
europlanet 2024
Research Infrastructure

Geology & Planetary Mapping
Winter School

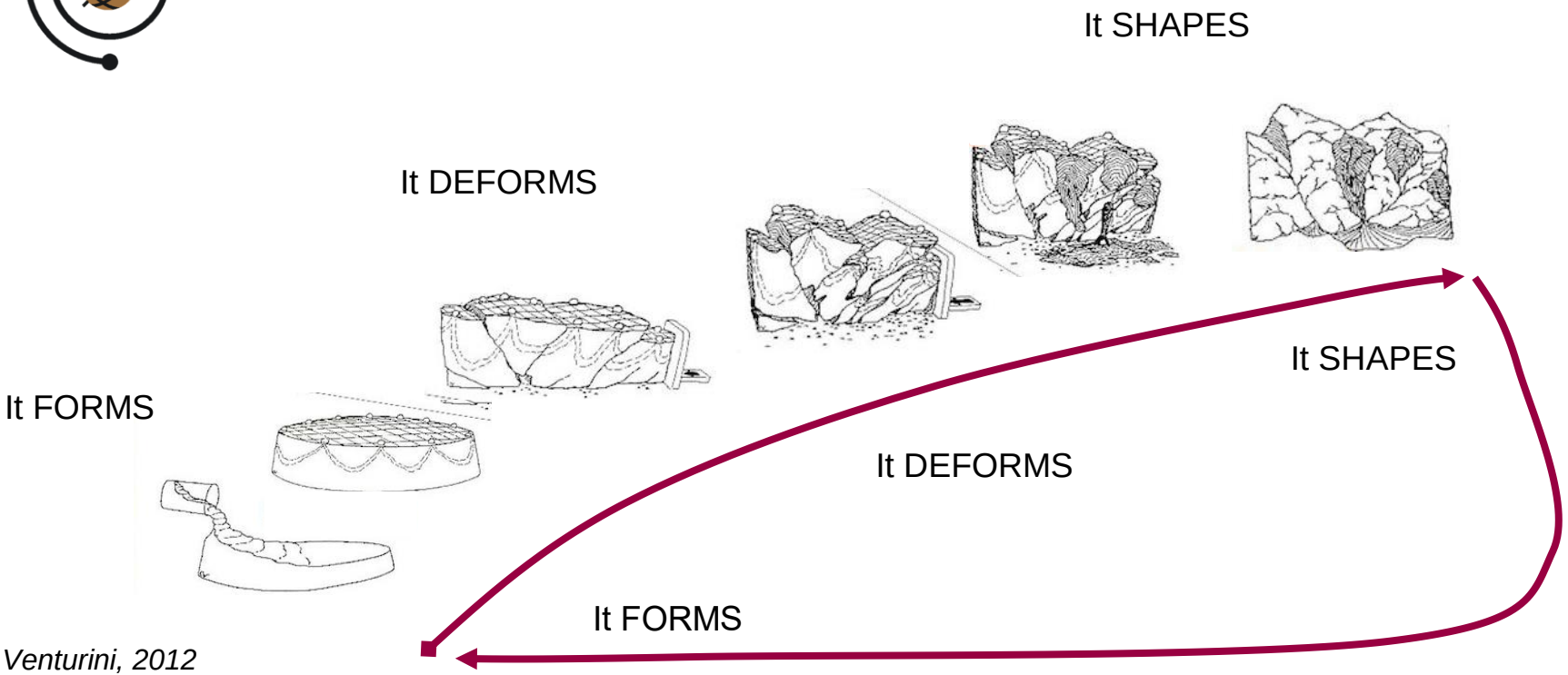
Terrestrial and Planetary geologic mapping: an overview

Matteo Massironi (UNIPD)

EUROPLANET 2024 Research Infrastructure

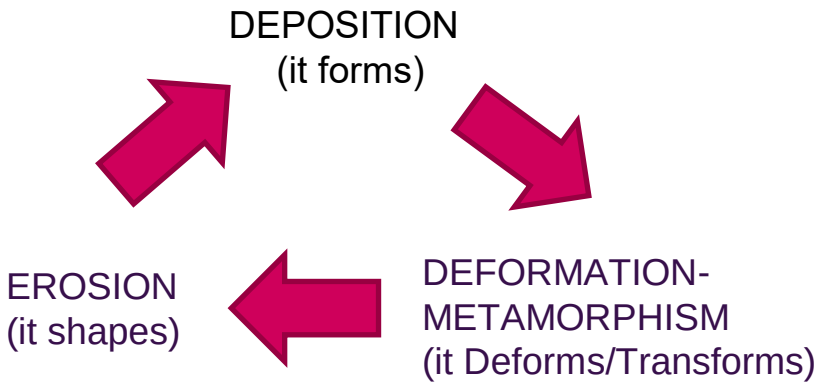
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871149.

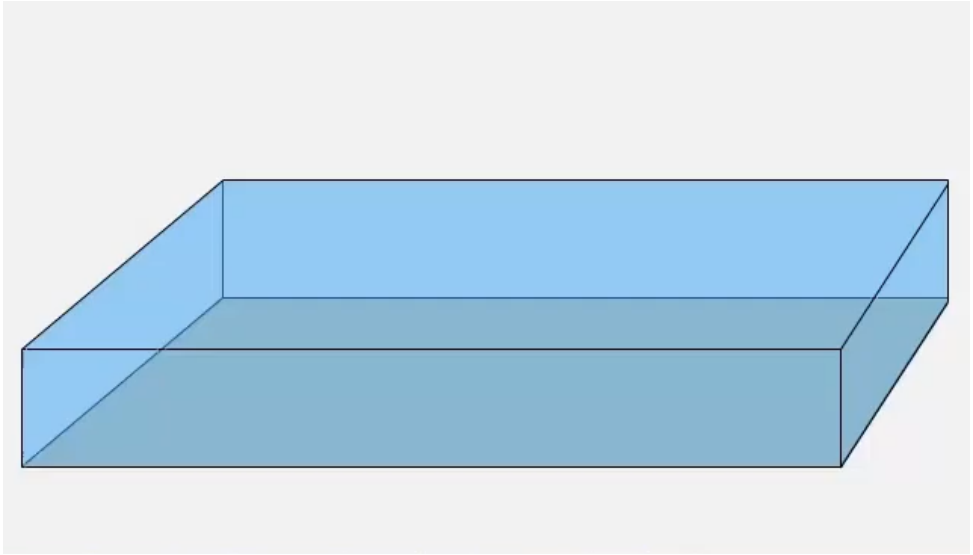
The distorted layer cake



Venturini, 2012

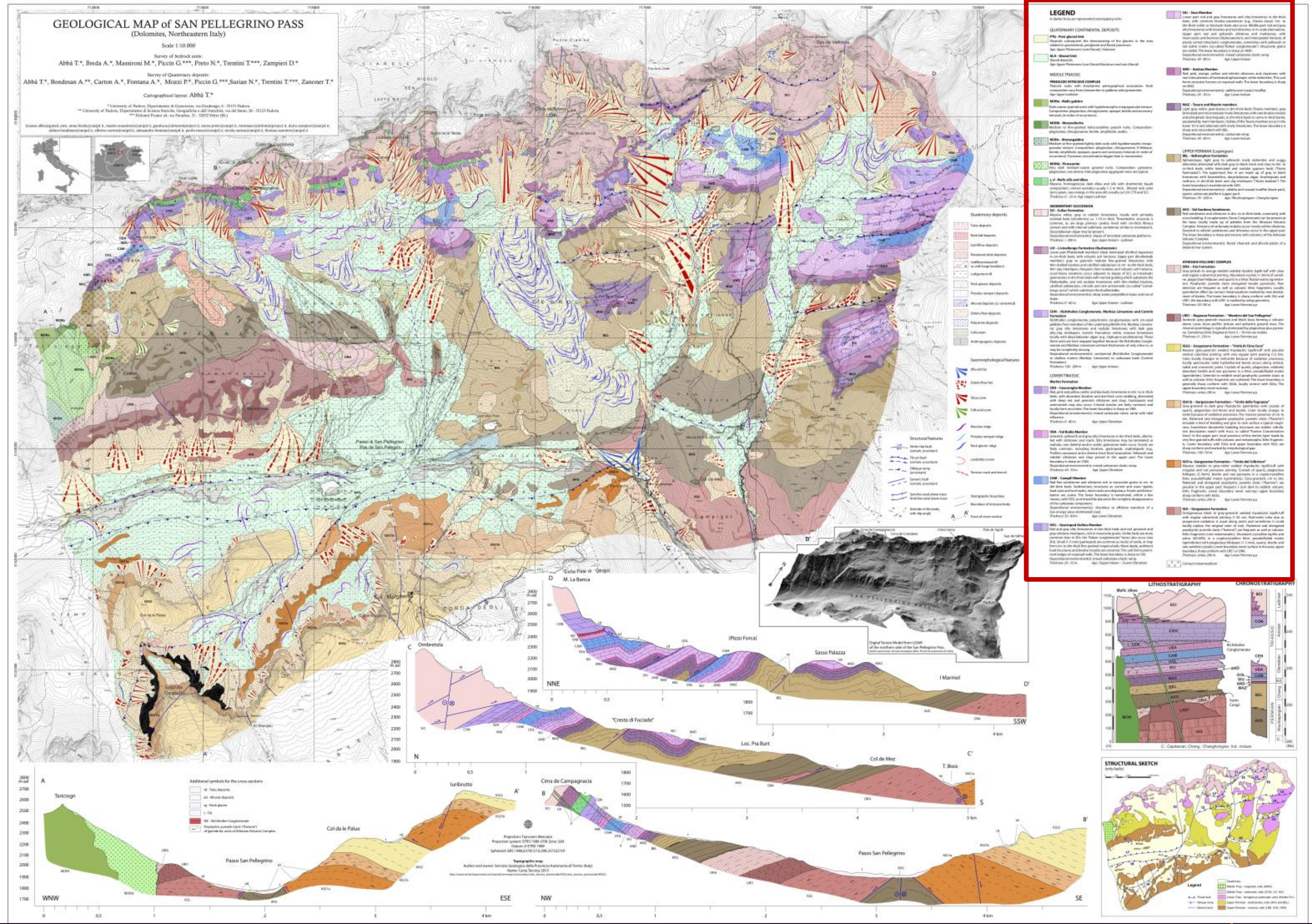
It forms, it deforms, it shapes






It shapes
It forms
It deforms
It deforms
It shapes

It forms: Geological units



Abba' et al. 2018

It forms: Geological units

LEGEND

In darker hues are represented outcropping rocks

QUATERNARY CONTINENTAL DEPOSITS

PTG - Post-glacial Unit
Deposits subsequent the downwasting of the glaciers in the area, related to gravitational, periglacial and fluvial processes.
Age: Upper Pleistocene (Late Glacial), Holocene

GLA - Glacial Unit
Glacial deposits.
Age: Upper Pleistocene (Last Glacial Maximum and Late Glacial)

MIDDLE TRIASSIC

PREDAZZO INTRUSIVE COMPLEX
Plutonic rocks with shoshonitic petrographical association. Rock composition vary from monzonites to gabbros and pyroxenites.
Age: Upper Ladinian

MONa - Mafic gabbro
Dark coarse-grained rocks with hypidiomorphic inequigranular texture. Composition: plagioclase, clinopyroxene, opaque, biotite and accessory minerals (in order of occurrence).

MONb - Monzodiorite
Medium to fine-grained holocrystalline greyish rocks. Composition: plagioclase, clinopyroxene, biotite, amphibole, oxides.

MONc - Monzogabbro
Medium to fine-grained lightly dark rocks with hypidiomorphic inequigranular texture. Composition: plagioclase, clinopyroxene, K-feldspar, biotite, amphibole, opaques, quartz and accessory minerals (in order of occurrence). Pyroxene concentration bigger than in monzonites.

MONd - Pirossenite
Very dark medium-coarse grained rocks. Composition: pyroxene, plagioclase, rare olivine. Pale plagioclase aggregate veins are typical.

s. d - Mafic sills and dikes
Massive, homogeneous dark dikes and sills with shoshonitic basalt composition; contact aureoles usually 1-2 m thick. Altered rock color turns green, rare orange. In the area sills usually cut LIV, CTR and SCI.
Thickness: 0 – 25 m. Age: Upper Ladinian

SEDIMENTARY SUCCESSION

SCI - Sciliar Formation
Massive white, gray or reddish limestones, locally with primarily inclined beds (clinoforms) ca. 1-10 m thick. Thrombolitic structure is common, as are large primary cavities lined with cm-thick fibrous cement and with internal sediment, sometimes similar to stromatactis. Dasycladacean algae may be present.
Depositional environment(s): slopes of microbial carbonate platforms.
Thickness: > 300 m. Age: Upper Anisian - Ladinian

LIV – Livinallongo Formation (Buchenstein)
Lower part (Plattenkalk member): black laminated silicified claystones in cm-thick beds, with volcanic ash horizons. Upper part (Knollenkalk member): gray to greenish nodular fine-grained limestones with thin-shelled bivalves and calcified radiolarians in cm- to dm-thick beds, thin clay interlayers, frequent chert nodules and volcanic ash horizons. Local facies variations occur adjacent to slopes of SCI, as intraclastic grainstones in dm-thick beds with normal grading which substitute the Plattenkalke, and red nodular limestones with thin-shelled bivalves, calcified radiolarians, crinoids and rare ammonoids (so-called "Livinallongo rosso") which substitute the Knollenkalke.
Depositional environment(s): deep-water periplatform basin and toe of slope.
Thickness: 0 - 60 m. Age: Upper Anisian - Ladinian

CON – Richthofen Conglomerate, Morbiac Limestone and Contrin Formation
Richthofen conglomerate: polychrome conglomerates with cm-sized pebbles from members of the underlying Werfen Fm. Morbiac Limestone: gray silty limestones and nodular limestones with dark gray silty-clay interlayers. Contrin Formation: white, massive limestones locally with dasycladacean algae (e.g., Diplopora anullatissima). These three units are here mapped together because the Richthofen Conglomerate and Morbiac Limestone achieve thicknesses of only a few m, or may be completely missing.
Depositional environment(s): continental (Richthofen Conglomerate) to shallow marine (Morbiac Limestone) to carbonate bank (Contrin Formation).
Thickness: 100 - 200 m. Age: Upper Anisian

