiodiversity (e.g., sub-ice oceans of the outer solar system)
Scientific and educational value	13. Solar system and Earth history	Origin of solar system, origin of life on Earth, compared geological histories of planets
	14. Scientific discovery	Geoprocesses, geotechnology, geoforensics
	15. History of research	Early identification of asteroids, of fluvial processes on Mars and Titan, of active volcanism…
	16. Environmental monitoring	Orbital satellite observations for environmental monitoring of meteorological or volcanic activity
	17. Education and training	Academic education, professional training in the field of planetary sciences

Mars and other planets. They may also be related to the historical or archaeological value of potential exogeosites. An emblematic example is the landing site of the Apollo 11 mission on the Moon, named "*Tranquillity Base*" (Fewer, 2007), with the first human footprints and associated archaeological artifacts preserved in situ, beyond the indisputable importance of this site for the history of humankind. Another candidate exogeoheritage of major cultural/historical value is the Halley's Comet, which has been observed by many times in history, including by the ancient Chinese and Babylonian astronomers as early as the 1st century BC (Matthews and MacMahon, 2018). The artistic value is also a cultural one: extraterrestrial landscapes have inspired painters, writers, cartoonists, filmmakers, etc., who contributed to varied forms of artistic representations on exogeodiversity (see below, section 3, for a historical overview). Finally, a spiritual or religious value has often been assigned to celestial bodies: for many religions, the universe is a divine creation, and as such it would deserve a kind of preservation.

(ii) aesthetic values may be assigned to exogeodiversity features even if the natural beauty of a landscape is a very subjective criterion, with much more difficulty without being in situ to judge it. The main way to appreciate the aesthetic or scenic value of extraterrestrial landscapes is based on the images provided by the numerous spacecraft missions (orbital and landed) and, more specifically, by the systematic photographic missions performed by orbital probes and planetary rovers (*landscape imaging*) (tab. 2). At larger scales accessible to the human eye via telescopes, our solar system abounds in beautiful features, from the gigantic rings of Saturn to the impressive landscapes of the Valles Marineris canyon on Mars.

(iii) economic values are necessarily utilitarian ones and might fall into the scope of ecosystem (provisioning) services: they include the provision of new energy resources (see the exploratory mining projects to exploit helium-3 on the Moon) as well as the projected exploitation of abundant metallic minerals at the surface of asteroids (iron, gold, silver, platinium, etc.). The development of space tourism is a very lucrative activity related to exogeodiversity and outer space. Moreover, new forms of virtual geotourism start to develop (see the "*Destination: Mars*" Virtual Reality Experience, opened in September 2016 at the Kennedy Space Center Visitor Complex in Florida, USA), with their economic benefits for multinational firms like Google LLC (*e.g.,* "*Mars Access*" virtual reality software, created from a collaboration with NASA).

(iv) functional values can range into the category of supporting services in the case where the planetary surfaces are viewed to serve as platforms for projects of habitat bases and infrastructure construction (Moon, Mars) or, potentially, as burial sites for nuclear or other human wastes. The functional value of exogeodiversity might also be associated with an expected ecological value because landforms, regolith and specific features of rocky bodies (*e.g.,* sub-ice oceans of outer solar system) may be potential habitats for a hypothetical exobiodiversity to be discovered.

(v) scientific and *educational values* are among the main criteria for considering exogeosites as valuable features to conserve, because they give us a huge amount of knowledge about the history of the solar system and planets, and precious information about the origin of life on Earth. Some places of the planetary surfaces have become key sites or reference types in various domains of the planetary sciences (stratigraphy, mineralogy, geomorphology, etc.). Other sites to conserve will provide physical evidence for further research as well as opportunities to train and educate professional geoscientists, students, scholars, and the general public.

Obviously, the appreciation of exogeodiversity values is likely to change in the future on the basis of as-yet-unknown direct observations on extended planetary surfaces. Yet, in the absence or scarcity of in situ observations to assess the values of exogeodiversity, the main source for valuation and discussion is provided by the scientific and artistic representations of planetary landscapes which can document this topic in a very prolific way. The great diversity of available images is directly related to the history of space exploration, in which scientific advances and discoveries are intimately entangled with artistic trends and imaginaries.

3. Representing exogeodiversity: cross-cutting contributions from planetary sciences and arts

3.1. Before spacecraft exploration: the telescopic age

Being the most obvious feature of our night sky, and our nearest neighbour, the Moon has naturally been the first planetary object to be closely observed (Leatherbarrow, 2018). Although it displays significant detail even to the unaided eye, the scientific exploration of its surface only started in 1609, when Galileo, using one of the first telescopes, revealed its rough topography. This was the beginning of the telescopic age of observation of planetary surfaces, which lasted (but not ended) until the first spacecrafts were launched towards our companions of the solar system. In spite of the technical improvements which provided more and more powerful instruments all along this period, until now, only the Moon (its visible face) could be observed with accurate detail, and even the NASA's Hubble Space Telescope can spot only major features such as the polar caps or the canyons of Valles Marineris (4000 km in length) on our other closest neighbour, Mars.

The original geodiversity of the Moon already appeared on drawings by Galileo (1610) and on the first maps drawn, with an astonishing wealth of details, by Hevelius, Langrenus or Cassini in the 17th century (fig. 3A). These documents clearly show the presence of dark plains – considered as seas by some of the first observers – and of numberless cirques or craters of all sizes, the origin of which remained a matter of discussions until the middle of the 20th century. Although drawn by hand directly from telescope observation, many of these maps and drawings reached a very good precision (fig. 3B), only surpassed when the use of photography allowed the acquisition of more objective portraits of our satellite, as soon as the years 1858-1862 (first good photographs by Warren de la Rue) and in the end of the 19th century (first photographic atlas of the Moon) (Pickering, 1904). In the 1960s, before the first systematic photographic missions performed by the Lunar Orbiter probes, more and more precise telescopic images were the only way to prepare the American Apollo program of manned missions, initiated by President Kennedy in 1962 (fig. 3C).

Although their interpretation was made more or less difficult by the shifting shadows of mountains, peaks and crater ramparts, all these documents were used as bases for scientific studies of the landforms of the lunar surface, as soon as the 18th century,

Tab. 2 – Listing of on-going or recent spacecraft missions, orbital and landed, to solid bodies returning imagery or topographic data comparable in type and quality to data of Earth. Modified, updated and augmented from Burr and Howard (2015).

Tab. 2 – Liste des missions spatiales, récentes ou en cours, sur des corps planétaires solides renvoyant des images ou des données topographiques comparables en type et en qualité à celles acquises sur Terre. Modifié, actualisé et augmenté d'après Burr et Howard (2015).

Body	Org.	Mission	Relevant imaging instruments
Mercury	NASA	MESSENGER (2004 -2015)	Lunar Reconnaissance Orbiter Camera (1 m/px)
	ESA -JAXA	BepicolomBo (2018 -)	Lunar Orbiter Laser Altimeter
			Laser Altimeter
			Radiometer and thermal infrared spectrometer
			Infrared imaging spectrometer (500 m/px)
			Imaging X-ray spectrometer
Moon	NASA	Lunar Reconnaissance Orbiter (2009 -)	Lunar Reconnaissance Orbiter Camera (1 m/px)
	CNSA	Chang'e 4 (2018 -)	Lunar Orbiter Laser Altimeter
			Panoramic and Terrain Cameras
			Visible and Near-Infrared Imaging Spectrometer
			Georadar LPR - Lunar Penetrating Radar
Mars	NASA	Mars Odyssey (2001 -)	Thermal Emission Imaging System (visible light 18 m/px; infrared 100 m/px)
		Mars Reconnaissance Orbiter (2015 -)	Context Camera (6 m/px)
		Mars Exploration Rovers (2003 -2019)	High Resolution Imaging Science Experiment (0.25 m/px)
			Panoramic Camera (landscape imaging)
		Curiosity (2012 -)	Microscopic Imager (sub-mm)
			Engineering Cameras (hazcams and navcams)
			Mast Camera (landscape imaging)
		InSight (2018 -)	Mars Hand Lens Imager (sub-mm scale)
			Mars Descent Imager (sub-orbital imaging)
			Instrument Deployment and Context Cameras
			HP3 -RAD Infrared Radiometer
	ESA	Mars Express (2003 -)	Seismometer (SEIS)
	ISRO	Mars Orbiter Mission (2013 -)	Heat Flow and Physical Properties Package instrument
			High Resolution Stereo Camera (2 – 10 m/px)
			Mars Colour Camera (25 m/px)
			Thermal Infrared imaging Spectrometer
Asteroids	JAXA	Hayabusa 2 (2014 -)	Optical Navigation Cameras (1024x1024 px)
			Near -infrared spectrometer
			Thermal Infrared Imager (320x240 px)
			LiDAR Laster Altimeter
	NASA	OSIRIS-REx (2016 -)	Panoramic and engineering Cameras (oscams)
			Laster Altimeter
			Visible and infrared spectrometer (variable)
			Regolith X-ray Imaging Spectrometer
Galilean and saturnian satellites	NASA-ESA	Cassini -Huygens (1997-2017)	Imaging Science Subsystem (variable)
			Visible and Infrared Mapping Spectrometer (variable)
	NASA	Juno (2016-)	Cassini Titan RADAR Mapper (variable)
			Jovian Infrared Auroral Mapper (JIRAM)
			JunoCam: visible light camera/telescope
Pluto and satellites	NASA	New Horizons (2015 -)	Long -Range Reconnaissance Imager (LORRI)
			Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI)
			Ultraviolet imaging spectrometer (Alice)
			Ralph telescope: MVIC (Multispectral Visible Imaging Camera) and LEISA (Linear Etalon Imaging Spectral Array), i.e. a near-infrared imaging spectrometer

with precise observations of topographic features by Herschel or Schröter. One of the main issues of this period which saw the Moon becoming an object of geological science (Wilhelms, 1993) was the origin of the craters: the volcanic hypothesis was the most favourite until the mid-20th century, although the great geologist Gilbert already dismissed it in 1893, in particular after the experiments he made in 1891 on a slab of clay impacted at different speeds by balls of clay (Gilbert, 1893; Greeley, 1985). Gilbert was the first to correctly interpret these features (fig. 3D), as well as the bright rays surrounding some craters such as Tycho, as the results of impacts. His views, extended to dark plains or "mare" (*e.g.,* the circular Mare Imbrium) interpreted as impact basins filled by volcanic products, were later confirmed by the lunar scientist Baldwin (1949), who had also studied bomb craters (including those of nuclear bombs experimented in the Nevada desert) during and after the Second World War, and who had described the effects of violent explosions caused by collisions at all scales, including that of large multi-ring basins.

