

WE

eur  **PLANET 2024**
Research Infrastructure





Geology & Planetary Mapping

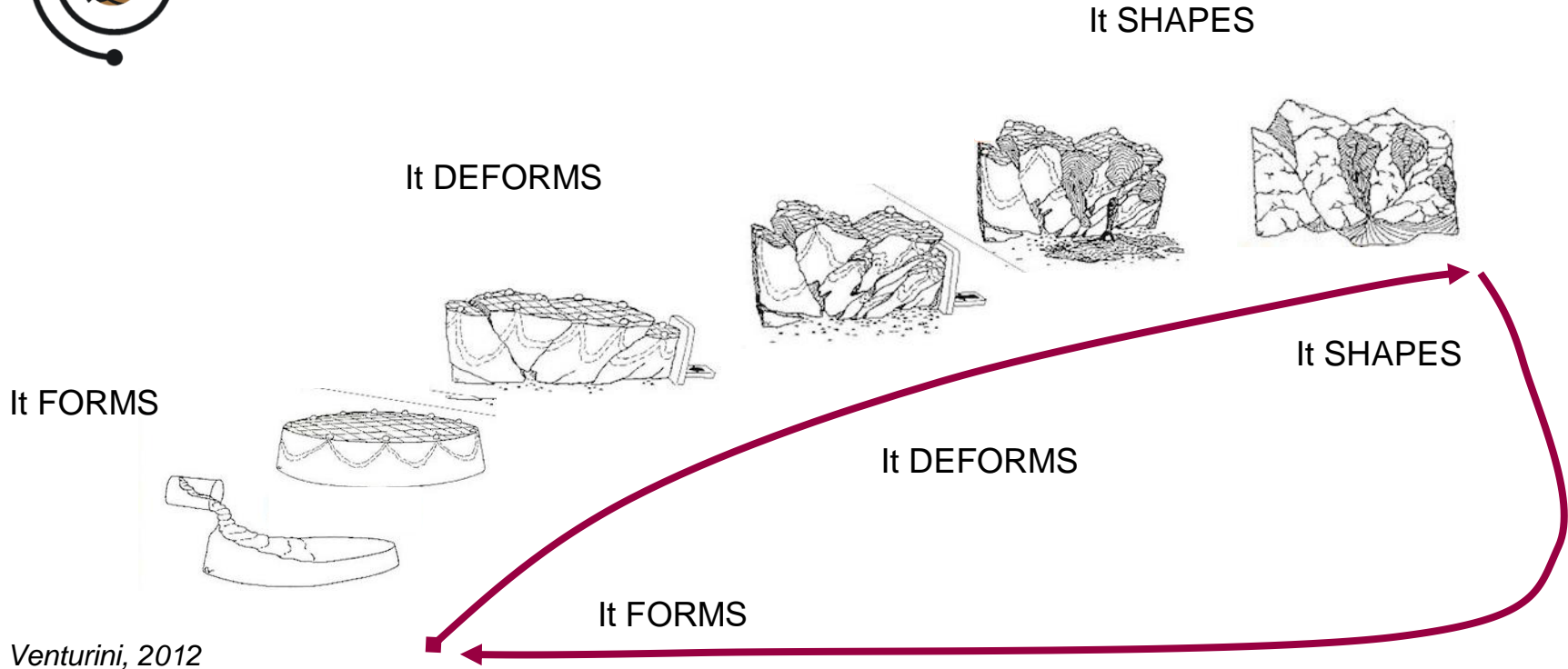
Winter School

Terrestrial and Planetary geologic mapping: an overview

Matteo Massironi (UNIPD)