SIU - Siusi Member
Lower part: red and gray limestones and silty limestones in dm-thick beds, with common bivalve pavements (e.g., Claraia clarai). Cm- to dm-thick oolitic or bioclastic beds also occur. Middle part: red and gray silty limestones with bivalves and red siltstones in m-scale alternations. Upper part: red and yellowish siltstones and marlstones, with mud-cracks and burrows (Diplocraterion), and intercalated horizons of poorly sorted intraclastic conglomerates, sometimes with yellowish or red oolitic matrix (so-called "Koken conglomerate"). Muscovite grains are visible. The lower boundary is sharp on AND.
Depositional environment(s): mixed carbonate-clastic ramp
Thickness: 50 - 80 m. Age: Upper Induan

AND – Andraz Member
Red, pink, orange, yellow and whitish siltstones and claystones with rare intercalations of laminated aphanotopic white dolomites. This unit forms recessive furrows on exposed walls. The lower boundary is sharp on MAZ.
Depositional environment(s): sabkha and coastal mudflat
Thickness: 20 - 30 m. Age: Lower Induan

MAZ – Tesero and Mazzin members
Light gray oolitic grainstones in dm-thick beds (Tesero member), gray laminated and micronodular marly limestones with rare bivalve moulds and phosphatic brachiopods, in dm-thick beds to some m-thick banks, separated by marl interlayers. Oolites of the Tesero member occur in the lower 10 m and alternate with marly limestones. The lower boundary is sharp and concordant with BEL.
Depositional environment(s): carbonate ramp.
Thickness: 30 - 60 m. Age: Lower Induan

UPPER PERMIAN (Lopingian)

BEL – Bellerophon Formation
Aphanotopic, light gray to yellowish marly dolomites and vuggy dolomites alternated with dark gray to black marls and clays in dm- to m-thick beds; white laminated and nodular gypsum beds ("facies flammazza"). The uppermost few m are made up of gray to black limestones with foraminifera, dasycladacean algae, brachiopods and molluscs, in dm-thick beds and clay interlayers ("facies badiota"). The lower boundary is transitional with AVG.
Depositional environment(s): sabkha and coastal mudflat (lower part), epeiric carbonate platform (upper part).
Thickness: 70 - 200 m. Age: ?Wuchiapingian - Changhsingian

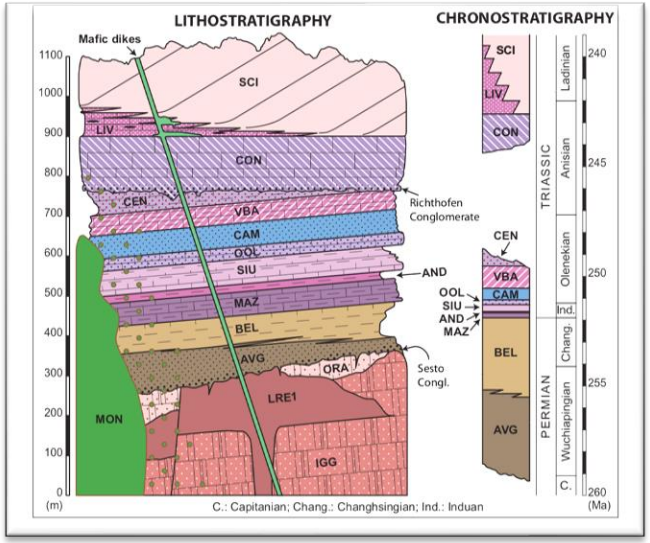
AVG – Val Gardena Sandstones
Red sandstones and siltstones in dm- to m-thick beds, commonly with cross bedding. A conglomerate (Sesto Conglomerate) can be present at the base, locally made up of pebbles from the Athesian Volcanic Complex. Horizons of carbonate nodules occur mostly within siltstones. Greenish to whitish sandstones and siltstones occur in the upper part. The lower boundary is sharp and erosive with volcanics of the Athesian Volcanic Complex.
Depositional environment(s): fluvial channels and alluvial plains of a dryland river system.

ATHESIAN VOLCANIC COMPLEX

ORA – Ora Formation
Grey-pinkish to orange-reddish welded rhyolitic lapilli-tuff with clear and regular subvertical jointing. Abundant crystals (1-3mm) of sanidine, plagioclase feldspars and quartz in a felsic fluidal matrix (ignimbrites). Porphyritic juvenile clasts elongated beside pyroclastic flow direction are frequent as well as volcanic lithic fragments. Locally ignimbrites affect by contact metamorphism marked by new development of biotite. The lower boundary is sharp conform with IGG and LRE1; the boundary with LRE1 is marked by onlap geometry.
Thickness: 50-100 m. Age: Lower Permian p.p.

LRE1 – Regnana Formation – "Membro del San Pellegrino"
Andesitic grey-greenish massive and block lavas forming a volcanic dome. Lavas show porfiric texture and aphanitic ground mass. The mineral assemblage is typically dominated by plagioclase plus pyroxene. Sometimes lithic fragments from 5 – 10 mm are visible.
Thickness: 0 - 330 m. Age: Lower Permian p.p.

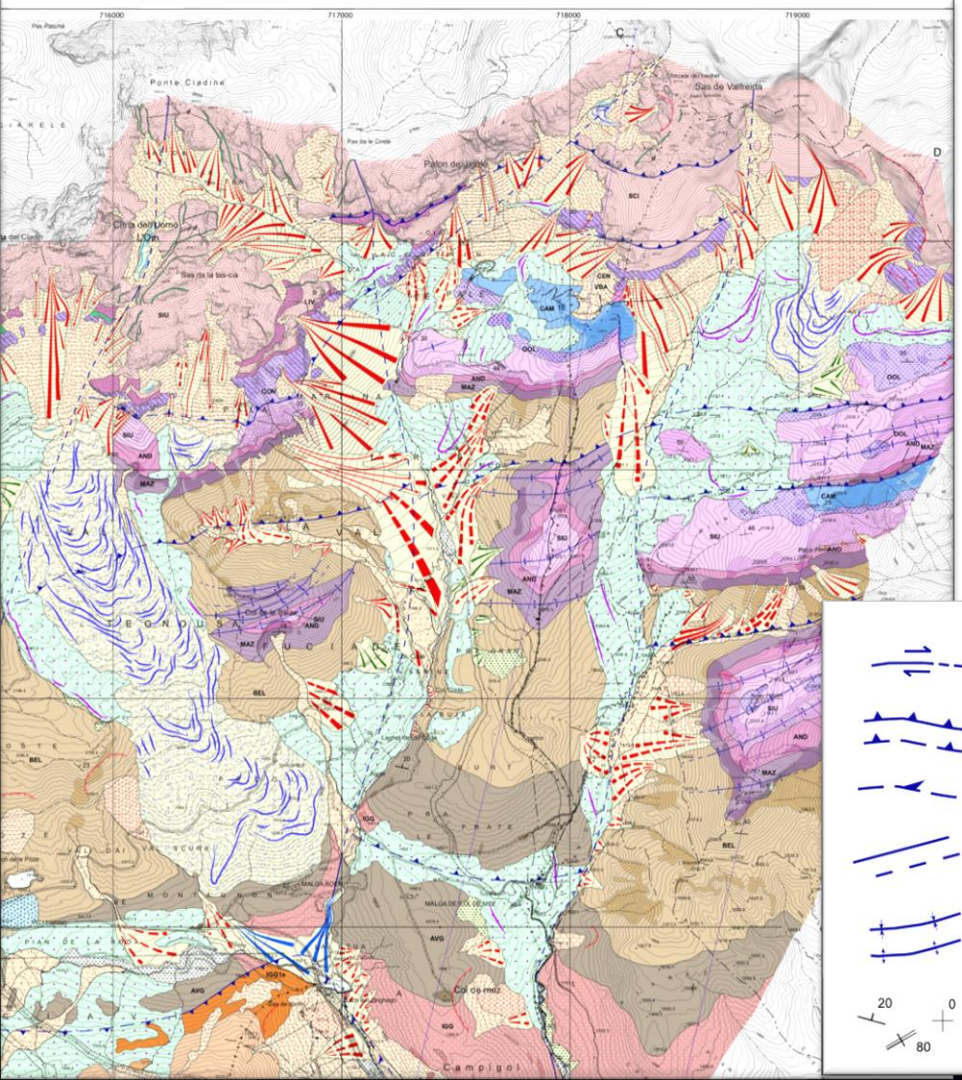
IGG2 – Gargazzone Formation – "Unità di Cima Cece"
Massive grey-greenish welded rhyodacitic lapilli-tuff with peculiar vertical columnar jointing, with very regular joint spacing (1,5-2m). Color locally changes to red/violet because of oxidation processes; locally spectacular violet hydrothermal bends occurs along vertical, radial and concentric joints. Crystals of quartz, plagioclase, relatively

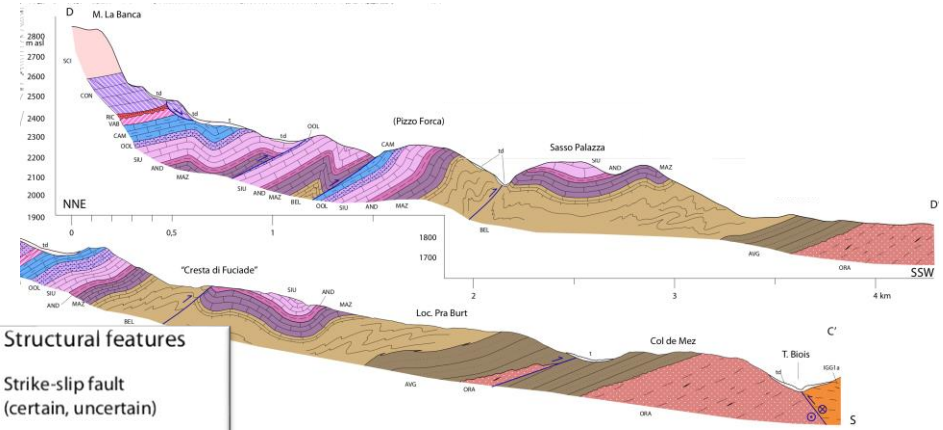


The lithostratigraphic units must:

- Have the **same lithological characters**
- **Clear stratigraphic relationship** with the adjacent
- Should be **easily recognizable in the field**

It deforms: Geological structures

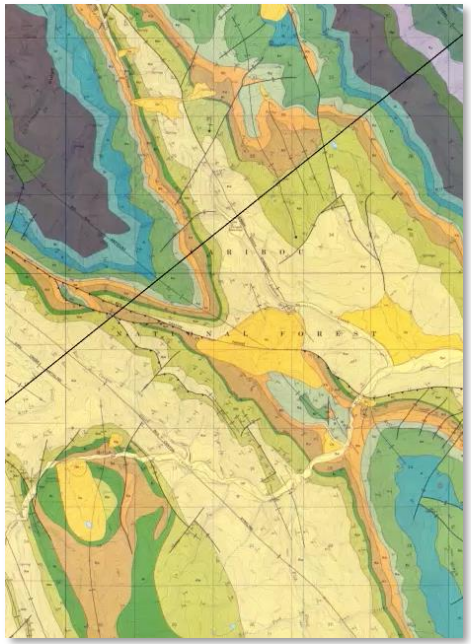


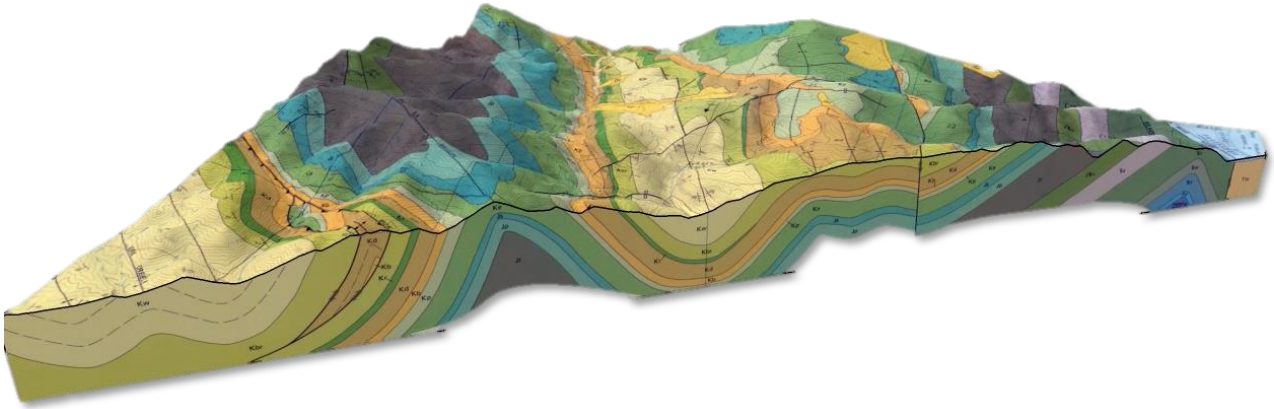


Structural features

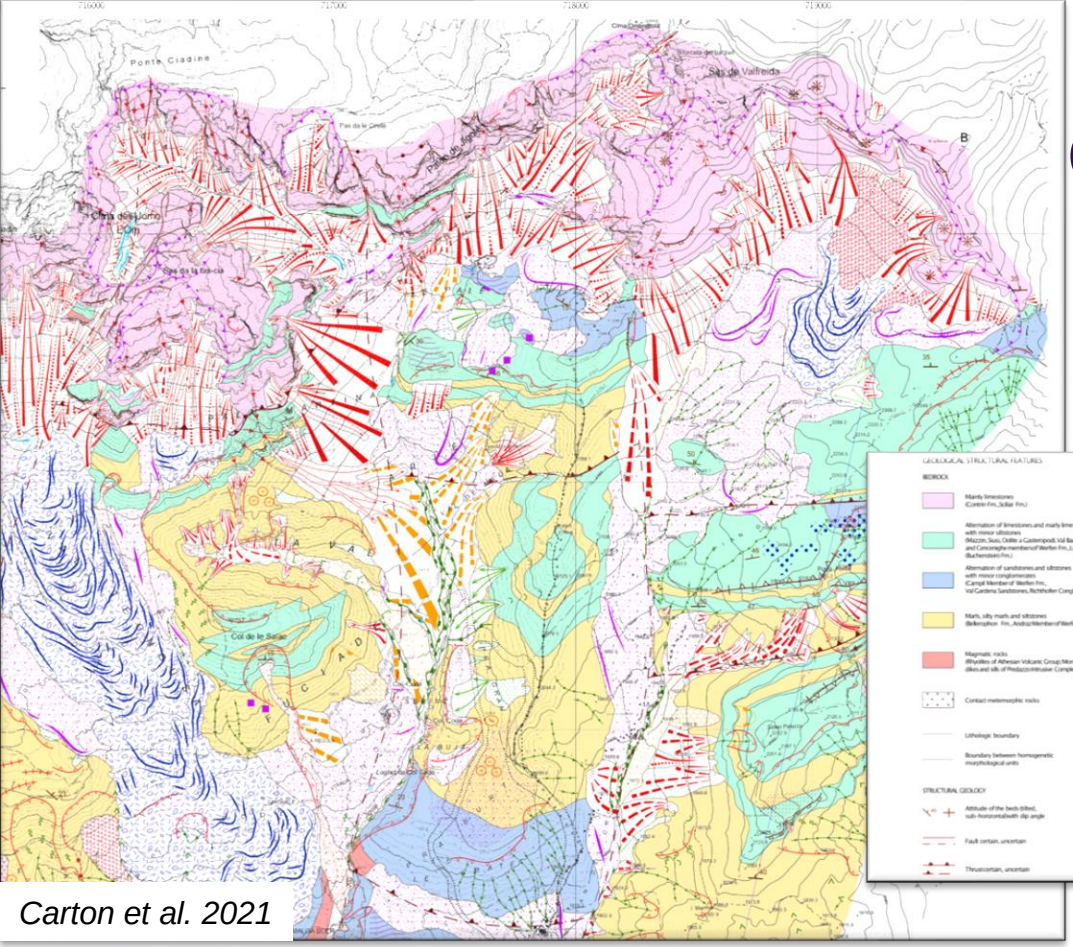
- Strike-slip fault (certain, uncertain)
- Thrust fault (certain, uncertain)
- Oblique ramp (uncertain)
- Generic fault (certain, uncertain)
- Syncline axial plane trace
  Anticline axial plane trace
- Attitude of the beds, with dip angle (20, 0, 80)