This was the context for the artistic representations produced before the Apollo missions. Some of the most famous ones were those drawn by Hergé in "*On a marché sur la Lune*" (1954) and those created in 1968 for Kubrick's film, "*2001, Space Odyssey*" (fig. 4A-

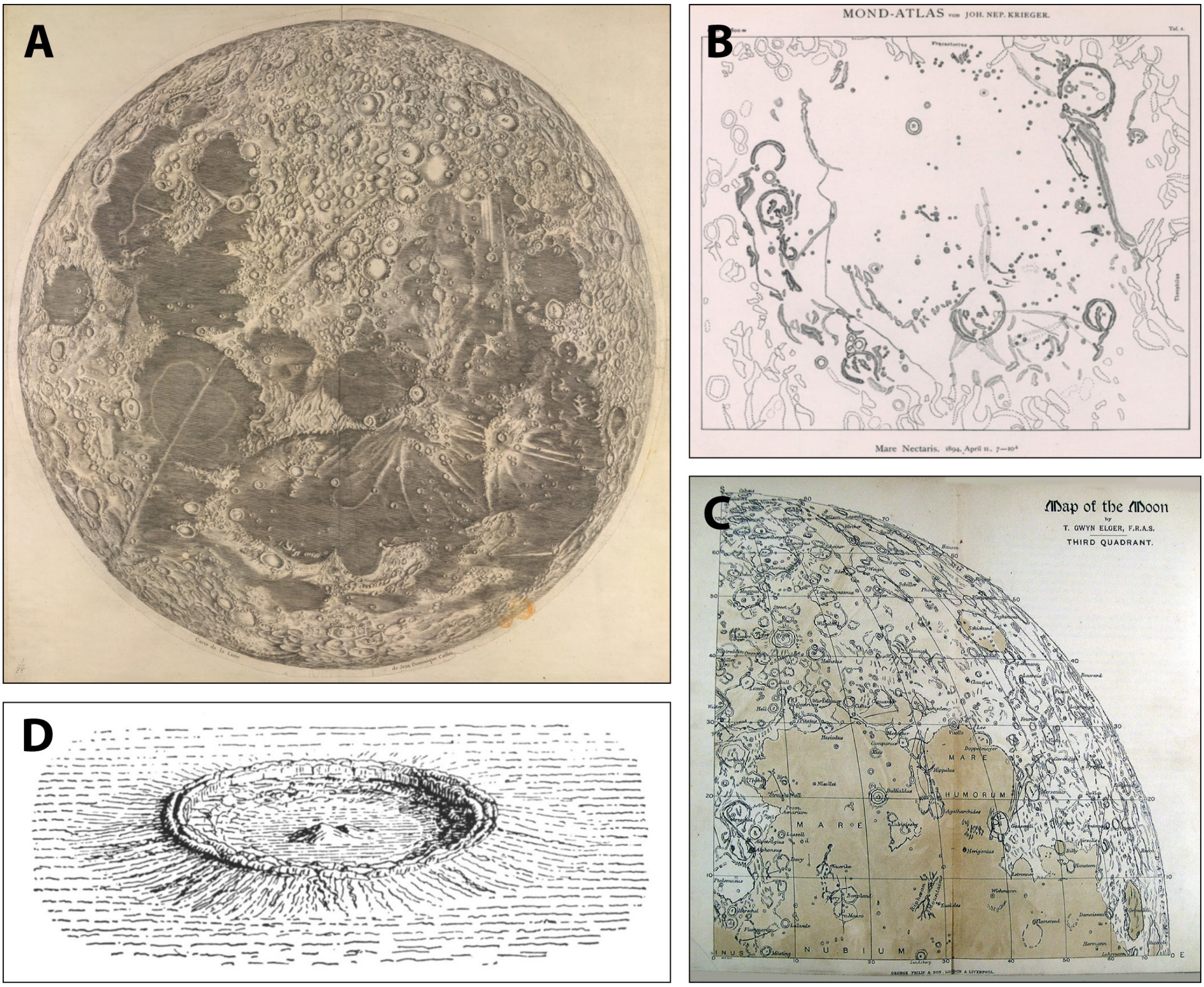

Fig. 3 – Historical representations of the Moon's geodiversity at various scales.

A: First scientific map of the Moon, produced in Paris by the Italian (naturalised French) astronomer G.D. Cassini in *ca.* 1679 from detailed telescope observations. Image credit © British Library (public domain). B: Cartographic board of the Atlas of the Moon, made by the German selenographer J.N. Krieger: Mare Nectaris, 1894. Image credit © David Rumsey Map Collection, www.davidrumsey.com. C: Third quadrant of the Map of the Moon, made by the British selenographer T.G. Elger in 1895; this lunar map was regarded as one of the best available until the 1960s. Image credit © C.A. Wood Collection. D: G.K. Gilbert's sketch of a typical lunar crater, interpreted for the very first time as the result of a meteorite impact (Gilbert, 1893, p. 243).

Fig. 3 – Représentations historiques de la géodiversité lunaire à différentes échelles.

A : Première carte scientifique détaillée de la Lune, réalisée par l'astronome italien (naturalisé français) G.D. Cassini vers 1679 à partir d'observations précises au télescope. Crédit image © British Library (domaine public). B : Planche cartographique de l'Atlas de la Lune, dessinée par le sélénographe allemand J.N. Krieger : Mare Nectaris, 1894. Crédit image © Collection David Rumsey, www.davidrumsey.com. C : Troisième quadrant de la Carte de la Lune, produit par le sélénographe britannique T.G. Elger en 1895 ; cette représentation est restée la plus précise des cartes disponibles de la Lune jusque dans les années 1960. Crédit image © Collection C.A. Wood. D : Croquis schématique d'un cratère lunaire par G.K. Gilbert (1893, p. 243), interprété pour la première fois comme résultant d'un impact de météorite.

B). Indeed, many illustrators had already provided drawings and paintings of lunar landscapes, since the end of the 19th century (Hardy, 1989), and some of them could have inspired these works. Among these early illustrations of science or science-fiction books, those by Moreux (*e.g.,* in "*A day in the Moon*", 1913), by the French artist and astronomer Rudaux (*e.g.,* in "*Sur les autres mondes*", 1937) (fig. 4C), or the American painter Bonnestell (fig. 4D) clearly prefigure the last pre-Apollo representations. It is interesting to note that Hergé adopted the impact theory of crater formation, as shown by the surprise of the Dupondt policemen when, shaken by a sudden jolt during their moon trip, they realized that their footprints had just been obliterated by a small crater freshly formed by the fall of a meteorite behind them. In most cases, one remains struck by the rugged aspect of the lunar topography on most drawings and film sceneries, with sharp peaks in mountains and crater ramparts, although Rudaux had already demonstrated that even low hills can cast long black shadows when illuminated by a low Sun (Hardy, 1989). This fact was later confirmed by the Apollo astronaut's landscape photographs.

On the contrary, the other rocky worlds, only visible as small and more or less blurred objects, even in the best telescopes, always remained beyond any realistic illustration before the space age. The best example is that of Mars, whose minimal distance from the Earth, during the best oppositions, is 190 times that of the Moon. The history of telescopic observation of this planet, after the first sketches by Huygens in 1659, was marked by undeniable progress permitted by technical improvements, as shown by the observation of the polar caps by Herschel, or the drawing of the first "detailed" maps in the 19th century. These maps were established from regional variations of colour and albedo which, together with seasonal changes of some of these features, lead their authors to make Mars in a brother planet of the Earth (De Blasio, 2018). For example, the maps drawn by Phillips or by Proctor and Dawes, both in 1865, represent seas, lakes, rivers and continents which probably prepared

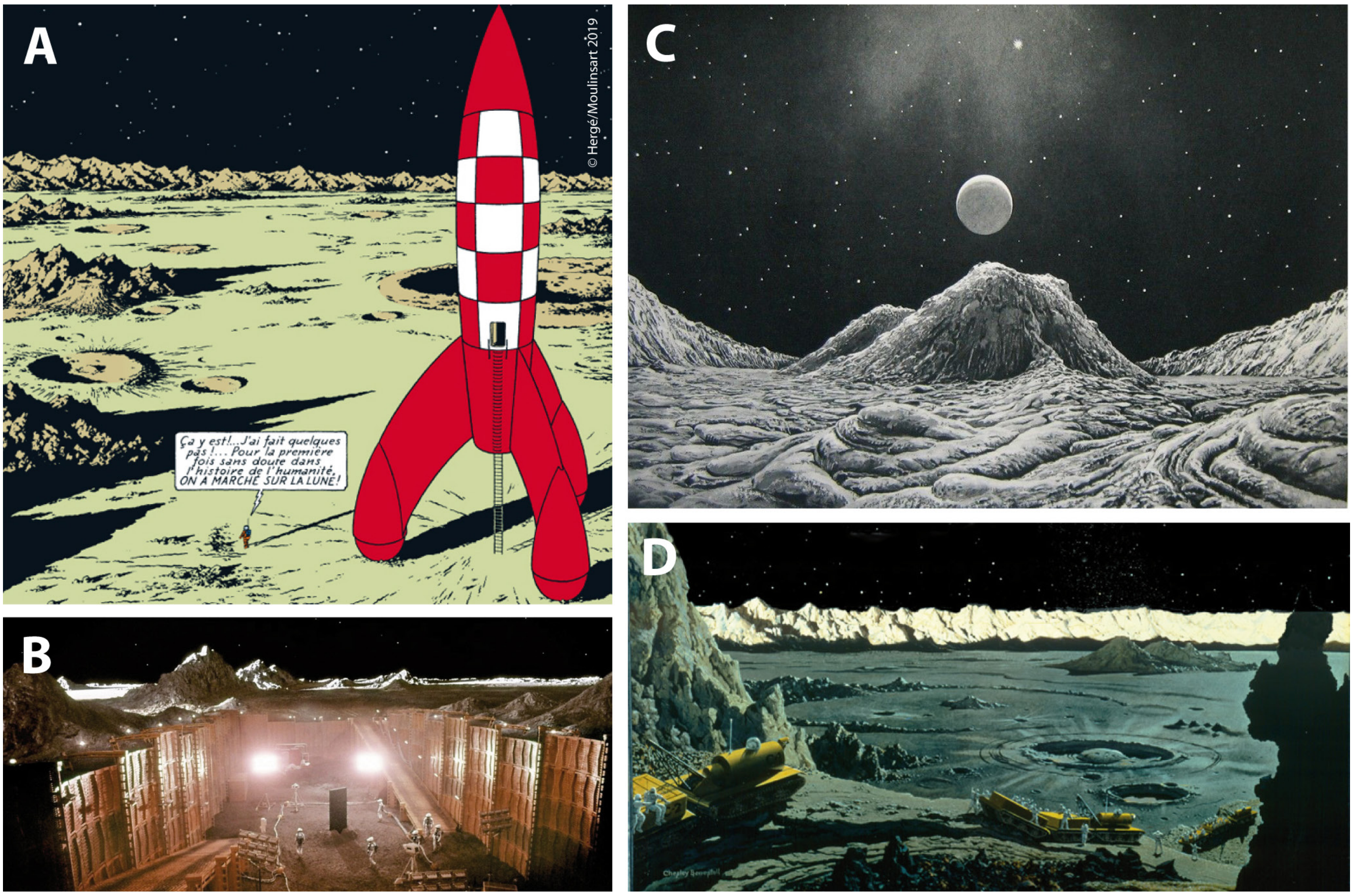

Fig. 4 – Landscape representations of the Moon before the Apollo missions.

A: "On a marché sur la Lune": just after landing in Professor Tournesol's rocket, Tintin makes a few small steps on the Moon, 15 years before the real "giant leap for mankind" of Neil Armstrong. Note the jagged peaks on the Hipparcos basin rampart, and the smaller impact craters on its floor. Image credit © Hergé / Moulinsart 2019. B: Excavating the monolith site on the Moon, in S. Kubrick's "2001, A space odyssey"; the topography is still represented as extremely rugged. Image credit © MGM, Stanley Kubrick Productions and « Polaris ». C: The planet Earth, as seen from the Moon, close to the central peak of a crater; such as represented, the topography suggests the presence of lava flows and a volcanic origin; drawing by L. Rudaux, 1937. D: "Exploring Sinus Roris on the Moon": the topography is very similar to that represented by Hergé. Painting by C. Bonnestell, *in* von Braun et al., 1952.

Fig. 4 – Représentations des paysages lunaires avant les missions Apollo.