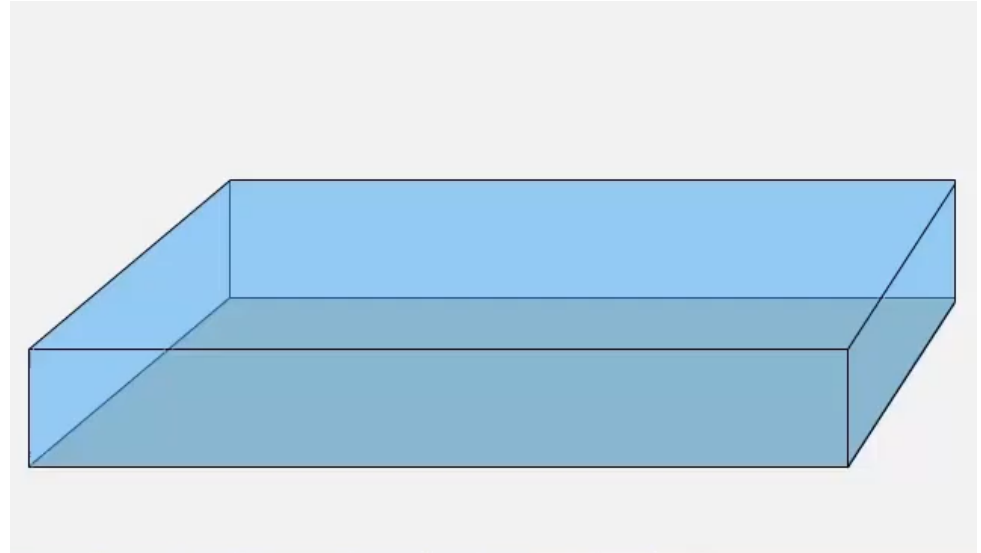
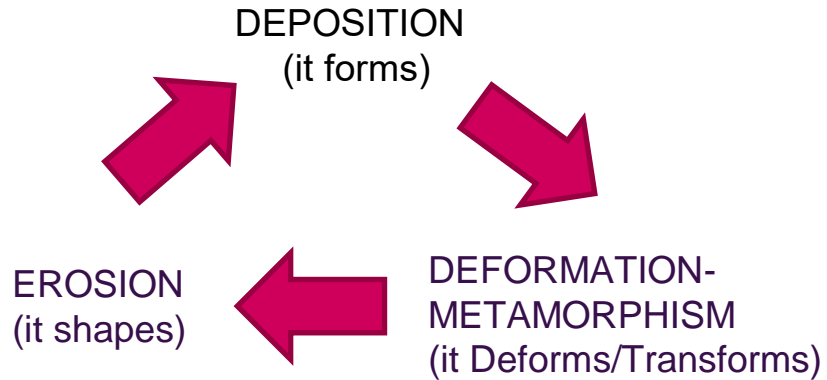


The distorted layer cake



Venturini, 2012

It forms, it deforms, it shapes





It forms

It shapes

It deforms

It deforms

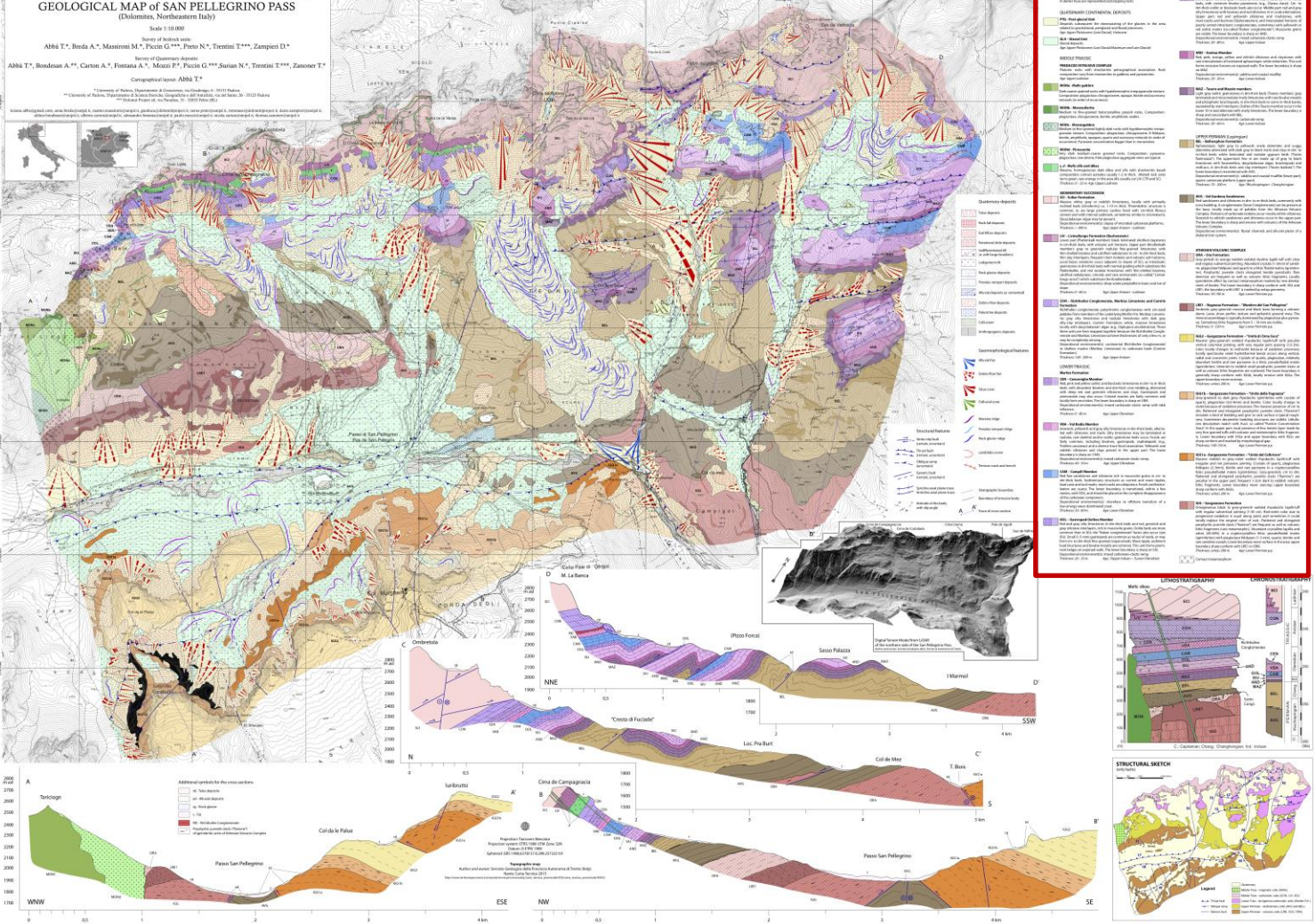
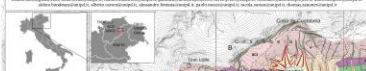
It shapes