It deforms: Geological structures



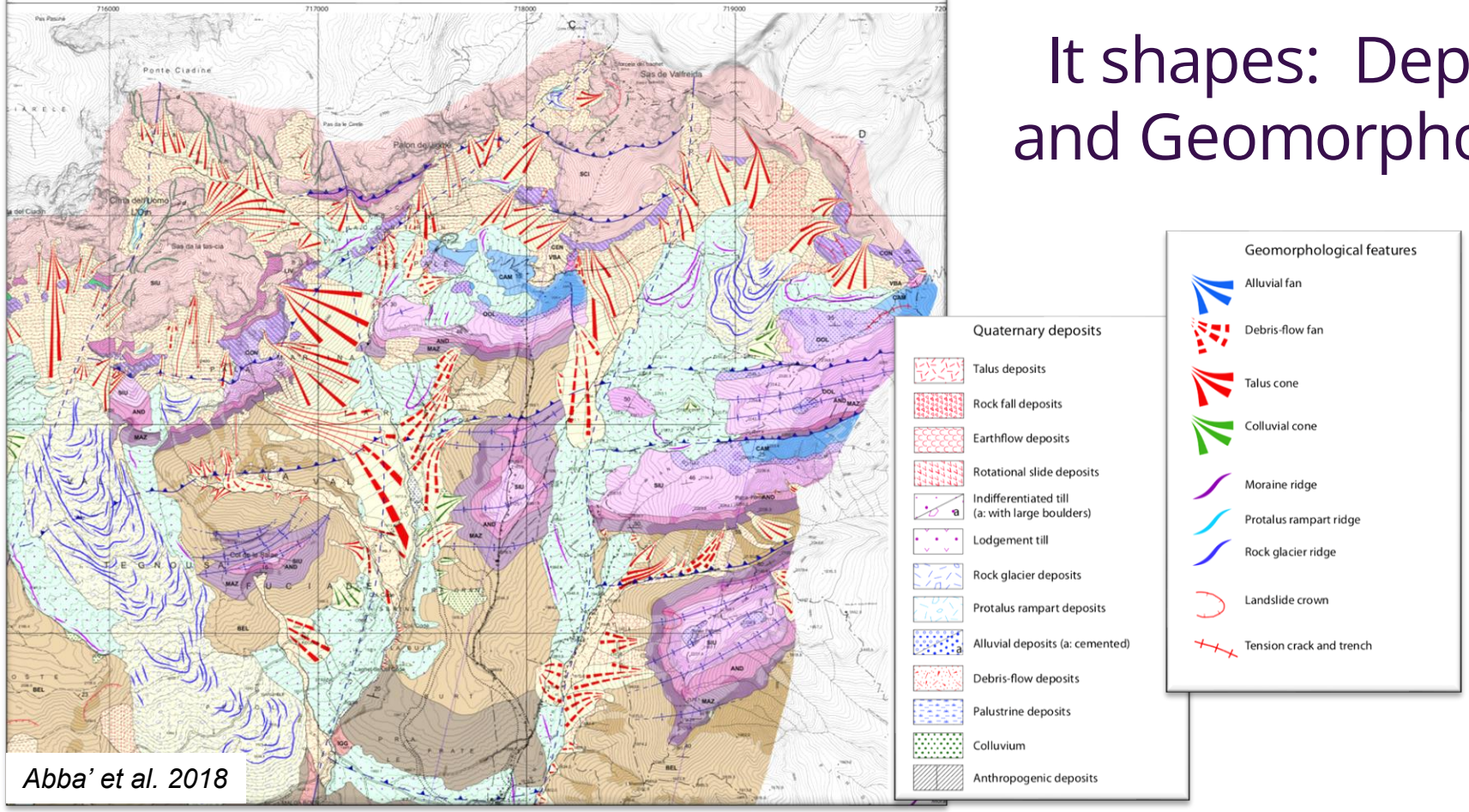


It shapes: Geomorphological maps



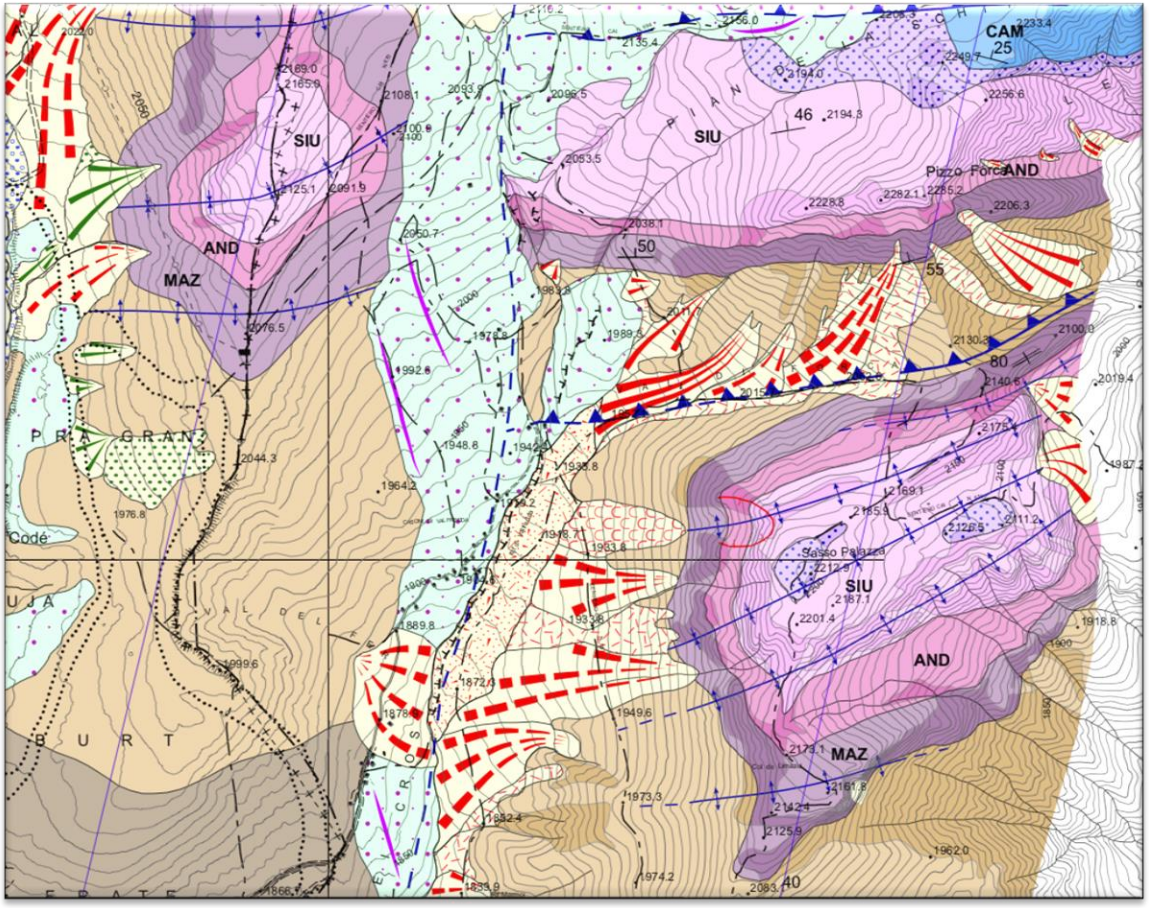
Carton et al. 2021

It shapes: Deposits and Geomorphology



Abba' et al. 2018

From details to the overall synthesis



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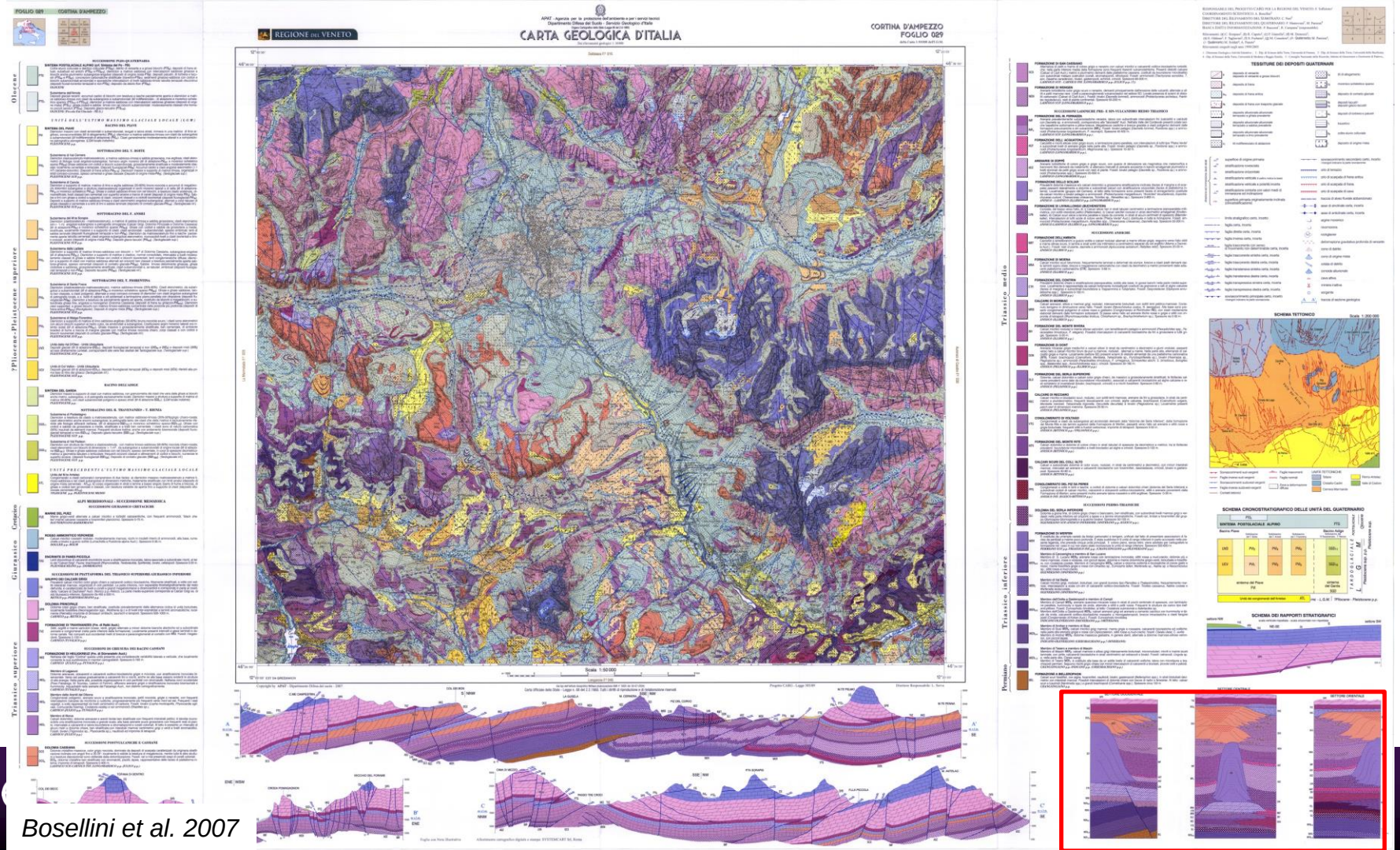
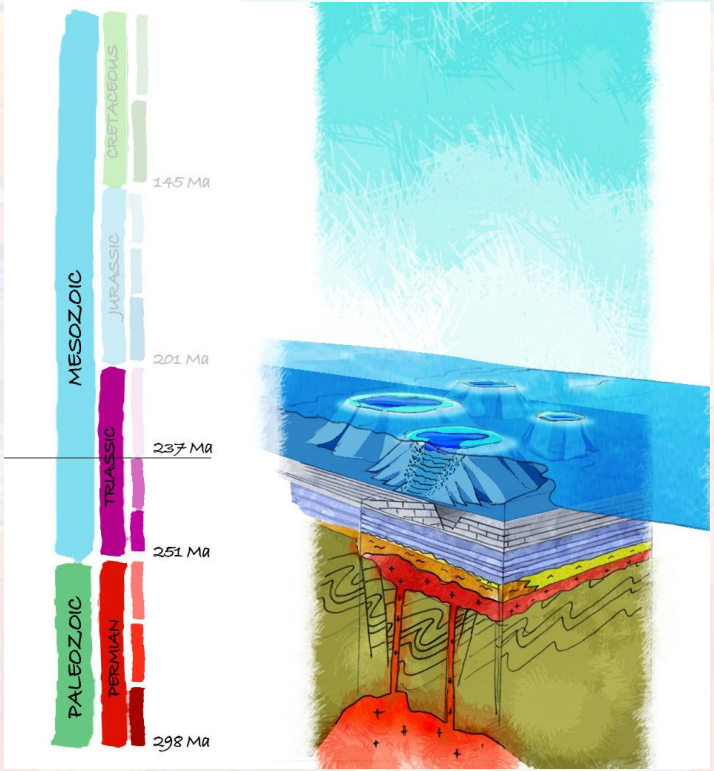