A : « On a marché sur la Lune » : juste après l'alunissage de la fusée conçue par le Professeur Tournesol, Tintin fait quelques « petits » pas sur la Lune, quinze ans avant le réel « grand pas pour l'Humanité » de Neil Armstrong ; noter les pics déchiquetés sur le rempart du bassin Hipparcos et les plus petits cratères d'impact sur son fond. Crédit image © Hergé / Moulinsart 2019. B : Excavation du monolithe sur la Lune, dans le film de S. Kubrick « 2001, l'Odyssée de l'Espace » ; la topographie est encore représentée comme extrêmement accidentée. Crédit image © MGM, Stanley Kubrick Productions et « Polaris ». C : La planète Terre vue de la Lune, près du pic central d'un cratère ; la topographie, telle qu'elle est représentée ici, suggère des coulées de lave et une origine volcanique du sol lunaire. Dessin de L. Rudaux, 1937. D : Exploration de Sinus Roris sur la Lune : la topographie apparaît très similaire à celle représentée par Hergé. Peinture par C. Bonnestell, dans von Braun et al., 1952.

many other astronomers to be victims of biased observations and to be the actors of "*one of the most famous blunders in the history of science: the case of the Martian canals*" (De Blasio, 2018).

This is what happened with the Italian astronomer Schiaparelli, who started the systematic observation of the planet during the opposition of 1877, reported many details on his maps (*e.g.,* a white spot named Nix Olympica and later identified as the volcano Olympus Mons), and studied seasonal variations which he attributed to evaporation and condensation of water and to atmospheric transport. With the "help" of his astigmatic sight (De Blasio, 2018), he also identified mysterious channels which appeared to cut the entire surface of the planet, between areas of low albedo (fig. 5A). For him, they had to be water channels, under an atmosphere sufficiently dense and warm to authorize the presence of liquid water. Although neutral about the origin of these features, this interpretation is at the origin of the incredible speculations which led to the popular representations of Martian landscapes and life that prevailed until the mid-20th century and the first Martian missions of the space age.

Unfortunately (or not!) the Italian word "canali" was translated in English publications as "canals", a word indicating an artificial origin. In the following years, maps were published with lots of details showing these straight and wide (100 km or more) arteries linking dark areas interpreted as lakes or seas, by Schiaparelli himself, and other enthusiastic astronomers such as Flammarion (1884). In his book "*Les terres du ciel*", Flammarion also wrote about the forms of life and the characteristics of the inhabitants of the planet, as well as their degree of civilization. What we now call geodiversity was not forgotten, as shown by imaginary landscapes of plains and canals drawn for "*Les terres du ciel*" (fig. 5B). These ideas were so popular that one of the Schiaparelli's followers, the wealthy American Lowell built an observatory in Flagstaff (Arizona), entirely dedicated to the observation of Mars. Not only he also "*saw*" the channels, but he mapped them as double canals, which could only be the products of an advanced civilization. A belief that remained popular until the 1930s, when a pre-Schiaparelli Mars returned in the opinion of the astronomers who realized that these straight features were merely the effects of optical illusions. However, many people still believed in the channels, and in strips of vegetation associated with water masses, until the deception caused by the first pictures of a lunar-type surface revealed by the 21 images of the Mariner 4 flyby mission in 1964. Thus, maps showing some of these features, such as those drawn by Slipher at the Lowell Observatory (fig. 5C), were still in use during the Mariner exploration (De Blasio, 2018).

Fantasy was much greater in the representation of the surfaces of other planets and satellites, since no detail was visible. For example, Mercury was represented as having one side, with high mountains, in the eternal day and the other always in the darkness. Venus could

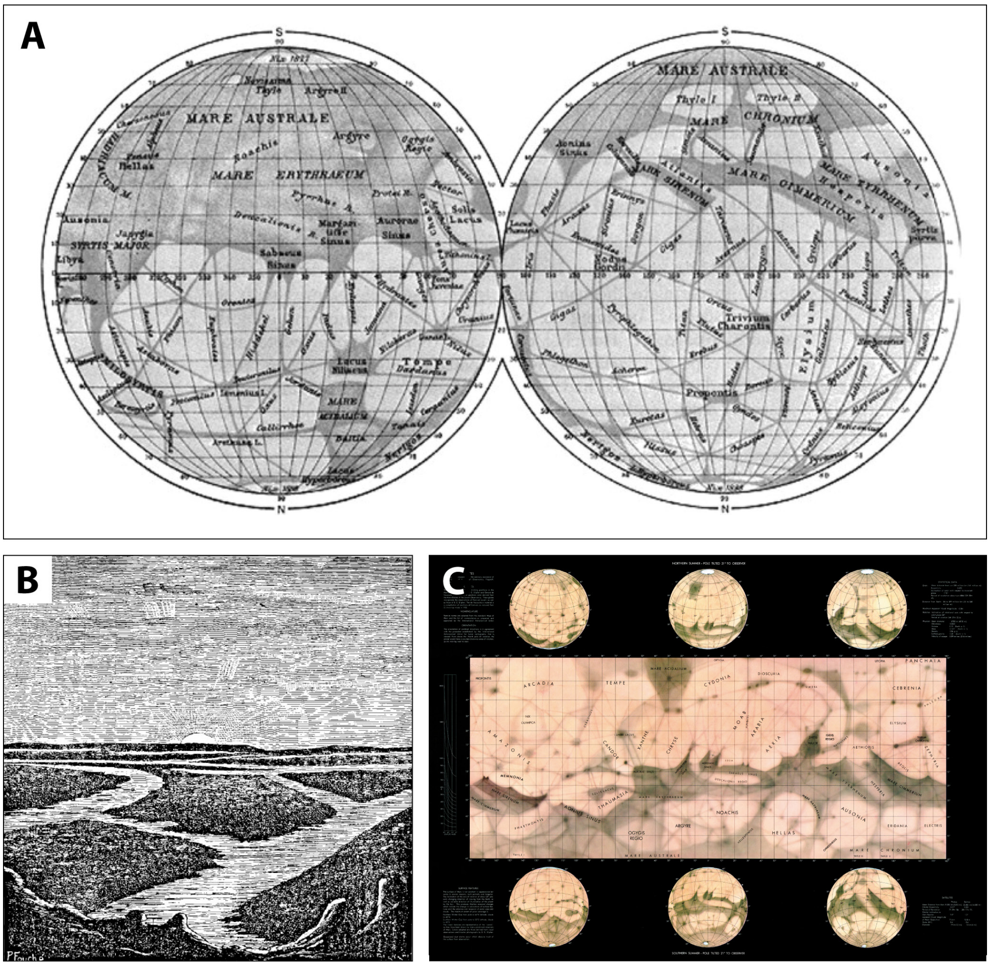

Fig. 5 – Historical representations of the Martian geodiversity and, in particular, of its controversial "canals".

A: Schiaparelli's map of Mars based on his observations of 1877–1888 showing the global network of "canals" (from NASA Special Publication 337). B: Engraving of a sunrise on the Martian "canals" (Flammarion, 1884, *Les Terres du Ciel*, p. 73). C: E.C. Slipher's Map of Mars: MEC-1 Prototype (Lowell Observatory) published by United States Air Force at 1:35,000,000; this map, still representing the "canals", was prepared in 1962 to assist with the upcoming Mariner missions to Mars. Image credit © Library of Congress Geography and Map Division Washington.

Fig. 5 – Représentations historiques de la géodiversité martienne et, en particulier, de son réseau de « canaux » à l'existence et à l'interprétation controversées.

A : Carte historique de Schiaparelli, basée sur ses observations de 1877-1878 et montrant le réseau planétaire de « canaux » martiens (d'après NASA Special Publication 337). B : Gravure d'un lever de soleil sur les « canaux » martiens (Flammarion, 1884, Les Terres du Ciel, p. 73). C : Carte de Slipher : MEC-1 Prototype (Observatoire Lowell) publiée par l'USAF (United States Air Force) à l'échelle 1/35 000 000 ; cette carte, représentant encore les « canaux » martiens, a été produite en 1962 pour préparer les futures missions Mariner. Crédit image © Library of Congress Geography and Map Division Washington.

have oceans of soda water or Carboniferous forests, possibly with monsters (Hardy, 1989). Among the moons of the giant planets, those of Jupiter were thought to have ice and fire surfaces, whereas the biggest one of Saturn, Titan, was known to have an atmosphere of methane, with clouds hiding any detail of its surface and opening it –like that of Venus– to all speculations of science-fiction writers and illustrators.

3.2. Space age: opening new worlds to geosciences and representations of exogeodiversity

3.2.1. Decisive technical progress in imaging and remote sensing

The representation of planetary landscapes underwent a complete revolution in the 1960s with sending of interplanetary probes, first towards our nearest neighbours, the Moon, Venus and Mars. As soon as 1959, the Soviet probe Luna 3 had got pictures of a surface which so far had remained forbidden to any observation: the far side of the Moon, which appeared almost completely ploughed by craters. From this date, new missions were launched every year, bringing a wealth of new details. This period –the 1960s and 1970s– is that of rapid progress in remote sensing techniques, stimulated by the rapid development of satellites dedicated to the observation of the Earth from space (Bell III et al., 1999; Wu et al., 2018).

These techniques include imaging systems, first developed from photography in spite of the difficult calibration of the photographs: it was used for the film system of Lunar Orbiter, whose photographs were sent to Earth by facsimile. The next step was the use of Vidicon imaging systems, where the image is first formed on a photoconductive surface whose negative charge is reduced in proportion to scene brightness, and then read out by a scanning electron beam, producing the video signal current and the image which is digitized and sent back to the Earth (Mariner probes, Viking, Voyager from 1964 to the late 1970s). The photoconductive surface was sensible to visible light, but multispectral data could already be obtained with the use of a filter wheel with several broadband filters. More recently, CCD cameras have replaced these visible wavelengths instruments, with detectors providing excellent dynamic range, linearity and responsivity from the near UV through the near IR. They operate by allowing incident photons to produce a current in silicon-based semiconducting chips divided into millions of independent pixels organized into 2-D arrays. Technical improvements have allowed the production of high-quality imaging, from telescopes as well from spacecraft cameras, at near-IR and mid-IR wavelengths (200 nm to 1,110 nm) with only modest cooling requirements. In the same time, radar remote sensing systems were developed, with application to the study of Earth and other planetary surfaces, from Earth-based telescopes as well as from satellites and spacecrafts. These active remote sensing systems were also used for producing altimetric data (radar altimetry of the Earth, Venus, Titan; laser altimetry: MOLA mapping of Mars). At last, since the 1990s, combining imaging and spectroscopic techniques brought decisive progress for the determination of compositional information and the mapping of this information across planetary surfaces at high resolution (tab. 2).

3.2.2. From automatic to human exploration: The Moon

The most rapid progress was accomplished on the Moon, with the preparation (in only 6 years!) of the Apollo manned missions, in the context of a tough competition with the Soviet program of exploration. The first preoccupation was to get the most precise images and maps at all scales, from space (Lunar Orbiter I to V, 1966) and on the ground (Surveyor and Luna "*soft*" landers, 1964-1968). These probes respectively provided the first global photographic cover, allowing the drawing of a global map and showing landscapes with numberless craters of all sizes (down to a few dm in diameter), rounded hills and mountains, rocky and dusty soils, under a deep black sky. The images of Surveyor 3, and then 7, which landed respectively in the plains of Oceanus Procellarum and on the rim of the crater Tycho in April 1967 and January 1968, were the first to show the lunar surface in high resolution (Greeley, 1985) (fig. 6A). Although very important in the history of landscape discovery and representation of other worlds, these black and white images do not bear the quality and the diversity of points of view that were offered in the following years (1969-1972) by the manned exploration of the Moon. In particular the pictures taken during the Apollo 11 mission, showing the first human beings walking in an alien environment, bore an emotional charge which completely transcended the scientific value of these scenes (fig. 6B). Hence, although not the most geologically interesting, the landing site where Neil Armstrong left the first foot print on the Moon (Tranquillity Base) is probably the most significant site of the space exploration history, as site to be absolutely preserved from the inevitable degradation which will occur with the next steps of exploration and colonization of our satellite (Fewer, 2007).