GEOLOGICAL MAP OF SAN PELLEGRINO PASS (Dolomites, Northeastern Italy)

Scale 1:10,000

Survey of geological units:
Abba T., Breda A., Mastorini M., Picoi G.**, Pano N., Trentini T.**, Zampieri D.*
Survey of Quaternary deposits:
Abba T., Boudreau A., Carton A., Fumana A.**, Masci P., Picoi G.**, Sartori N., Trentini T.**, Zanoner T.*
Geographical name: Abba T.*

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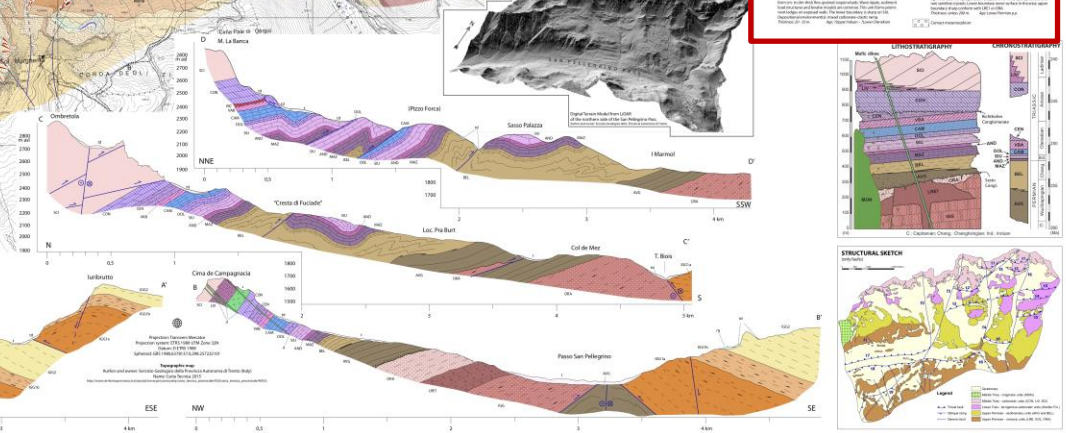
LEGEND

SCALE
Scale 1:10,000
Graphic scale: 0 to 1000 m

Geological units (Lithostratigraphic units)
Triassic (T)
T1: Lower Triassic (Silesite)
T2: Middle Triassic (Marmorato)
T3: Upper Triassic (Gröden)
Jurassic (J)
J1: Lower Jurassic (Lias)
J2: Middle Jurassic (Malm)
cretaceous (C)
C1: Lower Cretaceous (Grès)
C2: Middle Cretaceous (Malm)
C3: Upper Cretaceous (Grès)
Tertiary (T)
T4: Lower Tertiary (Lias)
T5: Middle Tertiary (Malm)
Quaternary (Q)
Q1: Recent (R)
Q2: Pleistocene (P)
Q3: Holocene (H)