Bosellini et al. 2007

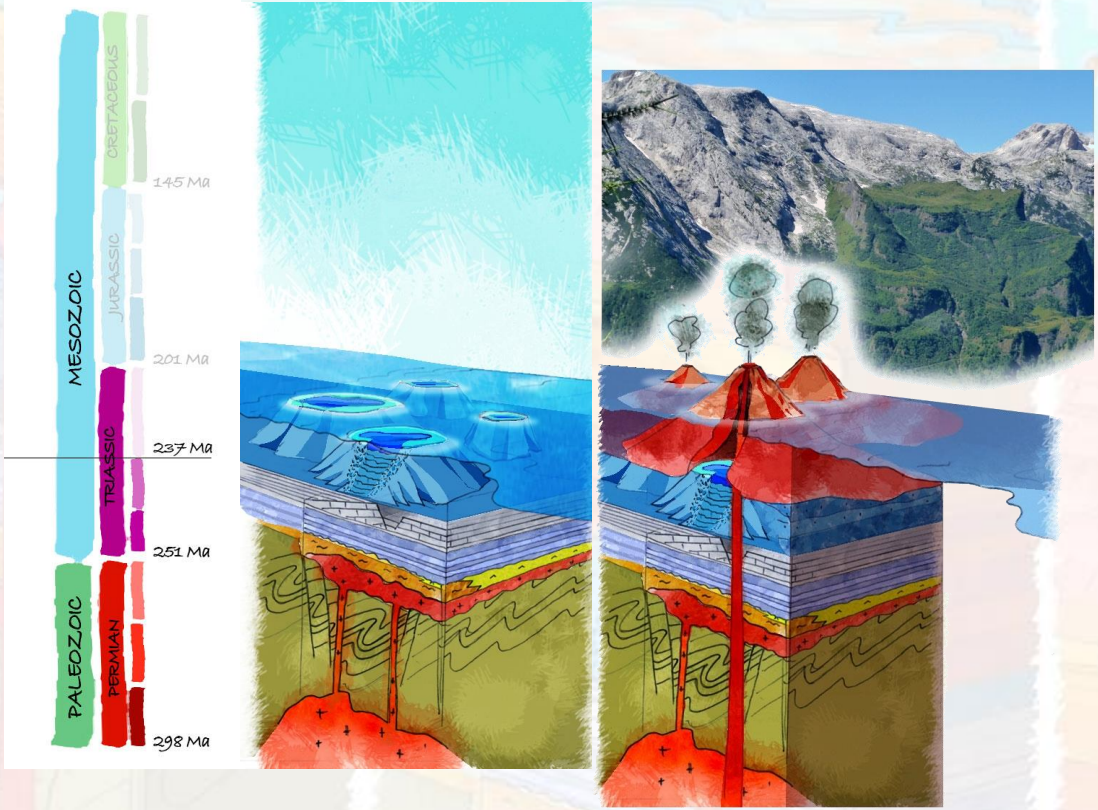
Reading the geologicalevolution from a stratigraphic scheme



Colonna stratigrafica realizzata utilizzando
i paesaggi presenti in Dolomiti milioni di anni fa.

Credits: E.Manfré
Fondazione Dolomiti Unesco www.dolomitiunesco.it

Dal progetto per la Fondazione Dolomiti Unesco www.dolomitiunesco.it



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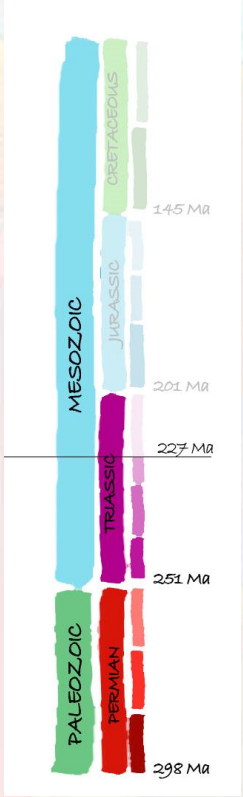

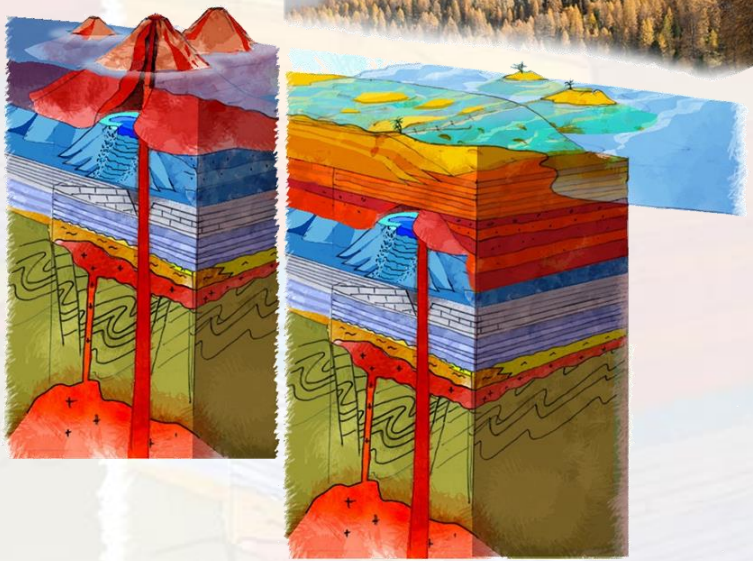

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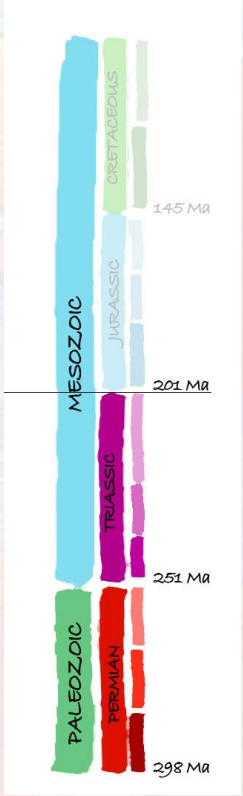

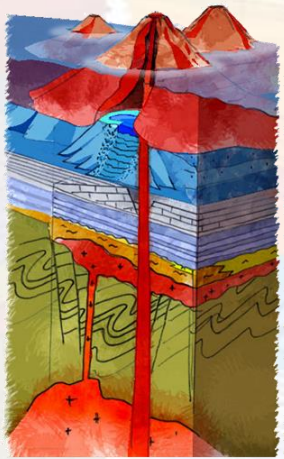

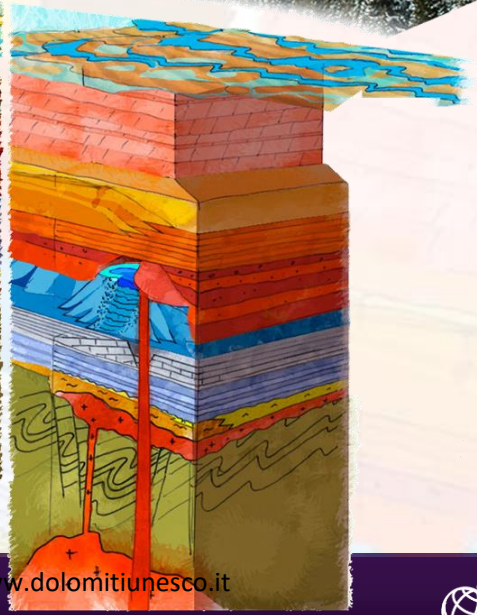

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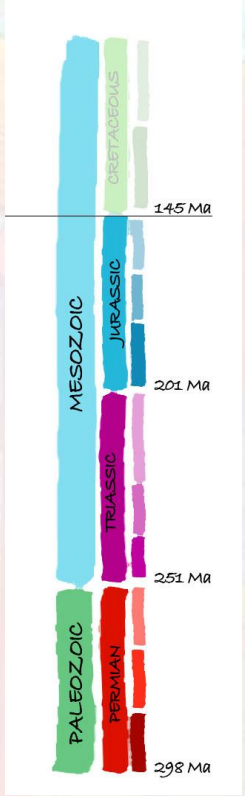

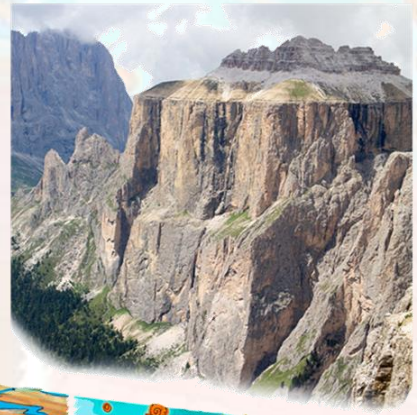

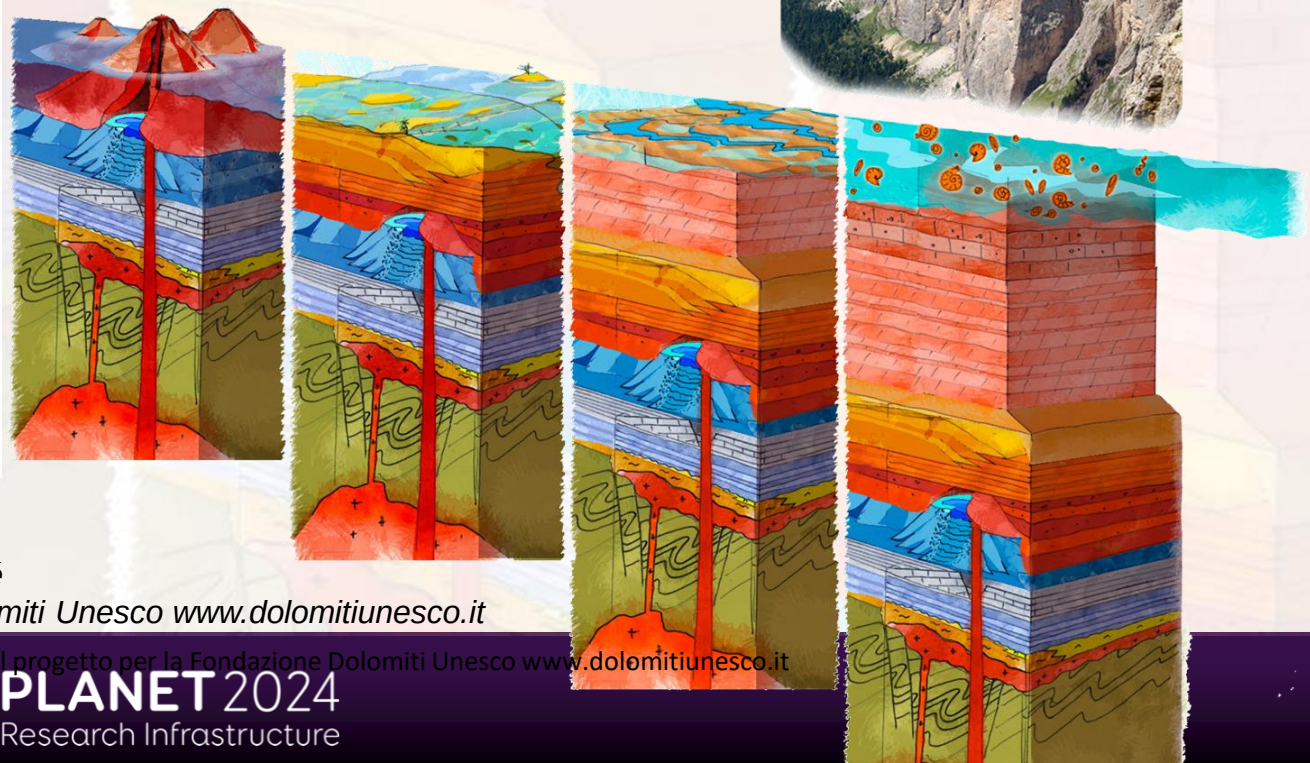

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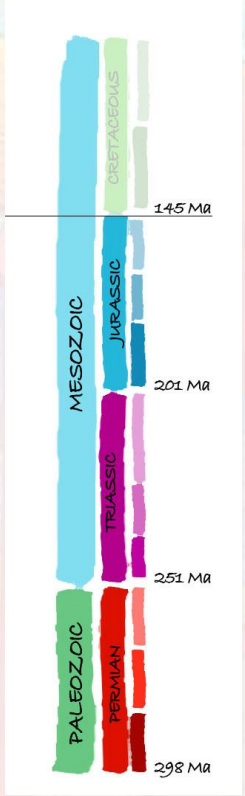

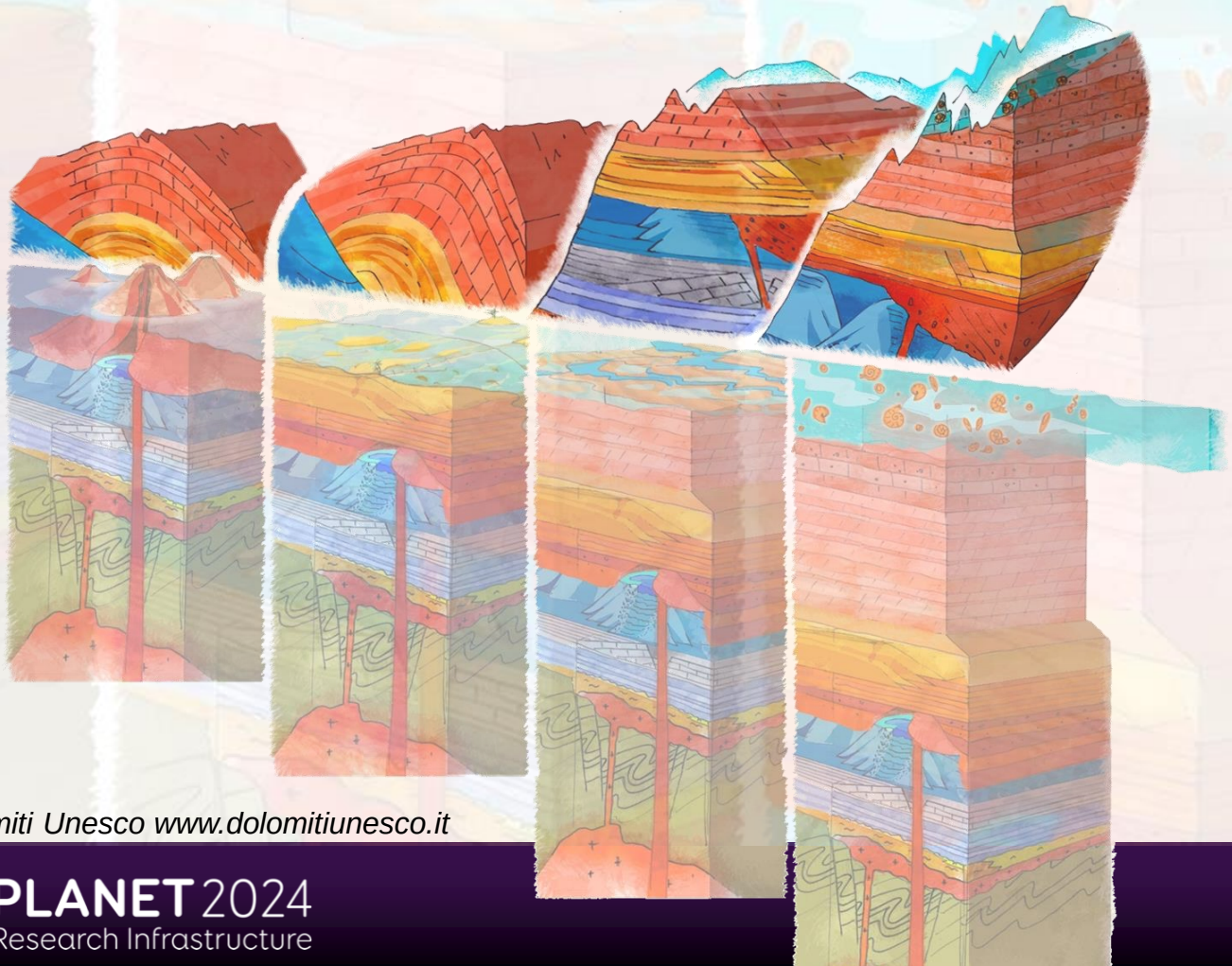

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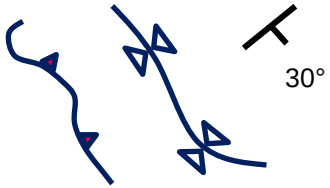
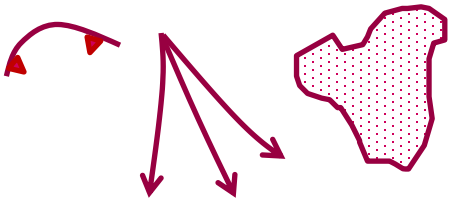
In Summary Earth Geological Maps