Field work during the next Apollo missions brought such a wealth of photographs, data and rock samples that their study is still ongoing. These field trips, first on foot (Apollo 12 and 14), and then with the help of a rover (Apollo 15, 16, 17) were turned towards a large diversity of geological and geomorphic targets, on increasing distances (up to 30,5 km for Apollo 17, the last mission, and the only one to include a geoscientist, *i.e.,* the geologist Schmidt). Completed by high resolution pictures taken from the Command Module in orbit, and more recently by various orbital probes equipped with CCD multispectral cameras (in particular the Lunar Reconnaissance Orbiter –LRO– since 2009), the ground based photographs allow geomorphological studies as precise as those that can be carried on Earth, since the points of view and scales of observation are exactly those required by the scientists during the field trip.

Among the sites that provided the greatest variety of landscapes and geological units, those visited by the astronauts of the Apollo 15 and 17 missions were probably the most spectacular: respectively the deep volcanic channel of Hadley Rille on the eastern margin of Mare Imbrium (fig. 6C) and the mountains and valleys of the Taurus-Littrow region, on the southeast margin of Mare Serenitatis. Beyond the scientific interest, and the aesthetic and even historic value of these sites represented on high resolution black and white or colour photographs (*e.g.,* the Surveyor 3 landing site and wreck visited by the Apollo 12 astronauts), the presence of human silhouettes and vehicles not only gives a familiar scale to these alien landscapes, but also gives them the supplementary

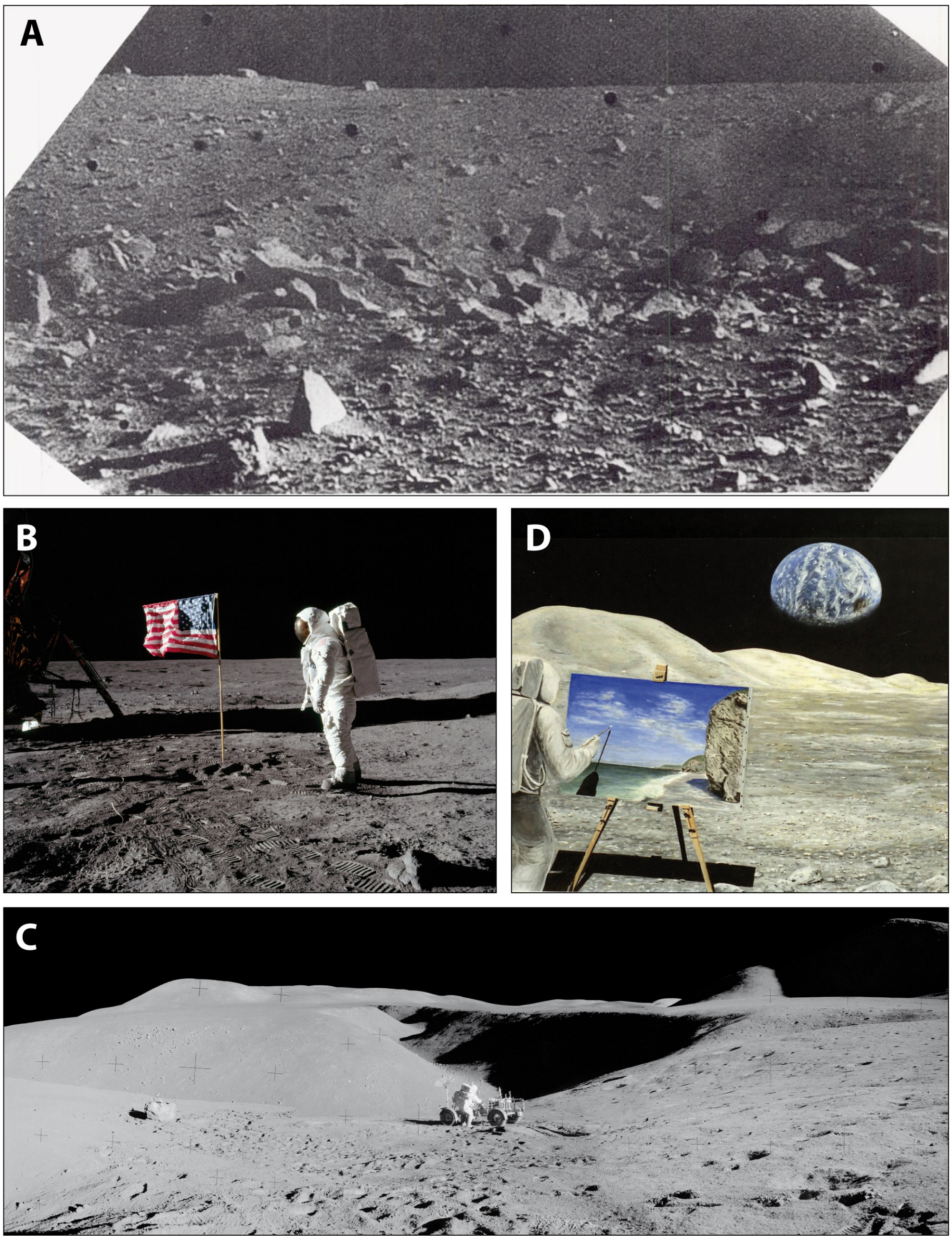

Fig. 6 – Lunar landscapes viewed by ground photography.

A: Lunar surface imaged by Surveyor 3 lander (April 21, 1967); Angular blocks, up to 2 meters in diameter, form part of a strewn field of blocks that surround a sharp-rim crater. B: Apollo 11 mission: Astronaut Buzz Aldrin with scientific equipment, US flag and human footprints (foreground) at Tranquility Base. Photo by Neil Armstrong. C: Apollo 15 mission: Astronaut Dave Scott and the Lunar Rover with a view up Hadley Rille in the background. D: The Moon, another point of view for studying the Earth? This was really the case in the history of Earth and planetary sciences, and for understanding the origin of our own planet. Painting by J.P. Peulvast. Image credits © Courtesy NASA/JPL (A, B, and C) and J.P. Peulvast (D).

Fig. 6 – Paysages lunaires vus à travers la photographie au sol.

A : Surface lunaire photographiée par la sonde américaine Surveyor 3 (21 avril 1967) ; des blocs anguleux, d'un diamètre pouvant atteindre 2 mètres, forment une partie d'un vaste champ de blocs entourant les remparts escarpés d'un cratère. B : Mission Apollo 11 : l'astronaute Buzz Aldrin avec son équipement scientifique, le drapeau américain et, au premier plan, les traces de pas des astronautes qui ont aujourd'hui une valeur archéologique (Base de la Tranquillité). Photo par Neil Armstrong. C : Mission Apollo 15 : l'astronaute Dave Scott et le rover lunaire avec vue sur le Sillon de Hadley à l'arrière-plan. D : La Lune, un autre point de vue pour étudier et représenter la Terre ? Ceci a réellement été le cas dans l'histoire des sciences de la Terre et des planètes, et pour la compréhension de l'origine de notre propre planète. Peinture par J.P. Peulvast. Crédits image © Avec la permission de NASA/JPL (A, B et C) et J.P. Peulvast (D).

dimension of a land open to human curiosity and imagination (fig. 6D). These missions and those which will take place in the future, mark the beginning of the same process of identification, evaluation, promotion and protection of geo(morpho)sites as currently operating on Earth.

3.2.3. Revealing the mysteries of the Red Planet

The same cannot yet be said of the Martian landscapes, although the extraordinary "*selfies*" constructed from pictures sent by the Curiosity rover operating in Gale Crater (southern margin of Elysium Planitia) partly give a comparable impression of a human presence in the desolated cold deserts of the Red Planet (fig. 7A). The first pictures taken on the Martian surface were sent in 1976 by the Viking I and II landers, from sites which had been chosen on low resolution views provided by the Mariner 9 orbiter (fig. 7B). After the end of an unexpected giant dust storm, in 1972, the Mariner 9 pictures had revealed the main features of the planet such as the dichotomy between highly cratered terrains of the southern hemisphere opposed to the flat plains of the northern hemisphere, the presence of huge volcanoes, the Valles Marineris canyons, etc. The Viking landing sites were respectively Chryse Planitia, at the mouth of the large complex of outflow channels which cuts the eastern part of the Tharsis plateau, and Utopia Planitia, both in the northern hemisphere (fig. 7C). As expected, they showed desert landscapes where soils strewn with rocks were partly covered by small dunes. This part of the mission dedicated to *in situ* geological observations and to the search for life was completed by a global mapping project based on higher resolution images (200 m and locally down to 10 m) provided by the Viking orbiters.

This global mapping based on 25,000 images remained the only one available during 20 years, until the Mars Global Surveyor (1996), Mars Odyssey (2001) and Mars Express (2003) missions. It was the base for decisive progress in the knowledge of the geology, geomorphology and other physical characteristics of Mars, with photomosaics of the whole planet using Mercator projection, detailed topographic maps (*e.g.,* Valles Marineris, in the Coprates Norhtwest Quadrangle: USGS, 1986), a complete set of "*geological*" (in fact, mainly morphostratigraphic) (Peulvast and Vanney, 2002) maps at 1:15,000,000 (Scott and Tanaka, 1986; Greeley and Guest, 1987; Tanaka and Scott, 1987), various regional geological maps such as Valles Marineris (Witbeck et al., 1991) and more local geomorphological maps (*e.g.,* Peulvast and Masson, 1993; Peulvast et al., 2001).

Hence, a relatively complete overview of the Red Planet had already been realized at the beginning of the 2000s. It showed the image of a cold, desert planet with periglacial features and permanent ice caps undergoing seasonal variations, under a thin CO$_2$ atmosphere. The planet was known to have undergone volcanism, water runoff and large outflow events in a remote past. The observation of differences in crater distribution and characteristics had allowed the elaboration of a geological chronology and of distribution models of ground ice, for example (Carr, 1981; Baker, 1982; Greeley, 1985; Costard, 1990; Uchupi and Emery, 1993). A large range of remarkable geological and geomorphological sites had been identified but their number had to increase with the following missions, including multispectral imagery, and high resolution altimetry and mapping (the MOC, THEMIS and HRSC images of Mars Odyssey and Mars Express, the MOLA altimeter of Mars Odyssey and then the high to very high resolution images of the MRO CTX and HiRISE cameras, since 2005) (tab. 2), which were used to elaborate precise altimetric models (MOLA DTM and map) (fig. 7C), detailed studies of geological, geochemical and morphological features of the planet at all scales, of its history and dynamics, and also to choose the best sites for in situ exploration.