Structural features
Faults: Strike-slip, Normal, Thrust
Folds: Synclinal, Anticlinal
Fault-scarps, Fault scarps, Fault scarps

It forms: Geological units

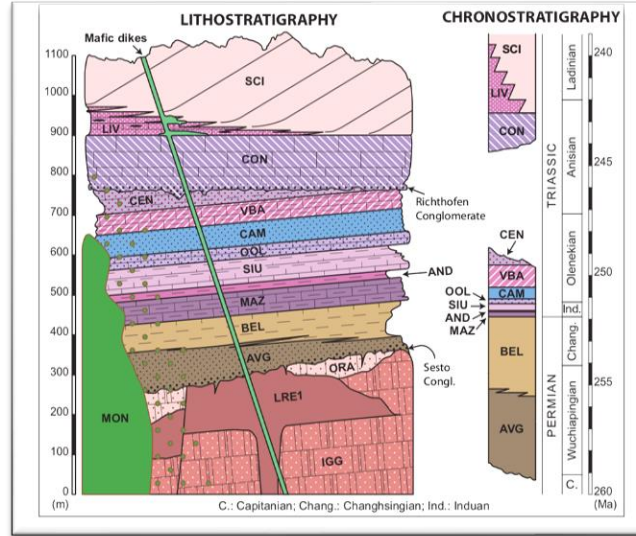


Abba' et al. 2018

It forms: Geological units

The lithostratigraphic units must:

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



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, aeolian 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 - Monzonitoid
Medium to fine-grained holocrystalline gneiss rocks. Composition: plagioclase, clinopyroxene, biotite, amphibole, oxides.

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

MONd - Piroxenite
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 primary inclined beds (kinofolds) ca. 1-10 m thick. Thrombotic structure is common, as are large primary cavities lined with cm-thick fibrous cement and with internal sediment, sometimes similar to stromatolites. Dasycladacean algae may be present.
Depositional environment(s): slopes of microbial carbonate platforms.
Thickness: 300 m. Age: Upper Anisian - Ladinian

LIV - Livinalonga Formation (Buchenstein)
Lower part (Planentalik member): black laminated silified claystones in cm-thick beds, with volcanic ash horizons. Upper part (Drofenalk 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 intracrystalline granitoides in dm-thick beds with normal grading which substitute the Planentalik, and red nodular limestones with thin-shelled bivalves, calcified radiolarians, crinoids and rare ammonoids (so-called "Livinalonga roses") which substitute the Knochenkalk.
Depositional environment(s): deep-water periplatform basin and toe of slope.
Thickness: 0 - 60 m. Age: Upper Anisian - Ladinian

CON - Richthofen Conglomerate, Morbatic Limestone and Contrin Formation
Richthofen conglomerate: polychrome conglomerates with cm-sized pebbles from members of the underlying Werfen fm. Morbatic 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 annulata*). These three units are here suggested together because the Richthofen Conglomerate and Morbatic Limestone achieve thicknesses of only a few m, or may be completely missing.
Depositional environment(s): continental (Richthofen Conglomerate) to shallow marine (Morbatic Limestone) to carbonate bank (Contrin Formation).
Thickness: 100 - 200 m. Age: Upper Anisian

SIU - Siusa Member
Lower part: red and gray limestones and silty limestones in dm-thick beds, with common bivalve pavements (e.g. *Carana clara*). Cm- to dm-thick oolitic or biotactic 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 (Diplocerasium), and intercalated horizons of poorly sorted intracrystalline conglomerates, sometimes with yellowish or red oolitic matrix (so-called "Koken conglomerate"). Muscovite grains are visible. The lower boundary is sharp on ANG.
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 aphanitic, 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 micromodular 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
Aphanitic, light gray to yellowish marly dolomites and wuggy dolomites alternated with dark gray to black marls and clays in dm- to m-thick beds; white laminated and nodular gypsum beds (facies *Fammazza*). The uppermost few m are made up of gray to black limestones with *Faxminella*, *dasycladacean* algae, brachiopods and molluscs, in dm-thick beds and clay interlayers ("facies *badotta*"). 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