Polygons

Lines
Points



Lines
Polygons

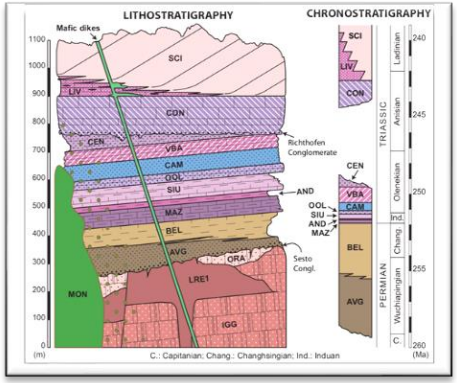


It forms – Geology –Lithostratigraphy
Chronostratigraphy

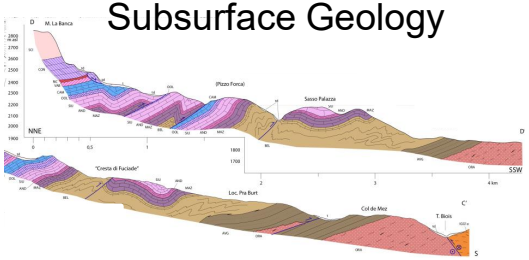
It deforms – Geological structures
and strata attitudes

It shapes – Geomorphology
and loose deposits

Geological Evolution



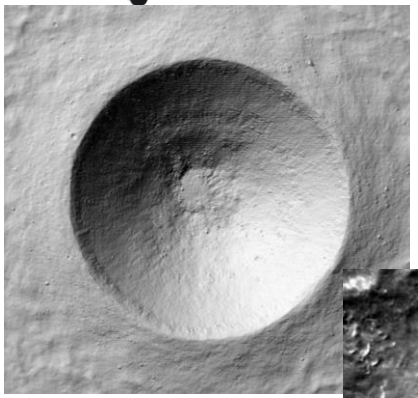
Subsurface Geology



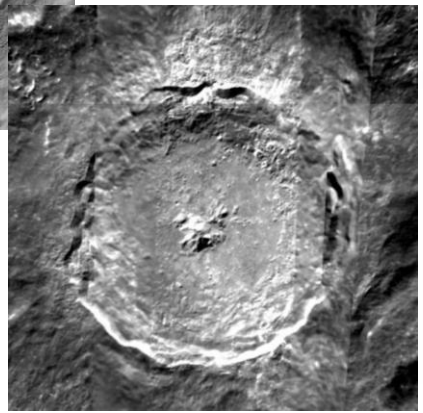
GMAP
Geological Mapping

Does it hold for Planetary surfaces?

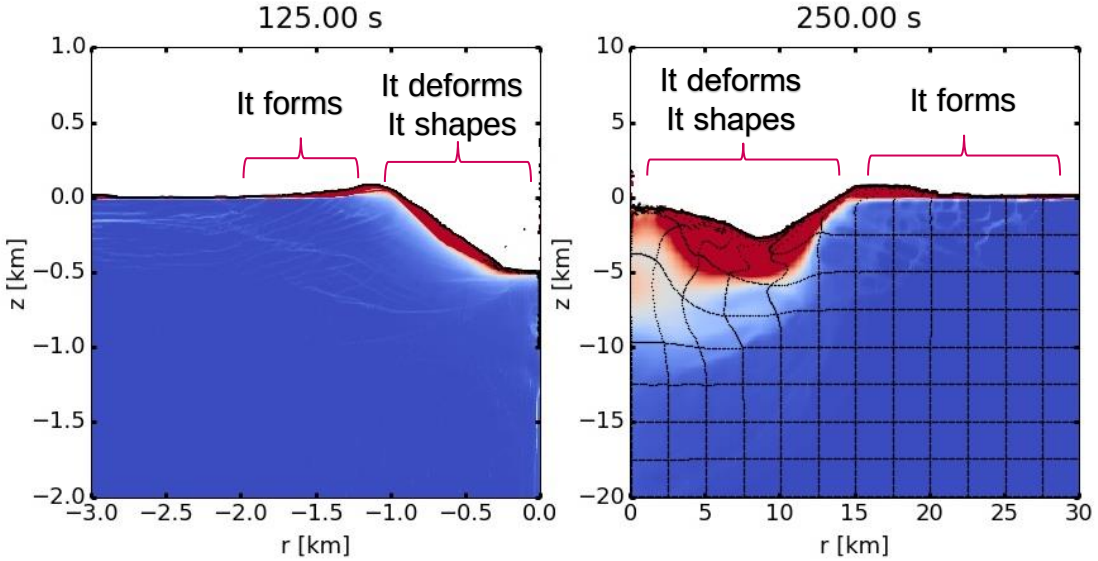
Does it hold for planetary surfaces? The Impact cratering problem



Linné (D: 2km)



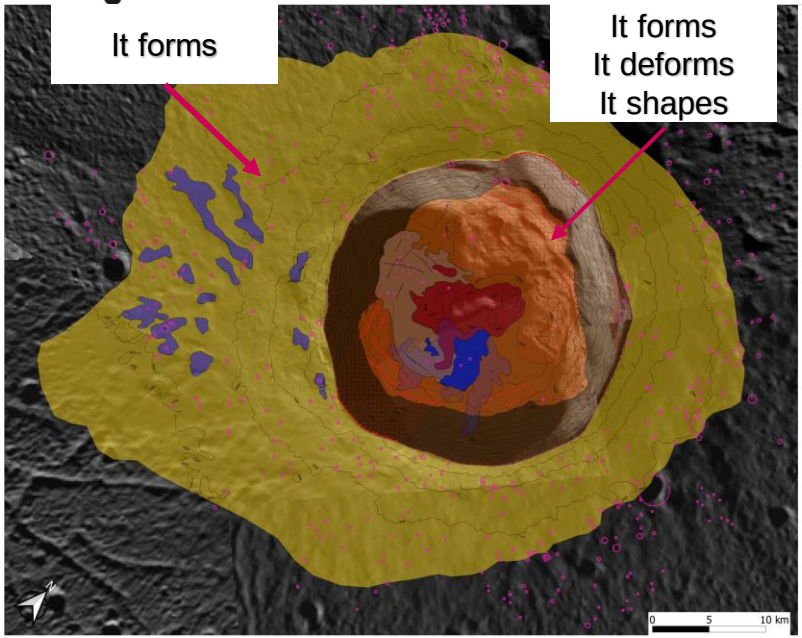
Thyco (D: 85km)

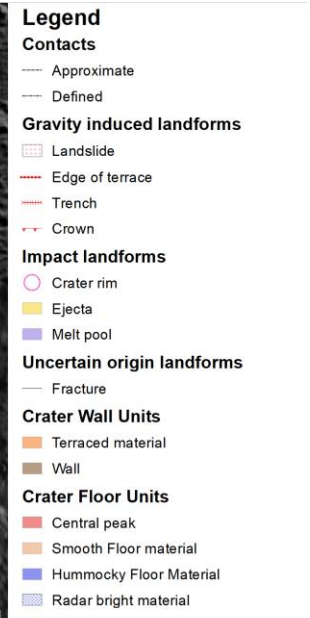


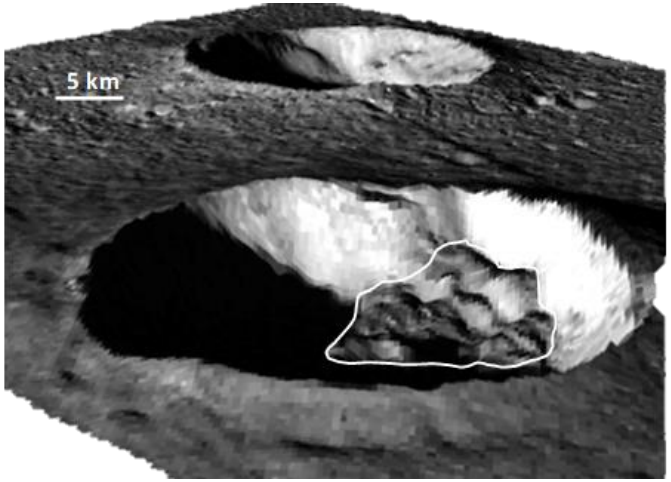
Courtesy: Elena Martellato

Does it hold for planetary surfaces? the Impact cratering problem

Fuller crater (Mercury)



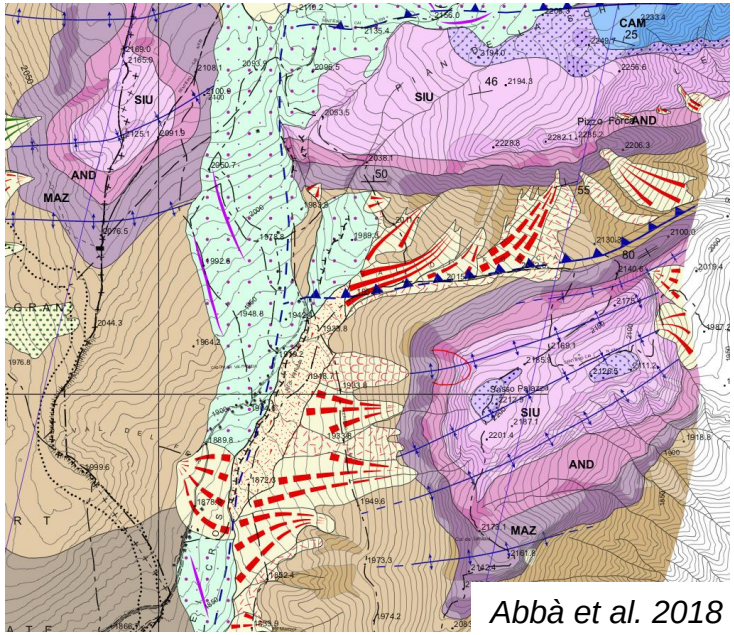




Bertioli et al. submitted

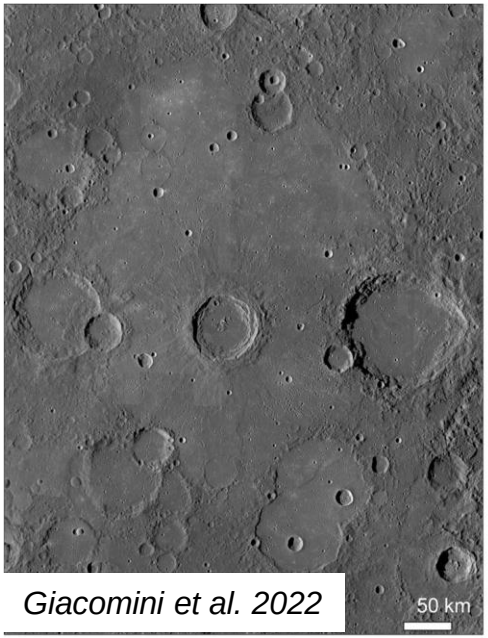
Does it hold for planetary surfaces?
In situ geology *vs* Photo-interpretation

Earth
(Dolomites - San Pellegrino Pass)

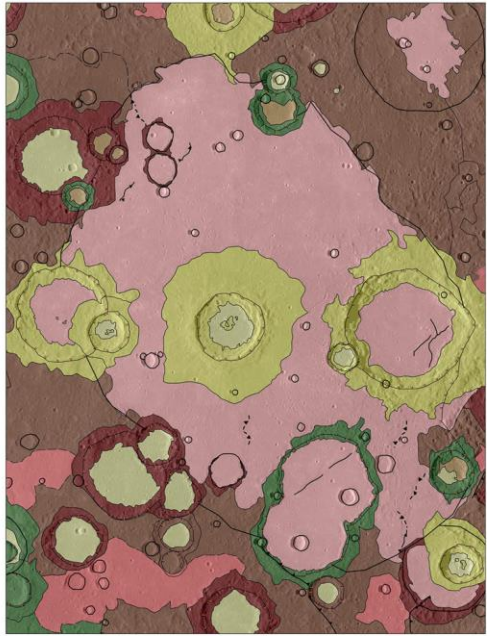


Abbà et al. 2018

Planet Mercury
(Keuper Quadrangle)



Giacomini et al. 2022



Does it hold for Planetary surfaces? Lithostratigraphic unit vs Morphostratigraphic unit