This was the base for the success of the next landing missions: Pathfinder, with the small rover Sojourner (1997), the Spirit and Opportunity rovers (landing in 2004), the Curiosity rover (since 2012) and the Phoenix and Insight landers (2008 and 2019). Not only a large range of landscapes and landforms such as river beds,

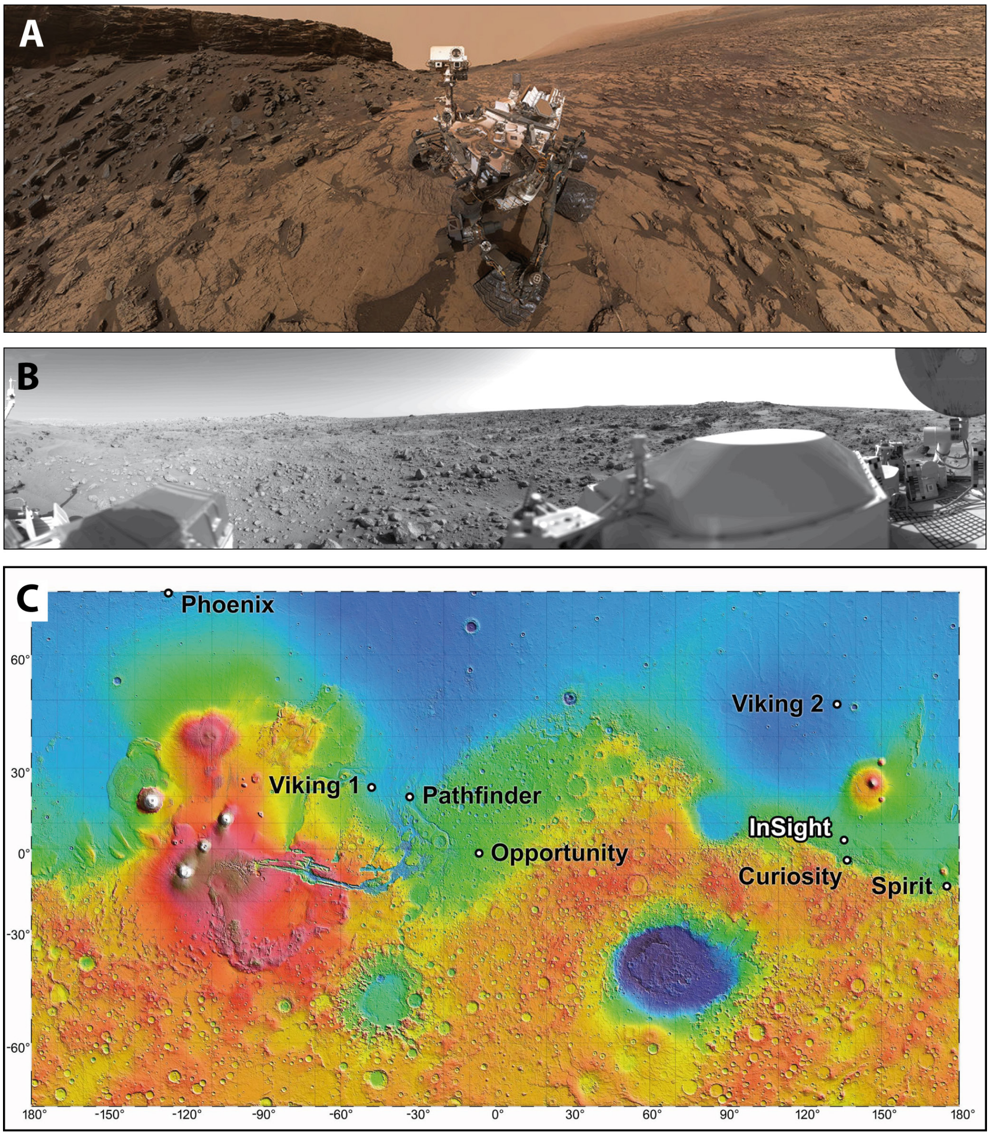

Fig. 7 – Landed spacecraft missions on Mars.

A: Curiosity Rover "selfie" (September 17, 2016) in the Murray Buttes region of Gale Crater (MSL Mastcam Panorama); note the pale outline of Aeolis Mons in the distance, to the right of the rover's mastcam. B: Panoramic view of the Martian terrain in Chryse Planitia at the Viking 1 landing site (July 20, 1976). C: Map of Mars showing the landing sites of the main Martian probes. Global topography from MOLA DTM (Mars Orbiter Laser Altimeter – Color Shaded Relief). Image Credits © Courtesy NASA/ JPL-Caltech/ GSFC.

Fig. 7 – Missions spatiales avec atterrisseur sur Mars.

A : « Selfie » du Rover Curiosity (17 septembre 2016) dans la région des Buttes Murray de Gale Crater (MSL Mastcam Panorama) ; à l'arrière-plan à droite, les hauteurs d'Aeolis Mons. B : Vue panoramique du sol martien dans la région de Chryse Planitia sur le site d'atterrissage de Viking 1 (20 juillet 1976). C : Carte du relief martien localisant les sites d'atterrissage des principales sondes spatiales. Topographie issue du MNT MOLA (Mars Orbiter Laser Altimeter) en relief ombré colorisé. Crédits image © Avec la permission de NASA/JPL-Caltech/ GSFC.

dunes, impact craters, etc., was revealed from these sites, at various latitudes and on increasing surfaces and distances, but also close-ups of geological structures such as the stratified deposits of the Gale Crater and Mount Sharp, which are fundamental, together with in situ mineralogical and geochemical analyses, for studying the past presence of water and possible life (fig. 7A).

Following the evolution of some of these features on orbital views during many seasons and years also helps identifying currently active processes such as wind action, occurrence of sand or debris flows on dunes and crater ramparts, or changes in enigmatic holes and other forms on the margins of the polar caps. These observations feed numberless publications and discussions on the role of phase transitions of water, brines and CO_2 in the dynamics which still shape the surface of the planet (Costard et al., 2002; Melosh, 2011; De Blasio, 2018).

Beyond the scientific value of these documents, processing of raw images allows the production of all kinds of false colour pictures and 3D perspective views which give an aesthetic dimension to an infinity of geomorphic or geological features of the planet, as shown by the superb illustrations of the big book "*Mars, the ultimate guide of the Red Planet*", by Sparrow (2014). Among them, the perspective views of Olympus Mons and Valles Marineris are the most spectacular, but indeed, most pictures provided by this fantastic bank of images (in free access on internet) might justify the identification of exogeomorphosites. Although the reality is already spectacular, artist views still increase this wealth of sights and landscapes, bringing new perspectives, simulations of past or future configurations (the possible seas or lakes of the Noachian era, or those possibly created in an improbable future by a process of terraformation) or even guides for space tourism (Lagrange and Huguet, 2003). The quality of the "*real*" imagery is such that it helps choosing or creating more and more realistic sceneries for anticipation films, often from comparable terrestrial landscapes (for example, Jordanian desert landscapes used by Scott in "*The Martian*" in 2015).

3.2.4. Unveiling hidden and remote worlds with unexpected geodiversity

Until the 1990s, the other planets of the solar system remained at the same time a domain of exciting discoveries, and of inaccessibility, because of their distance or their difficult environment (Mercury, Venus). The first observations of their unexpected diversity had often brought more questions than answers. Hence, during a long time, Mercury, the smallest of the telluric planets, remained poorly studied in spite of its relative proximity, since any mission is complex because of the high speeds to be reached and of the gravity field of the Sun which makes the orbits unstable. The first precise pictures were acquired during the three flybys of the Mariner 10 probe in 1975. These pictures only covered one half of the planet with various resolutions similar to those of telescopic images of the Moon. They revealed a highly cratered surface reminiscent of that of the Moon, in spite of the presence of original features (giant impact basins such as Caloris, smooth and inter-crater plains, systems of arcuate scarps and ridges, etc.), suggesting a different geodynamic history. Together with harsh temperature conditions which make impossible any human exploration in a predictable future, this is precisely what makes this planet a relatively secondary target in exploration programs. Indeed, one had to wait for the NASA's MESSENGER orbital mission (2004-2015) and the joint European–Japanese missions Bepi/Columbo (2 probes, 2018) to get a global high-resolution multispectral mapping of the planet.

Aiming Venus was less difficult and more tempting, because of its relative proximity and of some similarities with the Earth, in particular in size, which could allow speculations on its environment and possible life. Its perpetual cloud cover had always made it mysterious. This challenge explains that as soon as 1962, the NASA sent the first probe to make a flyby of another planet (Mariner 2). This mission revealed extreme conditions of pressure and temperature (estimated at the time to almost 500 °C) on the ground. Therefore, it appeared that no "*classical*" imaging technique could reveal the morphology of this planet.

The study of the Venusian surface could only begin in the 1970s with landings of Soviet Venera 9, 10, 13 and 14 spacecrafts (1975, 1981) which gave estimates of the composition of the surface materials, and images of plains or gentle hills where slabs or scattered rock outcrops alternate with loose material, in a reddish light. A global overview of the planet was obtained in the same time by Earth-based radar observations, which announced the beginning of the geological and geomorphological study of the planet (Greeley, 1985). The Pioneer Venus orbiter (1978) greatly contributed to this exploration owing to its radar altimeter, whose data, combined with the results of previous approaches and with radar images obtained by the Venera 15 and 16 orbiters, were the base, until the Magellan mission, for the construction by the USGS of the first global "topographic" map of the planet (1983). In fact, the radar images need a careful interpretation, since radio waves emitted or reflected from planetary surfaces yield complex information including estimates of surface roughness (from bright –rough– to dark –smooth), average surface slopes, and other physical and chemical characteristics such as the dielectric constant. This is why a "*Guide to Magellan Image Interpretation*" was published (Ford et al., 1993) in order to help scientists in the exploitation of data obtained by the Magellan orbiter launched by the NASA in 1989.

Until now, the global radar and altimetric cover by Magellan remains the most complete base for geological and geomorphological studies of Venus. The precise topographic maps and the mean to high resolution photomosaics, as well as magnificent 3D false colour pictures of volcanoes or craters obtained by combining radar images and laser altimetry, provided the image of a mainly volcanic world, only slightly modified by winds of its thick, heavy and hot CO_2 atmosphere, where rough highlands (up to 11 km) and low smooth plains are strewn with various types of original structures (impact craters, volcanoes, coronae, folded mountain belts, tesserae, etc.) revealing the wide geodiversity of a geologically active planet (Saunders, 1992). Its global geodynamics, nevertheless, differs from that of the Earth, mainly because of the loss of its water and of its high surface temperature (Peulvast and Vanney, 2002; Melosh, 2011). Despite its high interest, the extreme difficulty of ground exploration explains the relative paucity of the projects specifically designed for a study of the surface of Venus.

On the contrary, the solid worlds of the outer solar system retain more attention, for various reasons (Brahic, 2010). Identified but largely unknown in the telescopic age, they were visited relatively early in the space age, by the NASA probes Pioneer 10 and 11 (flyby of Jupiter in 1973, flybys of Jupiter and Saturn in 1974 and 1979), and then Voyager 1 (flybys of Jupiter and Saturn in 1979 and 1980), and Voyager 2 (flybys of Jupiter, Saturn, Uranus and Neptune in 1979, 1981, 1986, 1989). This was really the first phase of exploration of the giant planets, but also of their cold, icy or rocky satellites which form a wide collection of geological objects of all sizes and display an extraordinary exogeodiversity. Hence, many worlds were open to geomorphological exploration, from the biggest icy bodies (Europa, Ganymede, Callisto, Triton) to the most active volcanic world of the solar system (Io) and to the most mysterious (Titan), plus tens of smaller ice or rock satellites, and also the ring systems already known around Saturn, which appeared to exist also around the other giant planets. Owing to the visible and multispectral cameras mounted on the probes, large parts of these bodies were already mapped after these first missions (Uchupi and Emery, 1993), but decisive progress in resolution and cover percentage was accomplished with the orbiters of the Galileo (1995-2003), Cassini (2004-2017) and Juno (2016-) missions, not only for Jupiter and Saturn, but also for their satellites, including many small ones which so far were unknown. Imaging and mapping were performed in visible and infrared wave lengths, producing magnificent pictures, in particular of the active volcanoes of Io, or of the thin and fractured ice shell of Europa (fig. 8A-B). This last world, together with the Saturn and Uranus satellites Enceladus and Triton (fig. 9A), and their geysers, appear as geologically active, and Europa and Enceladus are considered as the most promising for the search of an eventual life in the depths of their global oceans. This is why they will be priorities for next missions to the outer solar system. But many other fascinating features were revealed, for example the unique morphology of Miranda (Uranus satellite), which looks like a giant patchwork with giant ice cliffs and ring structures (fig. 9B).