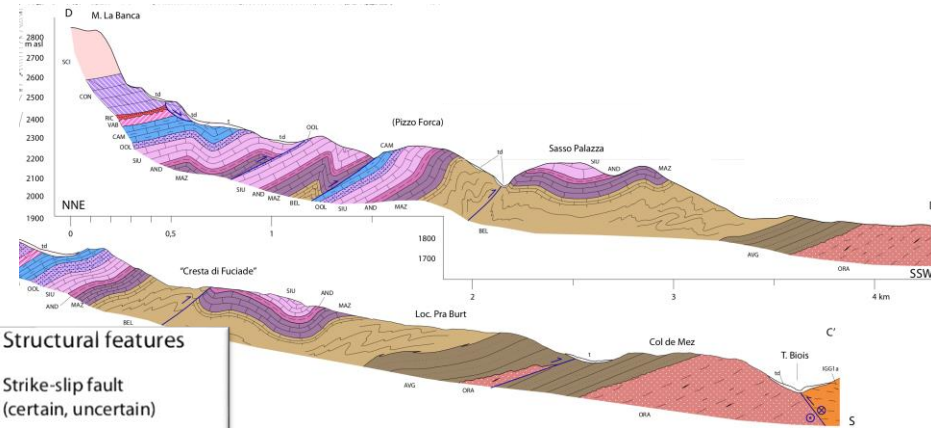
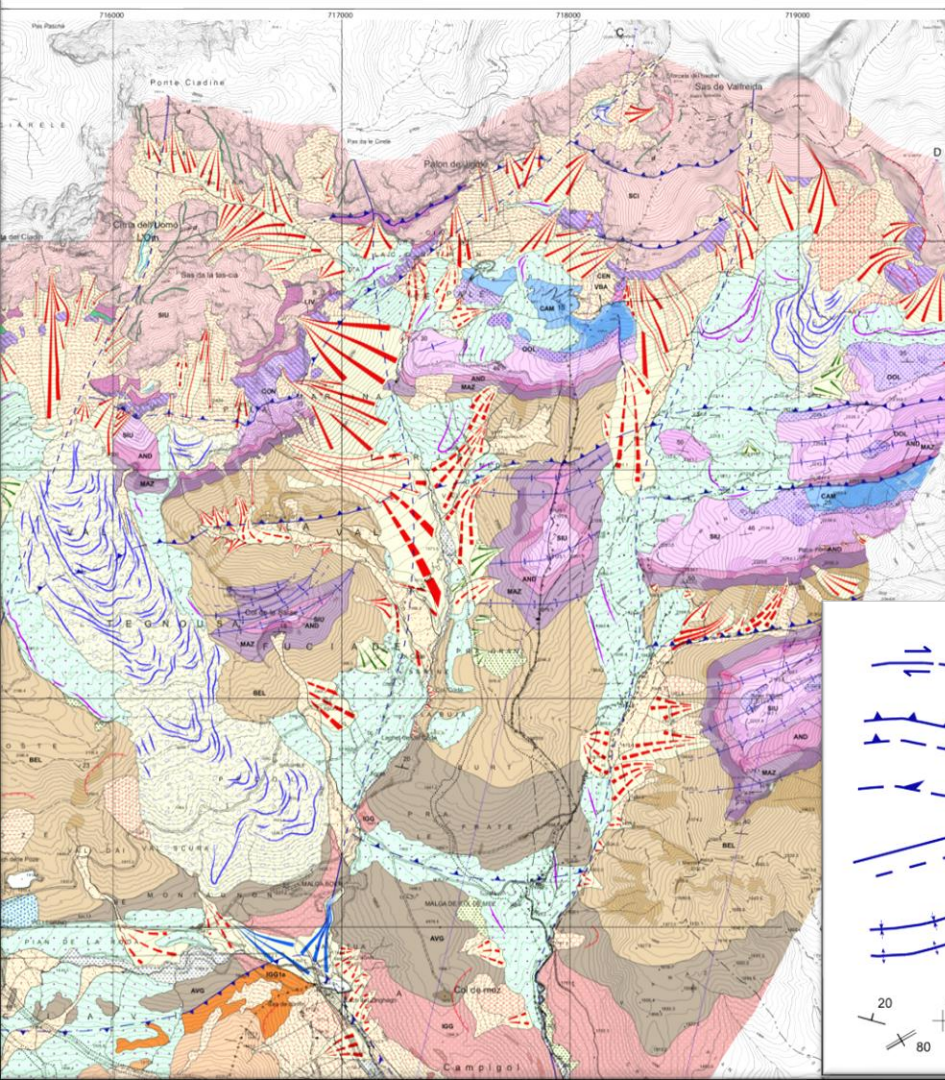
ORA - Ora Formation
Grey pinkish to orange-red welded rhyolitic lapilli-ruff with clear and regular subvertical jointing. Abundant crystals (1 - 3mm) of sanidine, plagioclase, feldspar and quartz in a felsic feldspar matrix (ignimbrite). Porphyritic juvenile clasts elongated beside pyroclastic flow direction are frequent as well as volcanic lithic fragments. Locally ignimbrite affected 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 pp.