GMAP Geological Mapping

SIU – Siusi Member
Lower part: red and gray limestones and silty limestones in dm-thick beds, with common bivalve pavements (e.g., Claraia clarai). Cm- to dm-thick oolitic or bioclastic beds also occur. Middle part: red and gray silty limestones with bivalves and red siltstones in m-scale alternations. Upper part: red and yellowish siltstones and marlstones, with mud-cracks and burrows (Diplocraterion), and intercalated horizons of poorly sorted intraclastic conglomerates, sometimes with yellowish or red oolitic matrix (so-called "Koken conglomerate"). Muscovite grains are visible. The lower boundary is sharp on AND.
Depositional environment(s): mixed carbonate-clastic ramp
Thickness: 50 - 80 m. *Age: Upper Induan*

AND – Andraz Member
Red, pink, orange, yellow and whitish siltstones and claystones with rare intercalations of laminated aphanotopic white dolomites. This unit forms recessive furrows on exposed walls. The lower boundary is sharp on MAZ.
Depositional environment(s): sabkha and coastal mudflat
Thickness: 20 - 30 m. *Age: Lower Induan*

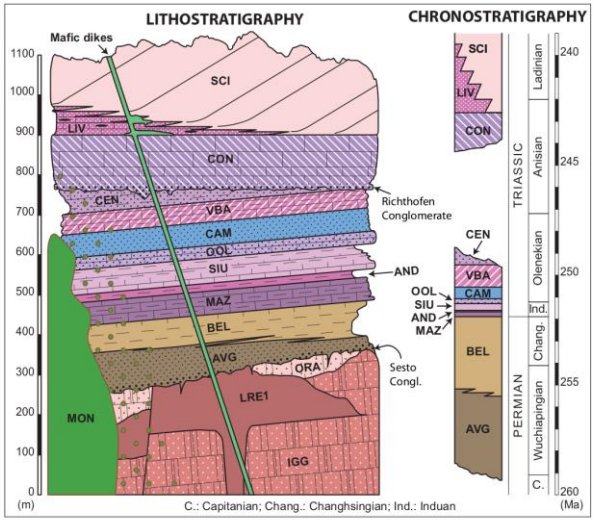
MAZ – Tesero and Mazzin members
Light gray oolitic grainstones in dm-thick beds (Tesero member), gray laminated and micronodular marly limestones with rare bivalve moulds and phosphatic brachiopods, in dm-thick beds to some m-thick banks, separated by marl interlayers. Oolites of the Tesero member occur in the lower 10 m and alternate with marly limestones. The lower boundary is sharp and concordant with BEL.
Depositional environment(s): carbonate ramp.
Thickness: 30 - 60 m. *Age: Lower Induan*

UPPER PERMIAN (Lopingian)

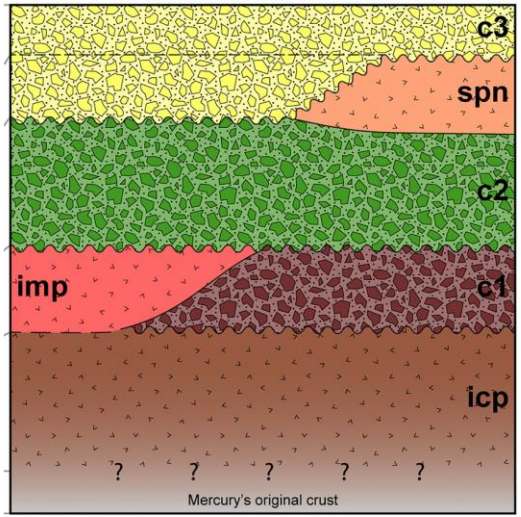
BEL – Bellerophon Formation
Aphanotopic, light gray to yellowish marly dolomites and vuggy dolomites alternated with dark gray to black marls and clays in dm- to m-thick beds; white laminated and nodular gypsum beds ("facies fiammazza"). The uppermost few m are made up of gray to black limestones with foraminifera, dasycladacean algae, brachiopods and molluscs, in dm-thick beds and clay interlayers ("facies badiota"). The lower boundary is transitional with AVG.
Depositional environment(s): sabkha and coastal mudflat (lower part), epeiric carbonate platform (upper part).
Thickness: 70 - 200 m. *Age: ?Wuchiapingian - Changhsingian*

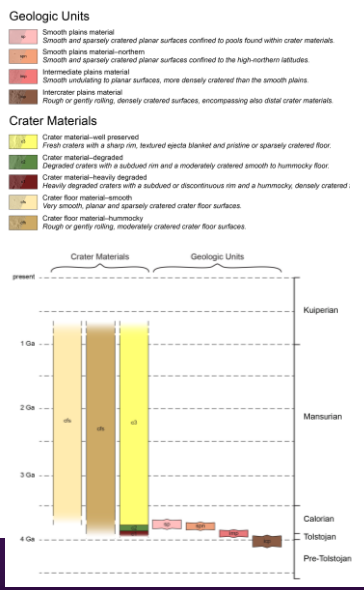
AVG – Val Gardena Sandstones
Red sandstones and siltstones in dm- to m-thick beds, commonly with cross bedding. A conglomerate (Sesto Conglomerate) can be present at the base, locally made up of pebbles from the Athesian Volcanic Complex. Horizons of carbonate nodules occur mostly within siltstones. Greenish to whitish sandstones and siltstones occur in the upper part. The lower boundary is sharp and erosive with volcanics of the Athesian Volcanic Complex.
Depositional environment(s): fluvial channels and alluvial plains of a dryland river system.

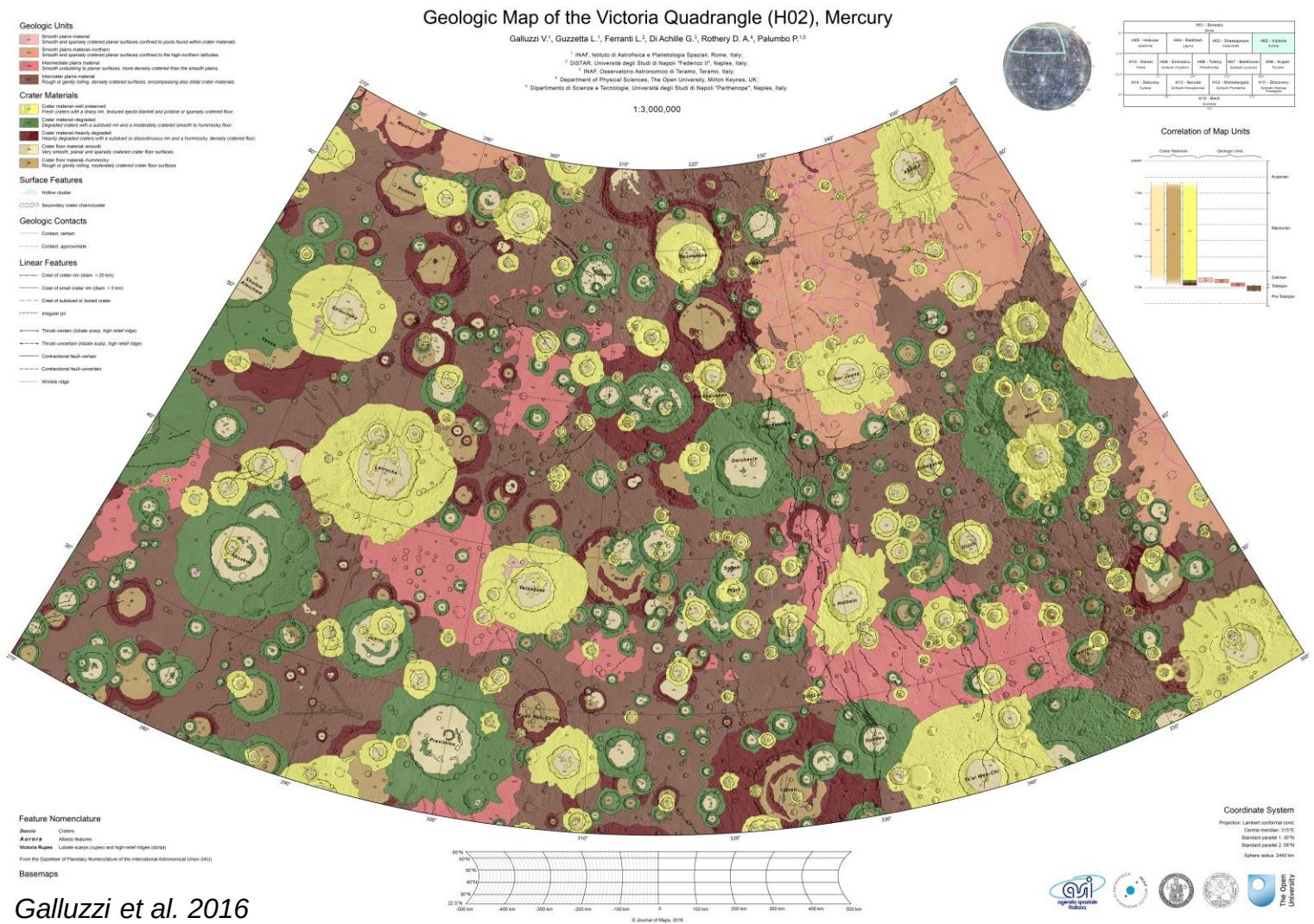
Lithostratigraphic and Chronostratigraphic units



Morphostratigraphic unit







Galluzzi et al. 2016

Geologic Map of the Victoria Quadrangle (H02), Mercury

Galluzzi V.[1], Guzzetta L.[1], Ferranti L.[2], Di Achille G.[3], Rothery D. A.[4], Palumbo P.[1,5]

[1] INAF, Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy;
[2] DiSTAR, Università degli Studi di Napoli "Federico II", Naples, Italy;
[3] INAF, Osservatorio Astronomico di Teramo, Teramo, Italy;
[4] Department of Physical Sciences, The Open University, Milton Keynes, UK;
[5] Dipartimento di Scienze e Tecnologie, Università degli Studi di Napoli "Parthenope", Naples, Italy.

Geologic Units

- Smooth plains material — Smooth and sparsely cratered planar surfaces confined to pools found within crater materials.
- Smooth plains material–northern — Smooth and sparsely cratered planar surfaces confined to the high-northern latitudes.
- Intermediate plains material — Smooth undulating to planar surfaces, more densely cratered than the smooth plains.
- Intercrater plains material — Rough or gently rolling, densely cratered surfaces, encompassing also distal crater materials.

Crater Materials

- Crater material–well preserved — Fresh craters with a sharp rim, textured ejecta blanket and pristine or sparsely cratered floor.
- Crater material–degraded — Degraded craters with a subdued rim and a moderately cratered smooth to hummocky floor.
- Crater material–heavily degraded — Heavily degraded craters with a subdued or discontinuous rim and a hummocky, densely cratered floor.
- Crater floor material–smooth — Very smooth, planar and sparsely cratered crater floor surfaces.
- Crater floor material–hummocky — Rough or gently rolling, moderately cratered crater floor surfaces.

Surface Features

- Hollow cluster
- Secondary crater chain/cluster

Geologic Contacts

- Contact, certain
- Contact, approximate

Linear Features

- Crest of crater rim (diam. > 20 km)
- Crest of small crater rim (diam. > 5 km)
- Crest of subdued or buried crater
- Irregular pit
- Thrust–certain (lobate scarp, high relief ridge)
- Thrust–uncertain (lobate scarp, high relief ridge)
- Contractional fault–certain
- Contractional fault–uncertain
- Wrinkle ridge

Feature Nomenclature

Duccio Craters
Aurora Albedo features
Victoria Rupes Lobate scarps (rupes) and high-relief ridges (cristae)

From the Gazetteer of Planetary Nomenclature of the International Astronomical Union (IAU)