However, one of these worlds remained out of reach the first salvo of spacecraft observations: Titan, the biggest satellite of Saturn, perpetually hidden by a continuous haze cover which could only be pierced by non-visible radiations (micro wave, infra-red). Its mysteries were largely unveiled by the specially designed Cassini-Huygens mission, which confirmed the models previously elaborated from Earth-based observations through the analysis of its atmosphere mainly composed of N_2 with clouds of ethane and methane: the presence of liquid methane bodies on a mainly icy surface (fig. 2G). The Cassini radar and infra-red pictures effectively detected their presence, whereas the Huygens lander finally showed a solid, sandy surface strewn with rounded blocks of ice (fig. 10A). Global mapping of Titan, obtained by combined radar and infra-red observations, shows a rugged surface mainly composed of water ice (plus possible organic material and a very dark unknown material at equatorial latitudes). The morphology presents high mountains, plain craters, complex river systems, lakes, seas, dune fields of probably organic dust (Solomonidou et al., 2017) (fig. 10B). The completely exotic environment, with extremely low temperatures allows the occurrence of methane rains and runoff, below ethane clouds, and rapid variations in lake volumes and surfaces (for example the Lake Ontario, in the southern hemisphere). The originality of this geodiversity lies in the composition of their elements more than in their appearance and the erosive process which shapes these landforms, which show many similarities with features of the terrestrial morphology.

More recently, the New Horizons probe, launched in 2006, reached in 2015 the remote Pluto, henceforth considered as one of the small planets of the solar system, and realized a flyby which gave exciting close-ups of the planet and of its icy satellites, including the biggest

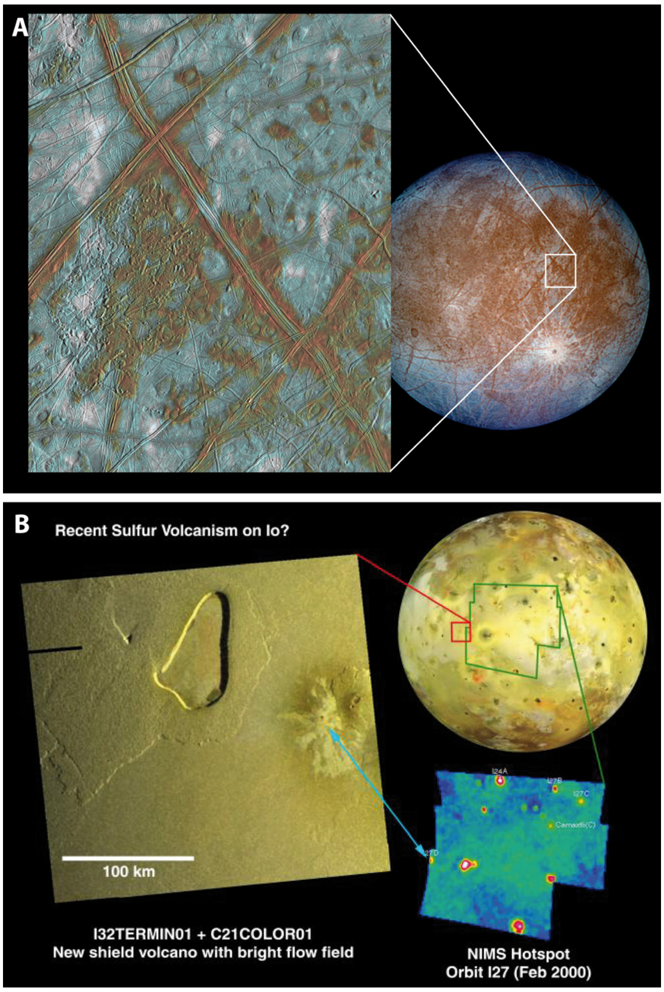

Fig. 8 – An overview of the geodiversity of Europa and Io (Jupiter's moons).

A: General view of the icy surface of Europa, and details on a region made of subdued blocks and faults; reddish-brown areas represent non-ice material resulting from recent geologic activity (Solid-State Imaging, Galileo Orbiter). B: General view of the buoyant volcanic surface of Io, and details on a region (left) showing a large patera, or volcanic depression, and a new shield volcano and associated lava flows of possible sulfur composition (Solid-State Imaging, Galileo Orbiter); this interpretation was supported by data acquired in February 2000 from near-infrared mapping spectrometer (lower right) showing the active hot spots in the equatorial region of Io. Image credits © Courtesy NASA/JPL/University of Arizona.

Fig. 8 – Un aperçu de la géodiversité des satellites Europe et Io (lunes de Jupiter).

A : Vue générale de la surface englacée d'Europe, et détails sur une région affectée de failles et de blocs subduits ; les zones brun rougeâtre représentent le matériel rocheux (absence de glace) résultant d'une activité géologique récente (Solid-State Imaging, Galileo Orbiter). B : Vue générale de la surface géologiquement active d'Io, et détails sur une région (image à gauche) montrant une large dépression volcanique et la formation d'un nouveau volcan-bouclier avec ses coulées de lave de probable composition sulfurée (Solid-State Imaging, Galileo Orbiter) ; cette interprétation a été confortée par les données acquises en février 2000 à partir d'une cartographie par spectrométrie infrarouge (en bas à droite) montrant les points chauds volcaniques dans la région équatoriale du satellite. Crédits image © Avec la permission de NASA/JPL/University of Arizona.

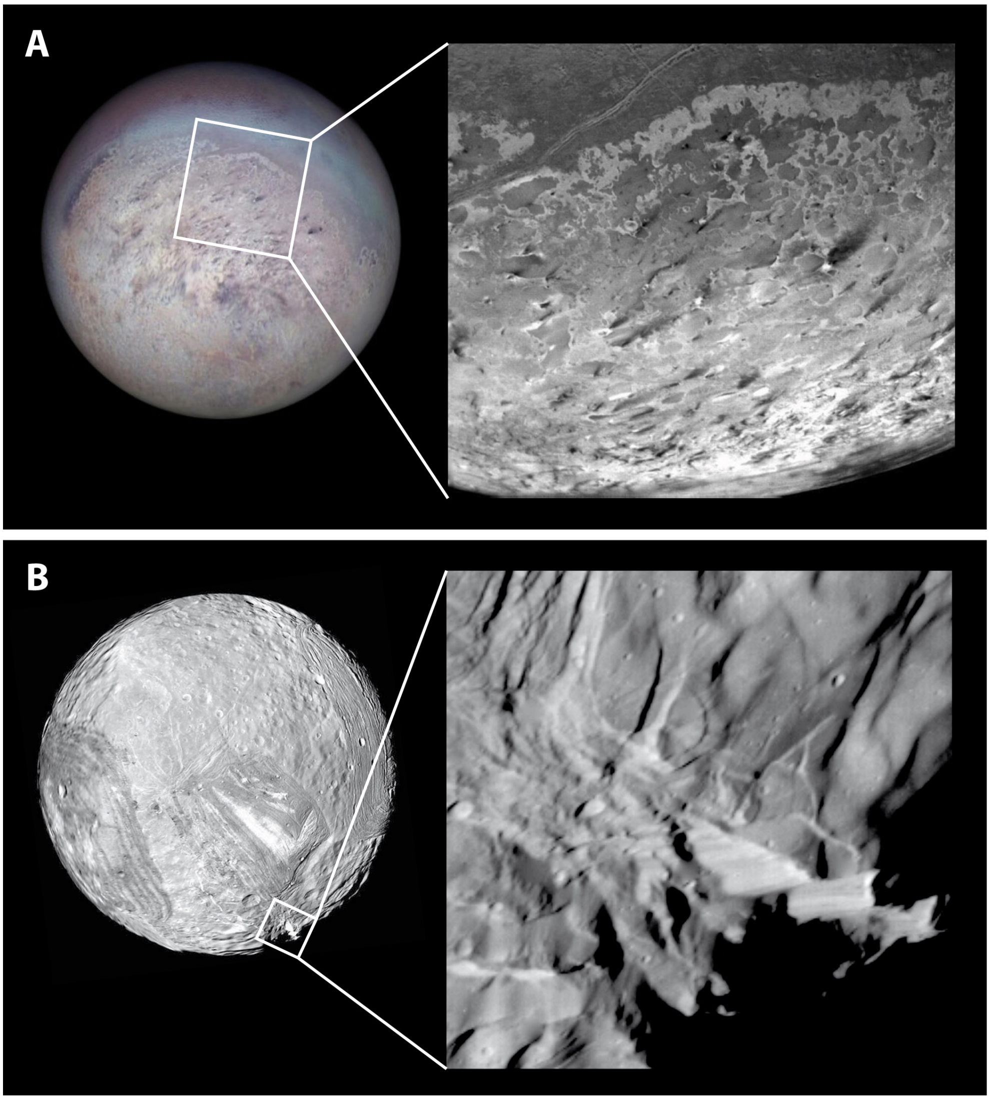

Fig. 9 – An overview of the geodiversity of Triton – the largest moon of Neptune – and of Miranda – the smallest and innermost of Uranus's five round satellites.

A: General view of the icy surface of Triton, and details on a 'Cantaloupe' terrain with dark plumes originating from nitrogen geysers and intersecting sets of structures of folds or faults (VG ISS, Voyager 2). B: General view of the rugged topography of Miranda, and details on one of the highest ice cliffs (below and right of center); this chaotic topography of ridges, scarps and valleys was probably produced by compressional tectonics, generating reverse fault scarps (VG ISS, Voyager 2). Image credits © Courtesy NASA/JPL.

Fig. 9 – Un aperçu de la géodiversité des satellites Triton – la plus grande lune de Neptune – et Miranda – la plus petite lune d'Uranus.

A : Vue générale de la surface gelée de Triton, et détails d'un terrain montrant des panaches sombres provenant de geysers d'azote et intersectant un ensemble affecté de plis et/ou de failles (VG ISS, Voyager 2). B : Vue générale de la topographie chaotique de Miranda, et détails d'une des plus hautes falaises de glace du satellite ; cette topographie très contrastée associant crêtes, escarpements et vallées profondes a probablement été produite par des dynamiques tectoniques compressives, générant des escarpements de faille inverse (VG ISS, Voyager 2). Crédits image © Avec la permission de NASA/JPL.

of them, Charon (Stern et al., 2015). Surprisingly, this reddish world appeared geologically active and, as some of the satellites of the giant planets, displays a fantastic geodiversity (fig. 11A). Pluto's encounter hemisphere shows ongoing surface geological activity centred on a vast basin (Sputnik Planum) containing a thick layer of volatile ices that appears to be involved in convection and advection, with a crater retention age no greater than ~10 Ma (Moore et al., 2016) (fig. 11B). Surrounding terrains show active glacial flow, apparent transport and rotation of large buoyant water-ice crustal blocks, and pitting, likely by sublimation erosion and/or collapse. More enigmatic features include tall mounds with central depressions which may be cryovolcanic, and complex ridges. Pluto also has ancient cratered terrains up to ~4 Ga old which are extensionally fractured and extensively mantled and perhaps eroded by glacial or other processes. Charon does not appear to be currently active, but shows the marks of major extensional tectonism and resurfacing (probably cryovolcanic) nearly 4 billion years ago.

Still more surprising is the past geological activity of Ceres, a dwarf planet of the asteroid belt, less than 1,000 km in diameter, studied and mapped from the orbiter of the Dawn spacecraft since 2015 (Buczkowski et al., 2016). Revealed by several cameras and altimetric instruments, its surface is mainly marked by impact craters of lunar type whose negligible relaxation indicates a mechanically strong crust. However, the identification of potentially cryogenic features (*e.g.,* large domes) suggests that there may be some ice in localized regions and in the interior of the planet, and that cryomagmatism has been active on Ceres.

The abundance of new imaging techniques and of topographic and other thematic maps, and the exogeodiversity revealed by the exploration of these remote worlds largely ultrapass the most audacious speculations of the pre-space age scientists and science fiction writers and illustrators. It is still wider if one considers the extraordinary diversity in the sizes and shapes of the asteroids and comets either visited on their way by the probes launched towards bigger objectives, or studied by spacecrafts specifically destinated to their exploration (*e.g.,* Rosetta mission, 2004-2016).

3.3. Beyond the scientific results: exogeodiversity in the future, from realistic anticipation to free imagination

The fantastic number and diversity of data, maps and images acquired, processed, elaborated and interpreted since the space age beginning have extended in huge proportions the scientific knowledge about domains which, so far, were more or less inaccessible. But, it also stimulated the production of many other representations, complementary of the "*objective*" ones coming from all types of observation platforms, and in which virtual 3D perspectives and artist views help reconstructing past or even future stages of planetary evolution, and are used for designing projects of colonization, or imagining the appearance of the other worlds still remaining beyond any possibility of access and direct observation.

Completing the magnificent 3D views and anaglyphs produced from MOLA DTM, and Mars Express and MRO HiRISE cameras, virtual perspective views of some giant features of Mars such as Chasma Boreale (north polar cap) or Olympus Mons, as well as of more local landforms such as huge landslides in Valles Marineris (fig. 2B) provide excellent bases for presenting and interpreting their geomorphological features, as was previously done in more traditional way by the use of hand-drawn block-diagrams (Peulvast and Masson, 1993). All of them are available online, on NASA, USGS and other sites, and may be downloaded, visualized as fictive flights on various platforms such as Google Moon or Access Mars. Production of virtual images combined with scientific data allow hypothetic representations of the ancient lakes and seas of the Red Planet, for example and, in this sense, contribute to the discussion of what could be the surface aspect and dynamics of an ancient "*hot*" and wet planet. Another use of these representations, where artistic design is also involved, is the elaboration of projects of vehicles, buildings and other infrastructures which could be constructed in the next steps of planetary exploration and colonization, on the Moon as well as on Mars (fig. 12).

As in the pre-space age of planetary exploration, there is still one domain where free imagination, hardly constrained by the scarce data obtained until now, is the immense and always increasing realm of the exoplanets. The geodiversity of the terrestrial-type exoplanets is probably as important or far wider and more unexpected than what was found in the solar system. Therefore, the field for imagination appears unlimited, as shown, for example by the floating mountains of Pandora, in Cameron's film "*Avatar*", or the tentative representations of the volcanic, icy or water worlds of recently found planetary systems and the exotic landscapes painted by the science-fiction illustrator Manchu, where some reminiscences can be found of those painted almost one century ago by Rudaux (Fossé and Manchu, 2018). New scientific data on exoplanetary surfaces, with images of higher and higher resolution, are expected to come in the next decades, that will necessarily change our perceptions and representations of such inaccessible

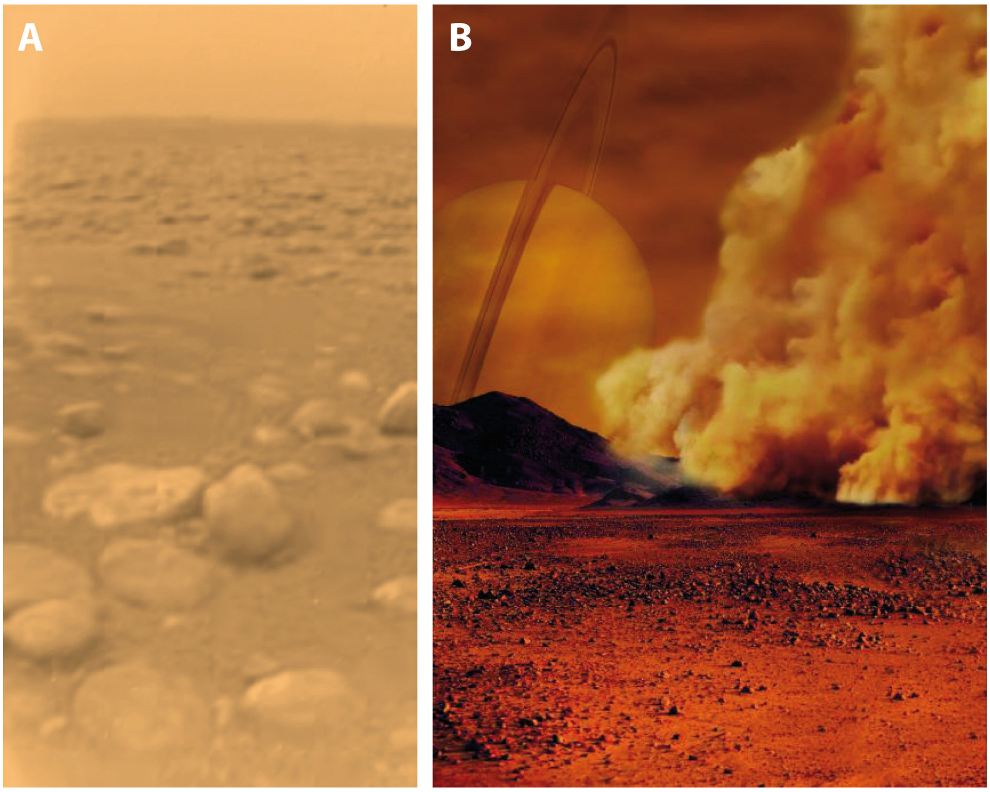

Fig. 10 – Complementary scientific and artist imageries of Titan's geodiversity.

A: First coloured view of the Titan surface, obtained by the European Space Agency's Huygens probe in 2005 as part of NASA's Cassini spacecraft to the Saturn system; note that the rounded blocks and pebbles, very similar to those of a river bed on Earth, were interpreted as evidence for fluvial activity, possibly by liquid methane or ethane. Image credit © NASA/JPL/ESA/University of Arizona. B: Artist's concept of a dust storm on Titan, whose N_2-rich atmosphere might be prone to powerful methane storms acting as efficient agents of wind erosion and dust deposition. Image credit © Courtesy NASA/ESA/IPGP/LabexUnivEarthS/University Paris Diderot.

Fig. 10 – Complémentarité de l'imagerie scientifique et artistique pour représenter la géodiversité de Titan.

A : Première photographie au sol de la surface de Titan, acquise par la sonde spatiale Huygens de l'Agence spatiale européenne (ESA) en 2005, partie intégrante de la mission Cassini (programme de la NASA) autour du système saturnien ; noter la présence de blocs et galets arrondis, similaires à ceux que l'on peut trouver dans les lits de rivière sur Terre, interprétés ici comme le résultat de processus fluviatiles en présence de méthane ou d'éthane liquide. Crédit image © NASA/JPL/ESA/University of Arizona. B : Vue d'artiste d'une tempête de poussière sur Titan, dont l'atmosphère riche en azote est favorable à l'activation de puissantes tempêtes méthanifères agissant comme des agents efficaces d'érosion éolienne. Crédit image © Avec la permission de NASA/ESA/IPGP/LabexUnivEarthS/University Paris Diderot.

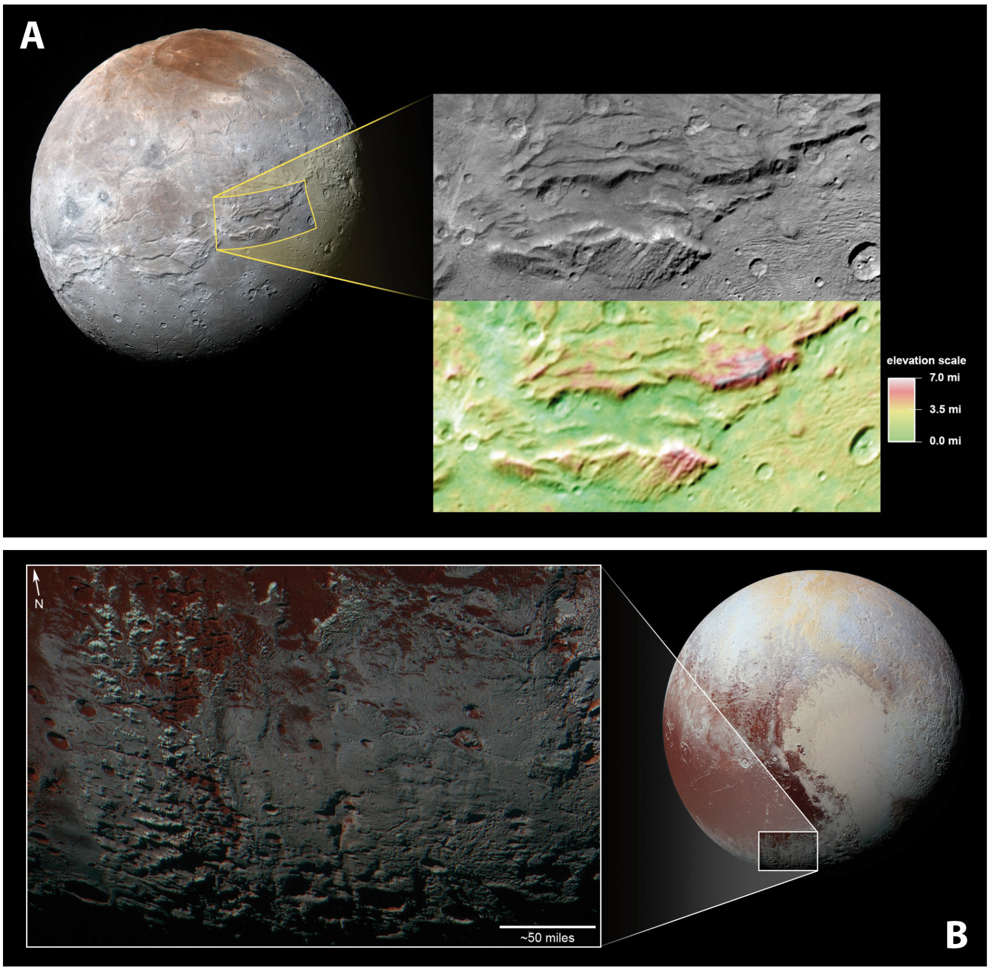

Fig. 11 – An overview of geodiversity of Pluto and of its largest moon, Charon.