Basemaps

Top-right Mercury globe: msdis_v3_color_1000_750_430_666mpp

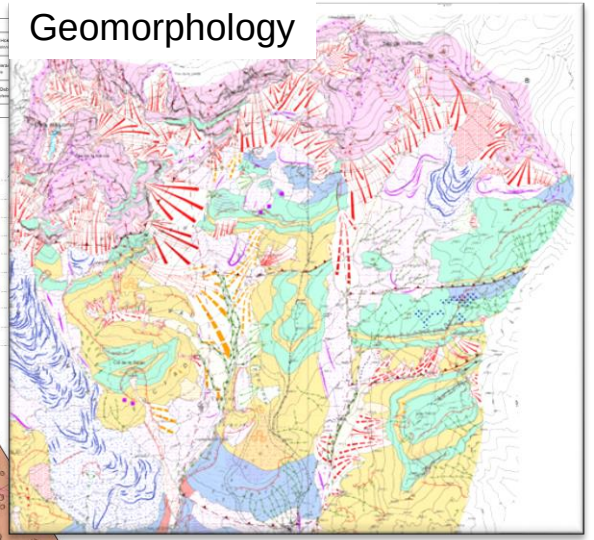
Central main map: msdis_v8_750mm_250mpp

Basemaps credits: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

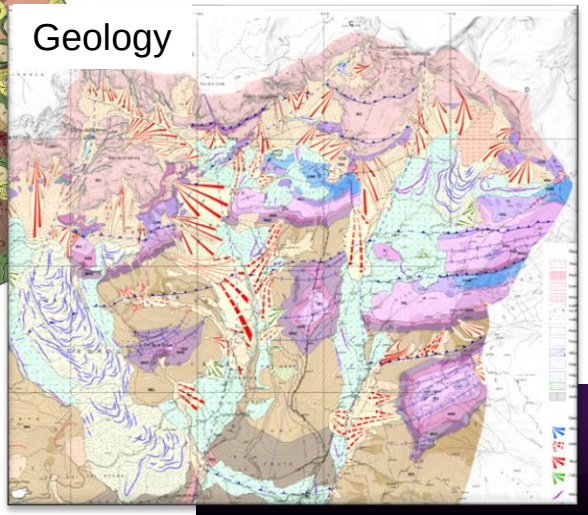
© Journal of Maps, 2018

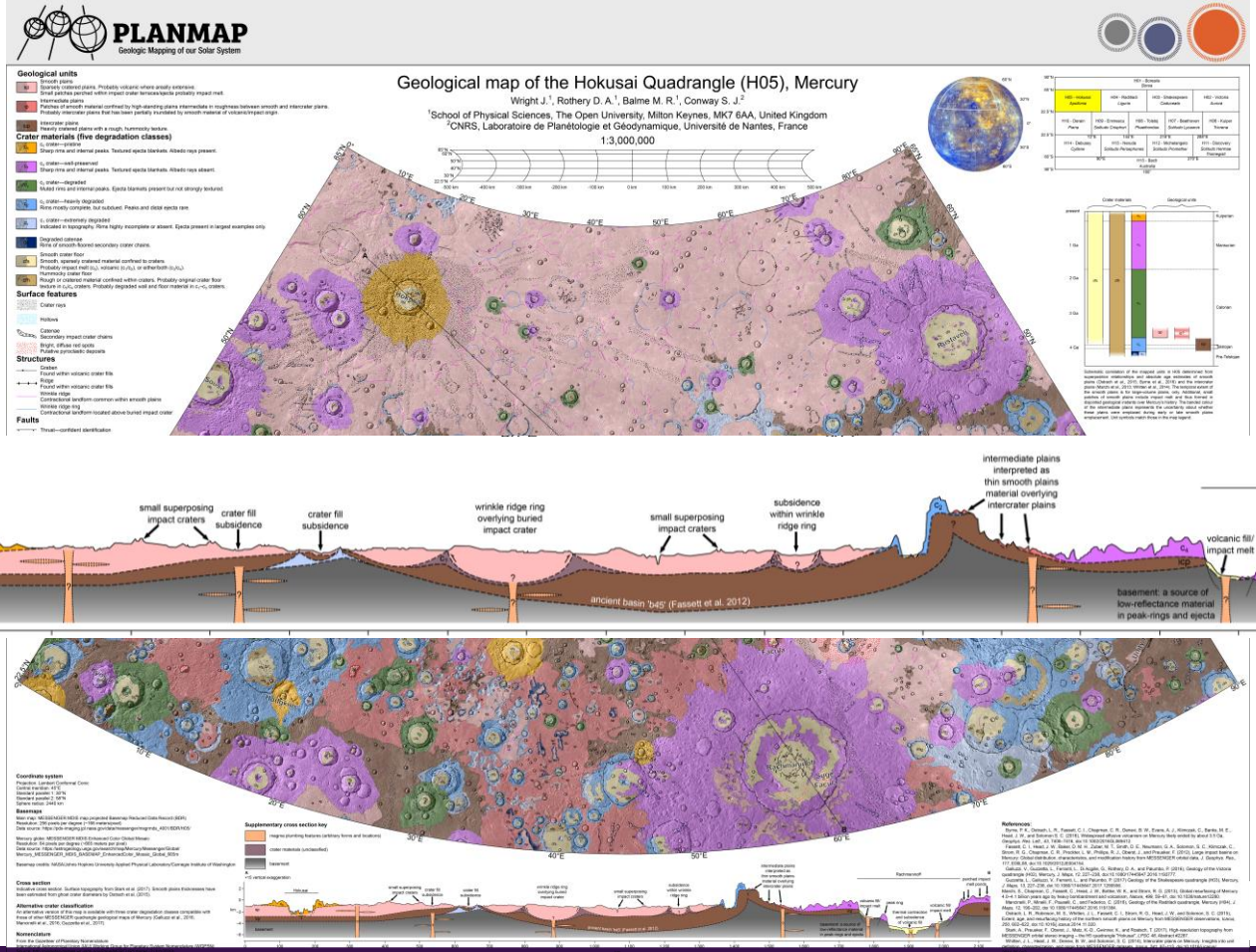
Morphostratigraphy

Geomorphology



Geology



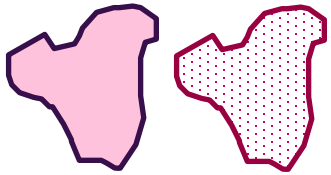


Wright et al. 2019

In Summary Planetary Morpho-stratigraphic Maps

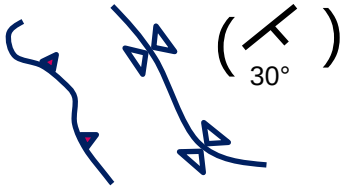
GMAP Geological Mapping

Polygons



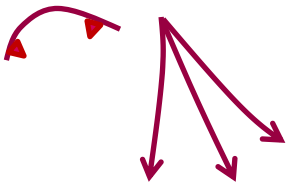
It forms – Morphostratigraphy

Lines
Points



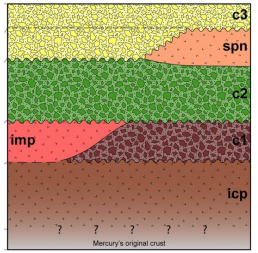
It deforms – Geological structures

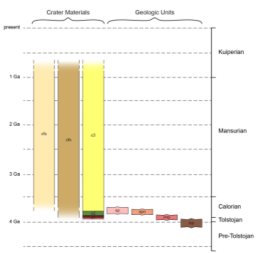
Lines



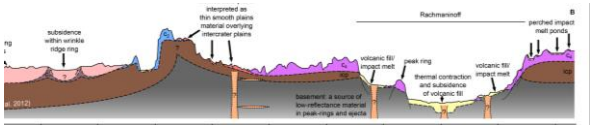
It shapes – Geomorphology

More Uncertain Geological Evolution

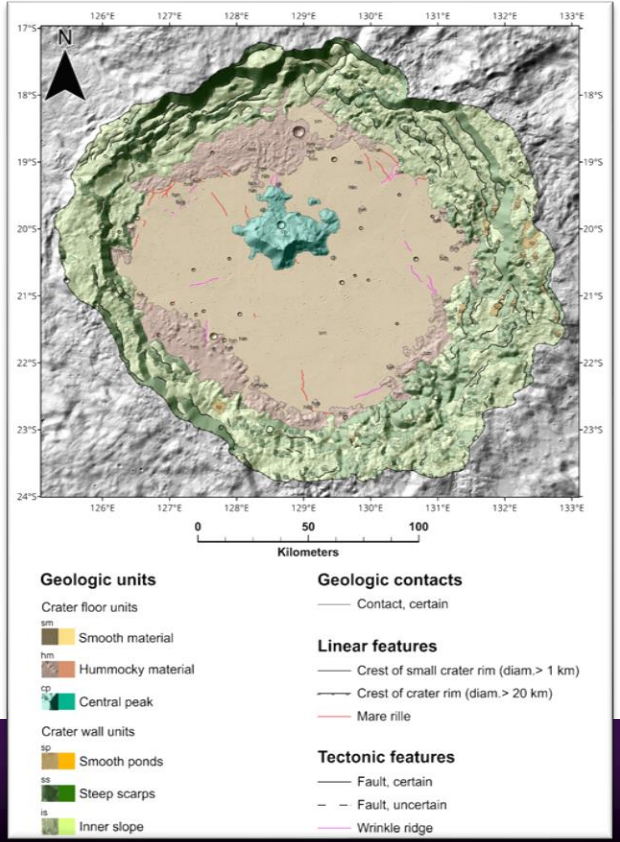


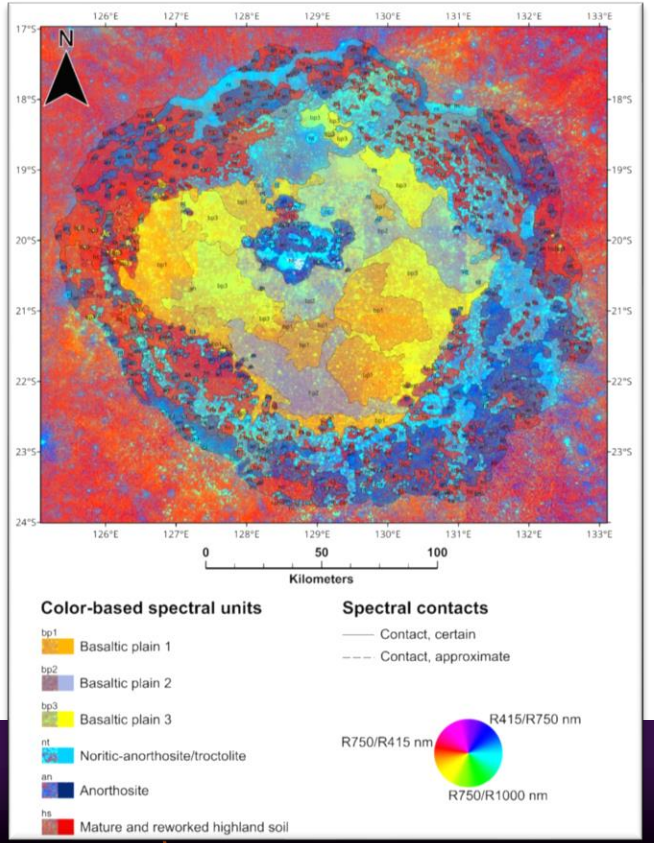


Limited Subsurface Geology



Towards Earth-like Geological Maps
Integrating colors and reflectance

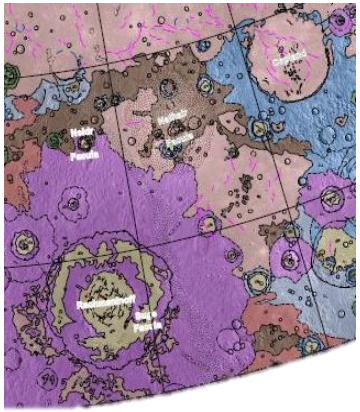




Tognon et al. 2021

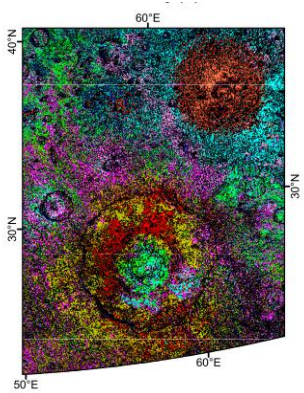
Integrating morpho-stratigraphy with spectral index

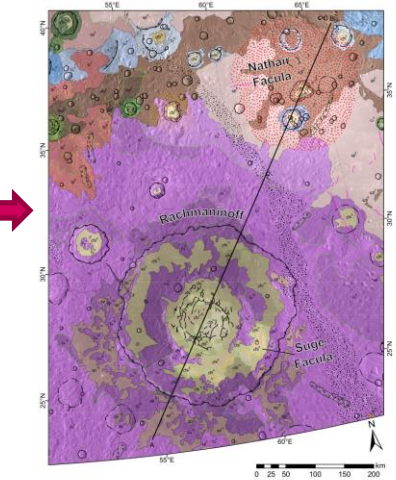
Morpho-stratigraphic map



+

Spectral Index map





PLANMAP
Geologic Mapping of our Solar System

Geostratigraphic map of Rachmaninoff crater and Nathair Facula in the Hokusai Quadrangle (H05) of Mercury

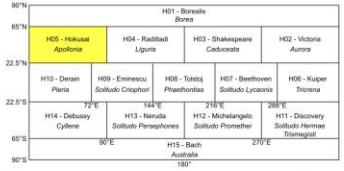
J. Wright[1], F. Zambon[2], C. Carli[2], D. A. Rothery[1], M. R. Balme[1], S. J. Conway[3]

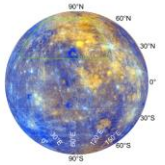
[1]School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
[2]INAF, Istituto di Astrofisica e Planetologia Spaziali (IAPS), Via del Fosso del Cavaliere, Rome 00133, Italy
[3]CNRS Laboratoire de Planétologie et Géodynamique de Nantes, Université de Nantes, 2 rue de la Houssiniere, 44322, Nantes, France

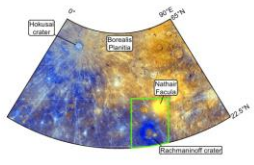
1:3,000,000

Introduction

This map combines the geomorphic units, mapped in the Hokusai quadrangle of Mercury (H05) by Wright et al. (2019), with spectral units, defined by Zambon et al. (in prep.) for the same quadrangle, to create 'geostratigraphic units'. As a first demonstration of this data fusion technique, a subregion of H05 encompassing Rachmaninoff crater and Nathair Facula was remapped. Wright et al. (2019) originally classified impact crater materials into five classes. Only four of those classes occur within subregion shown. Zambon et al. (in prep.) identified 11 spectral units (SU1–SU11) within H05. Only SU4–SU10 occur within the subregion shown.







Geostratigraphic map

Geostratigraphic units

Crater materials

C_4 craters

Well-preserved crater materials. Sharp rims and internal peaks. Textured ejecta blankets. Albedo rays absent. c_4^{10} is interpreted as Rachmaninoff ejecta mixed with melt. c_4^{1} is low-reflectance material excavated from Mercury's lower crust.

C_3 craters

Degraded crater materials. Muted rims and internal peaks. Ejecta blankets present but not strongly textured.

C_2 craters

Heavily degraded crater materials. Rims mostly complete, but subdued. Peaks and distal ejecta rare.

C_1 craters

Extremely degraded crater materials. Rims highly incomplete or absent. Ejecta present in largest examples only.

Smooth crater floor

Smooth, sparsely cratered material confined to craters. Either ponded impact melt or volcanic crater fill. cfs^5 and cfs^6 are post-impact volcanic infill of Rachmaninoff.

Hummocky crater floor

Rough or cratered material confined within craters. Either original floor texture or mass-wasted wall material.

Plains materials

Smooth plains

Sparsely cratered plains. Probably volcanic where areally extensive. Small patches within impact crater terraces/ejecta probably impact melt. sp^{10} is probably ponded Rachmaninoff impact melt.

Intermediate plains

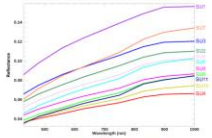
Patches of smooth material confined by high-standing plains intermediate in roughness between smooth and intercrater plains. Probably intercrater plains that has been partially inundated by smooth material of volcanic/impact origin.

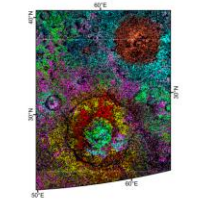
Intercrater plains

Heavily cratered plains with a rough, hummocky texture. Probably akin to smooth plains but older and thus more heavily cratered.

Geostratigraphic units are labelled with their original geomorphic unit symbol from Wright et al. (2019) followed by a superscript of their spectral unit number from Zambon et al. (in prep.). Geostratigraphic units of the same original geomorphic unit are symbolised in shades of their original symbol from Wright et al. (2019). Darker shades are used for geostratigraphic units with spectral units with lower overall reflectance. Spectral units uniquely correlated with surface features such as crater rays (SU9) and Nathair Facula (SU7), rather than 'bedrock' geology are shown by surface feature symbols.

Spectral units





Top: Reflectance spectra of Zambon et al. (in prep.) spectral units. Bottom: Map of Zambon et al. (in prep.) spectral units used to create this geostratigraphic map.