A: General view of the rugged topography of Charon whose outer layer is primarily water ice, and topographic details on Serenity Chasma, part of a vast equatorial belt of chasms characterized by a system of “pull apart” tectonic faults which are expressed as sharp ridges, scarps and valleys (Long-Range Reconnaissance Imager – LORRI, New Horizons). B: General view of the contrasted surface of Pluto, and details on Cthulhu Regio, southwest of the vast nitrogen ice plains (in white-beige) of Sputnik Planitia; the detailed color image shows a system of bright mountains covered by a snowcap of atmospheric methane, interrupted by sharply cut valleys and flat-floored depressions (Multispectral Visible Imaging Camera – MVIC, New Horizons). Image credits © Courtesy NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute.

Fig. 11 – Un aperçu de la géodiversité de Pluton et de sa lune Charon.

A : Vue générale de la surface de Charon dont la couche supérieure est formée de glace, et détails topographiques sur la région de Serenity Chasma appartenant à une vaste ceinture équatoriale de gouffres et de dépressions guidées par des structures tectoniques en « pull-apart », lesquelles sont à l’origine de crêtes aigues, de grands escarpements et de vallées profondes (Long-Range Reconnaissance Imager – LORRI, New Horizons). B : Vue générale de la surface de Pluton, et détails sur la région de Cthulhu située au sud-ouest des vastes plaines d’azote gelé (en blanc-beige) de Sputnik Planitia ; l’image couleur détaillée montre un système de montagnes enneigées (neige de méthane atmosphérique), interrompues par des vallées profondes et des dépressions à fond plat (Caméra d’imagerie visible multispectrale – MVIC, New Horizons). Crédit image © Avec la permission de NASA/Johns Hopkins University Applied Physics Laboratory/ Southwest Research Institute.

Fig. 12 – Project of scientific station on Mars: Project Eagle Mars base. Image credit © Courtesy Blackbird interactive and NASA/JPL.

Fig. 12 – Projet de base scientifique sur Mars : le Projet de la Base Eagle Mars. Crédit image © Avec la permission de Blackbird interactive and NASA/JPL.

environments. Contrary to the solar system planets, exoplanets may not ever be visited by humans because of their distance, or may only be visited by humans in such a distant future that it is not possible to imagine the trajectories of our future representations, with a set of values possibly modified of influenced by the increasing use of artificial intelligence.

Whatever the future developments in engineering of robotic systems, the present combination of digital technologies and artistic representations appear as a promising tool for the promotion of exogeodiversity, and as an indirect way to protect it facing predictable threats by showing the extraordinary variety of its features in the solar system and beyond. Inspired by applications and experiences developed for the virtual discovery of our Earth's geoheritage (Cayla, 2014; Martínez-Graña et al., 2019), one domain of potential application is the development of virtual geological/geomorphological itineraries on celestial bodies where have been accumulated a lot of images in the very last years, *e.g.,* Mars and Titan. This perspective implies to develop new assessment methods adapted to the inventory and selection of exogeosites, including a precise evaluation of their scientific, historic, aesthetic, functional, cultural or artistic values.

4. Conclusion

This exploratory paper is a first attempt to deal with exogeodiversity – geodiversity being generally limited to Earth's abiotic diversity (Gray, 2013). It stresses the importance of both scientific and artistic imageries to assess exogeodiversity and its values, in the absence of direct (*in situ*) observations. Given the numerous threats that could affect exogeodiversity in the future, images and related new digital technologies offer a number of possible mitigation strategies to protect exogeodiversity in an indirect way, *e.g.,* by academic education. The "Planetary Geomorphology Image of the Month" (by Dr. de Haas and Dr. Conway: https://planetarygeomorphology.wordpress.com/) is one example of exogeodiversity promotion by the image under the auspices of the IAG (International Association of Geomorphologists), a popularization process to be continued and expanded by new ways. Among the interesting avenues to explore, the development of digital applications allowing virtual geological/geomorphological itineraries on celestial bodies *(e.g.,* Google Moon, Access Mars) is a promising issue in order to imagine new forms of virtual –rather than real and socially unequal– exogeotourism.

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Dans les approches traditionnelles développées depuis le milieu des années 1990, le concept de géodiversité a été limité, par convention, à la diversité abiotique de la planète Terre (Sharples, 1993 ; Kozlowski, 2004 ; Zwoliński, 2004 ; Serrano et Ruiz Flaño, 2007 ; Gray, 2013). Pourtant, dans le même temps, les missions d'exploration planétaire conduites par la NASA et/ou les autres agences spatiales –européenne, russe, japonaise, chinoise– ont révélé une étonnante diversité géologique et géomorphologique sur l'ensemble des corps planétaires solides du système solaire (planètes telluriques, satellites des planètes géantes, comètes et astéroïdes) et potentiellement au-delà (exoplanètes).

Dans cet article, nous proposons d'introduire le terme « exogéodiversité » pour désigner la diversité naturelle des corps solides extraterrestres dans leurs composantes géologique (structures, roches, minéraux), géomorphologique (formes de relief, processus d'érosion), pédologique (sols, régolithe) et hydrologique (eau et autres fluides), incluant leurs assemblages, relations, propriétés et systèmes. Comparée à la diversité abiotique de la Terre, la géodiversité extraterrestre possède plusieurs particularités telles que l'absence de fossiles et de matière organique dans les roches et dans les sols, respectivement –tout du moins jusqu'à preuve du contraire–, ainsi que par la présence d'une hydrosphère possiblement composée d'autres fluides, i.e., mers, lacs et rivières de méthane liquide sur Titan (Mitri et al., 2007 ; Neish et al., 2016). Toutefois et comme pour la géodiversité terrestre, l'exogéodiversité s'exprime à des échelles variées, depuis l'échelle globale des grandes structures planétaires (fig. 1), jusqu'à l'échelle élémentaire des atomes et particules, en passant par l'échelle intermédiaire du paysage, riche en traits géologiques et géomorphologiques variés (structures tectoniques et reliefs de faille, volcans et volcanisme, processus et formes fluviales, champs de dunes et processus éoliens, paysages glaciaires et périglaciaires, etc.) (fig. 2).

Évaluer la géodiversité extraterrestre revêt aujourd'hui un intérêt particulier dans le cadre des enjeux géoconservatoires récemment mis en évidence par quelques auteurs (Fewer, 2007 ; Matthews et McMahon, 2018). En effet, plusieurs sites et objets extraterrestres se trouvent directement menacés par les projets de colonisation spatiale et d'exploitation des ressources plus ou moins planifiés à court et moyen terme, sur la Lune, sur Mars et d'autres objets interplanétaires (astéroïdes). Sortant de ce qui a longtemps été considéré comme de la science-fiction, ce constat pose la question de l'évaluation de cette géodiversité extraterrestre et de la sélection des exogéosites à conserver, en fonction des valeurs sociétales qui leur sont associées (valeurs culturelle, esthétique, fonctionnelle, scientifique et éducative) (tab. 1).

En l'absence d'observations directes (in situ) à l'exception notable de la Lune (cf. missions habitées américaines du programme Apollo, 1969-1975), l'analyse de l'imagerie scientifique et des représentations artistiques –dont les trajectoires historiques sont étroitement articulées– semble être la principale voie d'évaluation (indirecte) de cette géodiversité peu ou non accessible. Les premières formes de représentation de la géodiversité extraterrestre sont à mettre en relation avec les prémices et l'histoire de l'astronomie (fig. 3). Toutefois, les premières descriptions et représentations scientifiques détaillées de la Lune, pourtant proche de la Terre, remontent seulement au début du XVII^e^ siècle, quand Galilée (1610) révéla et dessina la topographie contrastée de notre satellite naturel à l'aide de la lunette astronomique qu'il avait mise au point. Il faut attendre la fin du XIX^e^ siècle pour voir apparaître les premières bonnes photographies de la Lune (Pickering, 1904) avec un niveau de détail et de précision dépassant celui des premiers télescopes. Ces premières descriptions ont donné lieu à des divergences d'interprétation sur l'origine des cratères lunaires, notamment. Ceci a été le contexte de diverses représentations artistiques produites avant les missions Apollo, au premier rang desquelles on citera l'album visionnaire de Hergé « On a marché sur la Lune » (1954), le film de Kubrick « 2001, l'Odyssée de l'Espace » (1968), ou encore les réalisations de l'artiste français Rudaux « Sur les autres mondes » (1937), et celles du peintre Bonnestell (fig. 4). Sur les autres corps planétaires solides, notamment Mars, les représentations et les interprétations sont longtemps restées « fantaisistes », comme les « canaux » martiens décrits par Schiaparelli et Flammarion au XIX^e^ siècle illustrés par la Figure 5 (De Blasio, 2018).

La représentation de la géodiversité extraterrestre a connu une révolution complète dans les années 1960 avec l'avènement des premières missions spatiales, d'abord destinées à l'exploration planétaire de nos plus proches « voisins » (Lune, Mars et Vénus), dans une période de développement accéléré de la télédétection satellitaire (optique, thermique, radar et infra-rouge). Depuis les années 1990, la combinaison des techniques d'imagerie et de spectroscopie a permis des progrès décisifs dans les représentations et la cartographie haute résolution des surfaces planétaires ; ces approches incluent l'acquisition de données topographiques et la production de modèles numériques de terrain (tab. 2). Les missions habitées américaines du programme Apollo ont également révolutionné notre représentation des paysages lunaires, lesquels comptent des exogéosites à forte valeur historique et archéologique tel le site d'alunissage de la célèbre mission Apollo 11, Tranquility Base (Fewer, 2007) (fig. 6). Malgré l'absence de missions habitées, la planète Mars a tout de même été au centre de toutes les attentions et de la programmation des missions d'exploration spatiale depuis les années 1970 (programmes Viking, Mariner, Mars Global Surveyor, Mars Odyssey, Mars Express, InSight). Ces différentes missions ont permis de recueillir des données « images » variées (photomosaïques, MNT) et leurs produits cartographiques associés (cartes topographiques, géologiques et géomorphologiques à différentes échelles). L'acquisition récente de données à très haute résolution (e.g., images HiRISE, MNT MOLA) a marqué un pas décisif dans la description de la géodiversité martienne aux échelles fines (fig. 7).

Jusque dans les années 1990, les autres planètes du système solaire sont restées un domaine potentiellement sujet à d'extraordinaires découvertes scientifiques et des imaginaires géographiques illimités, en raison de leur inaccessibilité liée à une trop grande distance et/ou à un environnement contraignant pour des observations rapprochées (Mercure, Vénus). Paradoxalement, ce sont les corps planétaires solides les plus externes du système solaire, en particulier les satellites des planètes géantes, qui ont retenu le plus d'attention au cours des dernières décennies, notamment parce qu'ils représentent les meilleurs candidats à la découverte de vie extraterrestre. Grâce aux dernières missions spatiales qui leur ont été dédiées (orbiteurs *des missions Galileo, Juno et Cassini), ceux-ci ont révélé une extraordinaire géodiversité, comme celle qui caractérise les satellites de Jupiter, Saturne, Uranus et Neptune (fig. 8-10), ou encore le couple Pluton-Charon (fig. 11).*

Par-delà les découvertes scientifiques, la diversité et le nombre fantastique de données, cartes et images acquises, élaborées et interprétées depuis le début de « l'âge spatial », ont considérablement étendu le champ de la connaissance de la géodiversité extraterrestre en même temps qu'ils ont stimulé la production d'autres formes de représentations, notamment artistiques, complémentaires des premières (fig. 12). Ensemble, ces données peuvent constituer le support de nouvelles formes de valorisation d'une exogéodiversité méconnue, à l'heure des technologies numériques, par exemple en imaginant des itinéraires virtuels de géotourisme « non-invasif » sur les planètes riches en banques d'images (e.g., Lune, Mars, Titan).