Linework and Ornaments

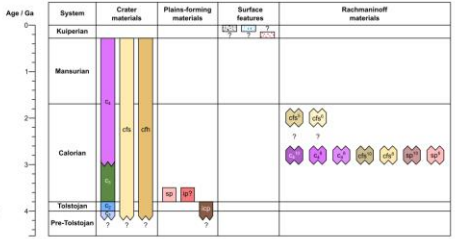
Contacts
certain
approximate
spectral

Structures
graben
ridge
wrinkle ridge
wrinkle ridge ring

Crater rims
large
small
buried
pit

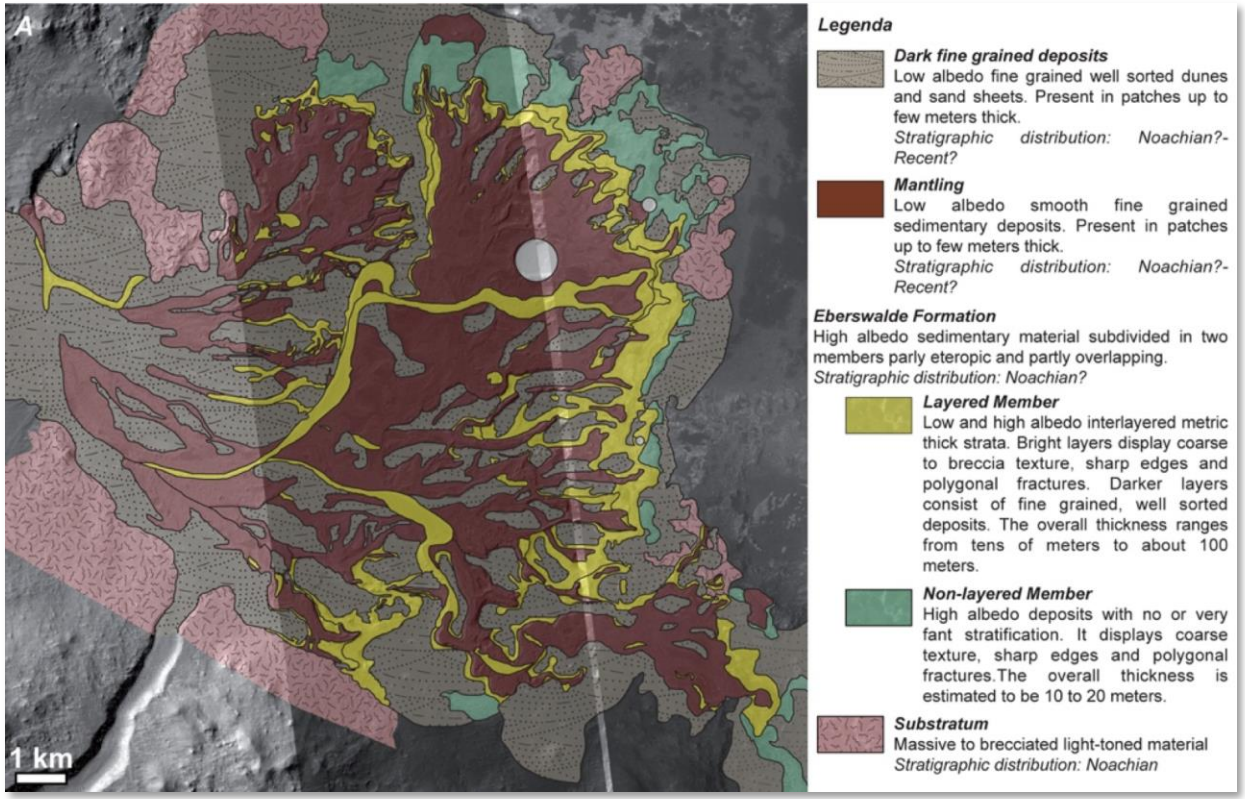
Surface features
catena
crater ray
facula
Nathair Facula
hollow

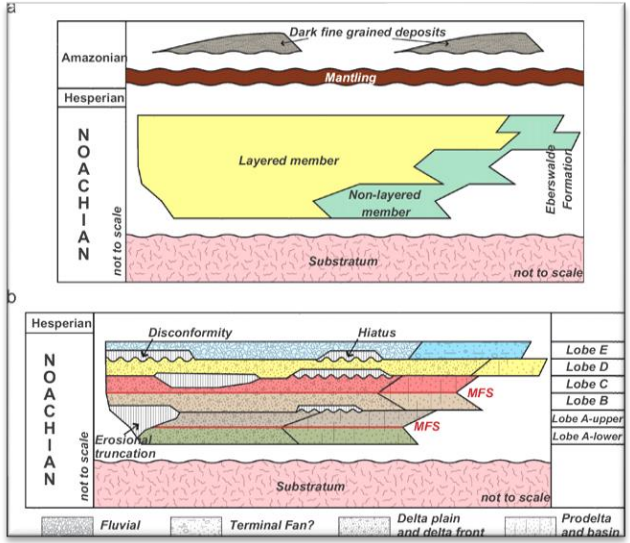
Correlation of Map Units



Schematic correlation of the geostratigraphic units of Rachmaninoff and Nathair Facula. Estimates of the absolute model ages of the Kuiperian and Mansurian (Banks et al., 2017), smooth plains (Ostrach et al., 2015; Byrne et al., 2016), and intercrater plains (Marchi et al., 2013; Whitten et al., 2014) are taken from appropriate literature values. It is uncertain whether intermediate plains were emplaced during early or late smooth plains emplacement. Crater size-frequency distributions show that central floor units of Rachmaninoff are younger than the rest of the crater materials (Chapman et al., 2012). Unit symbols match those in the map legend.

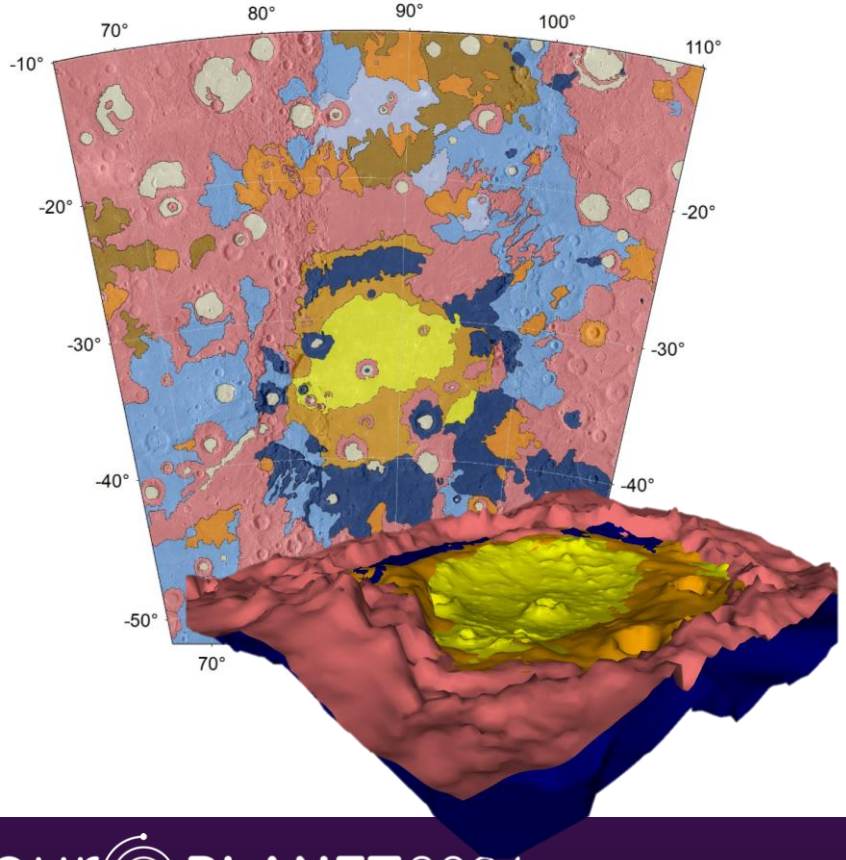
Towards Earth-like Geological Maps: Stratigraphy

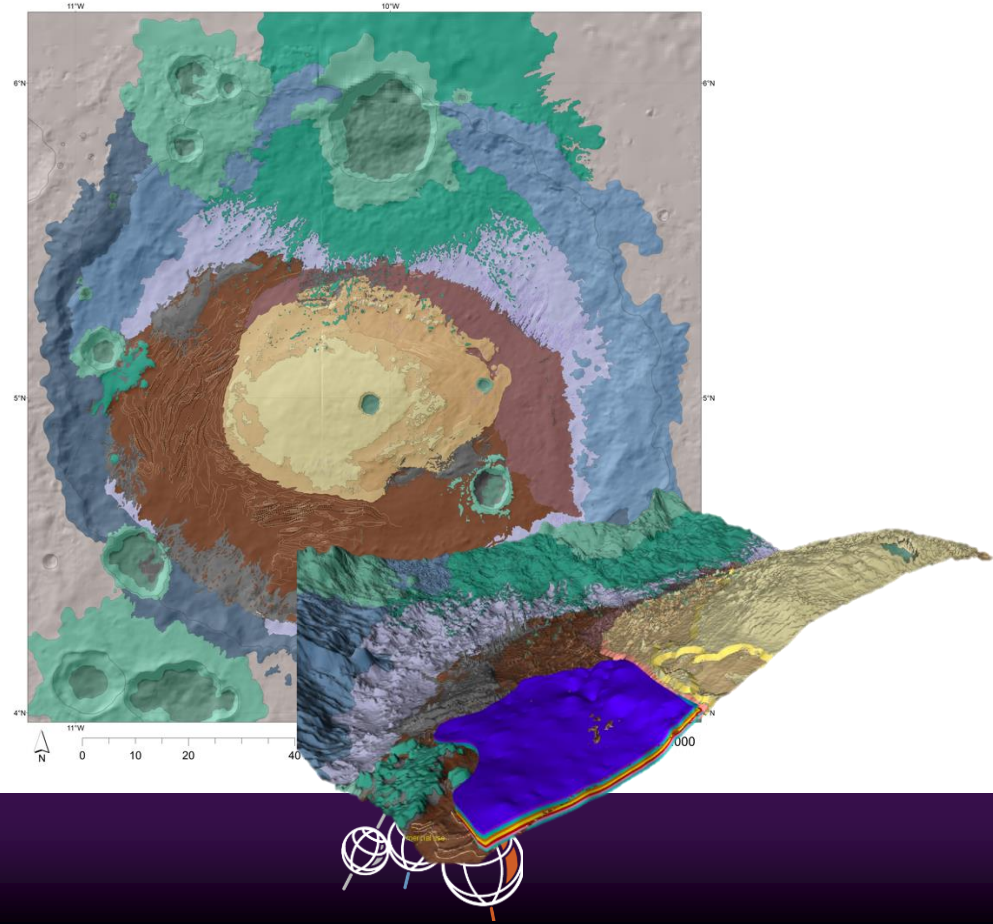




Pondrelli et al. 2011

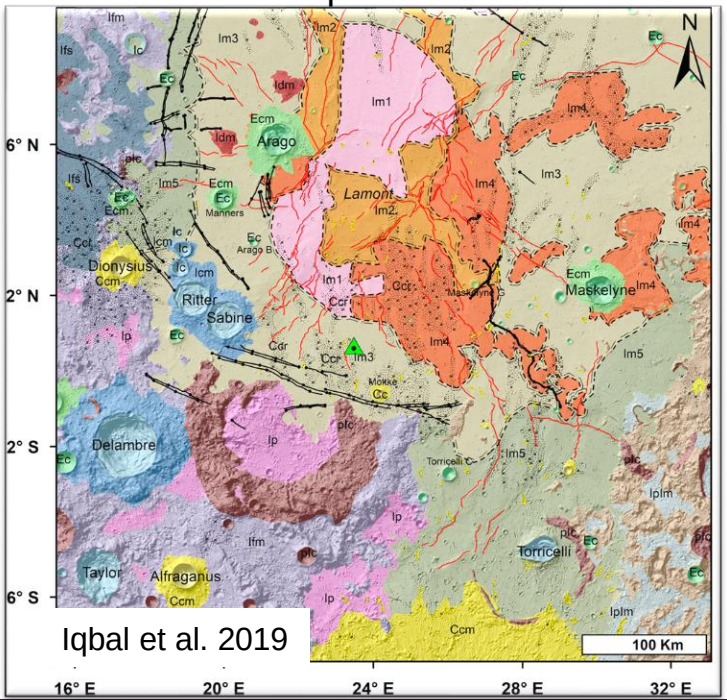
Towards Earth-like Geological Maps: Subsurface





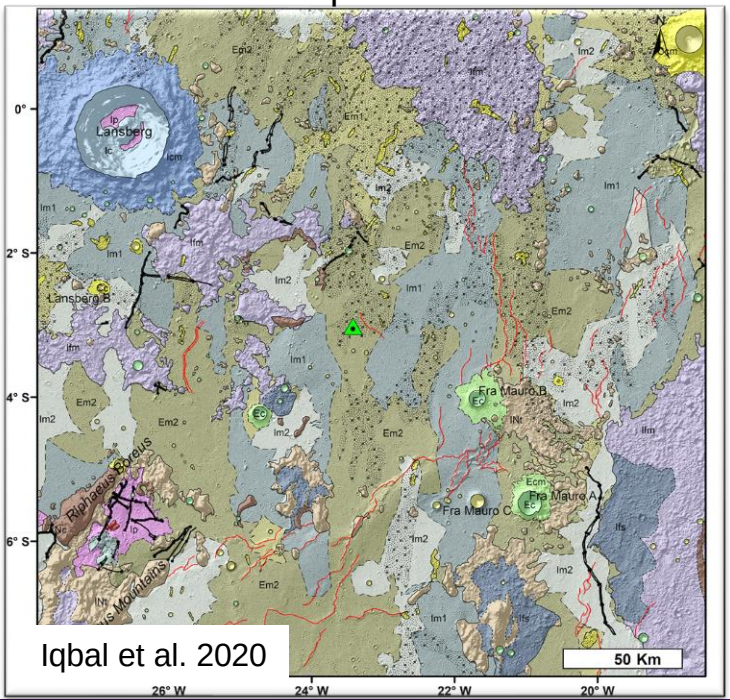
Towards Earth-like Geological Maps
highly detailed maps

Apollo 11



Iqbal et al. 2019

Apollo 12



Iqbal et al. 2020

Conclusions

- Any geological map should provide information on the evolution of a given territory in terms of formation, deformation and shaping

- Earth geological maps are produced mainly through in situ surveys and based on Litho-stratigraphy

- Planetary geological Maps are produced through photointerpretation and based on Morpho-stratigraphy

- For several reasons (dominant impact cratering and lack of in situ information) it will be a long way for planetary geological maps to approach the Earth ones,

- Important improvements have been made in the last decade including compositional (reflectance) information, stratigraphic correlations, subsurface reconstructions and detailed mapping (for landing sites characterization).