LRE1 - Regana Formation - "Membro del San Pellegrino"
Andesitic grey-greenish massive and black lavas forming a volcanic dome. Lavas show porphyritic 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 pp.







IGG2 - Gargazzone Formation - "Unità di Cima Cece"
Massive grey-greenish welded rhyolitic lapilli-ruff with peculiar vertical columnar jointing, with very regular joint spacing (1.5-2 m). Color locally changes to red/violet because of oxidation processes; locally spectacular violet hydrothermal bands occur along vertical, radial and concentric joints. Crystals of quartz, plagioclase, relatively




It deforms: Geological structures



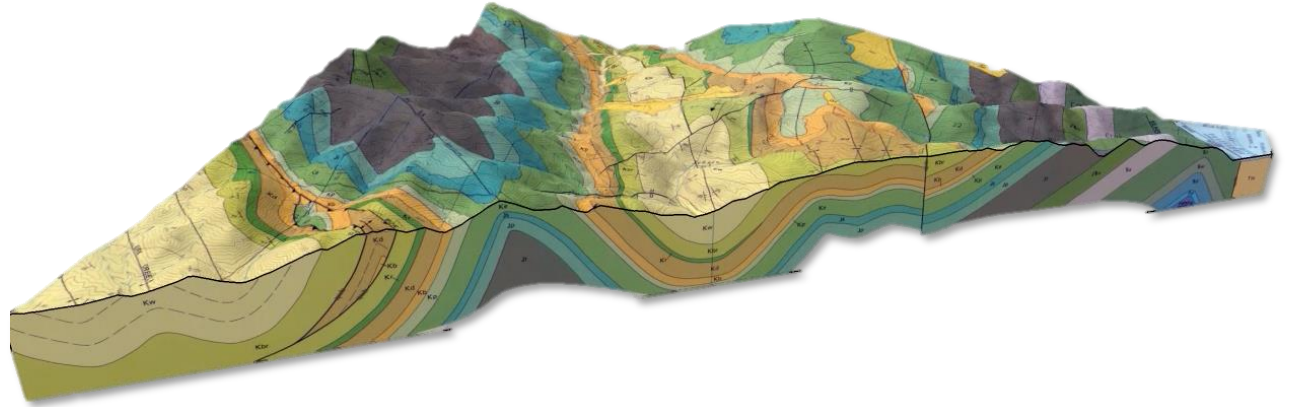
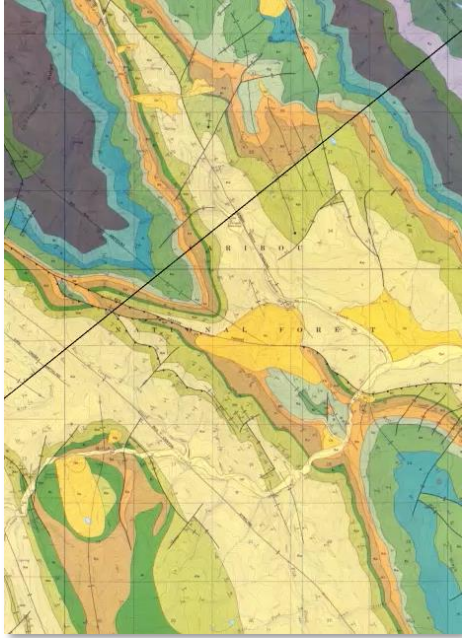
Structural features

-  Strike-slip fault
(certain, uncertain)
-  Thrust fault
(certain, uncertain)
-  Oblique ramp
(uncertain)
-  Generic fault
(certain, uncertain)
-  Syncline axial plane trace
-  Anticline axial plane trace

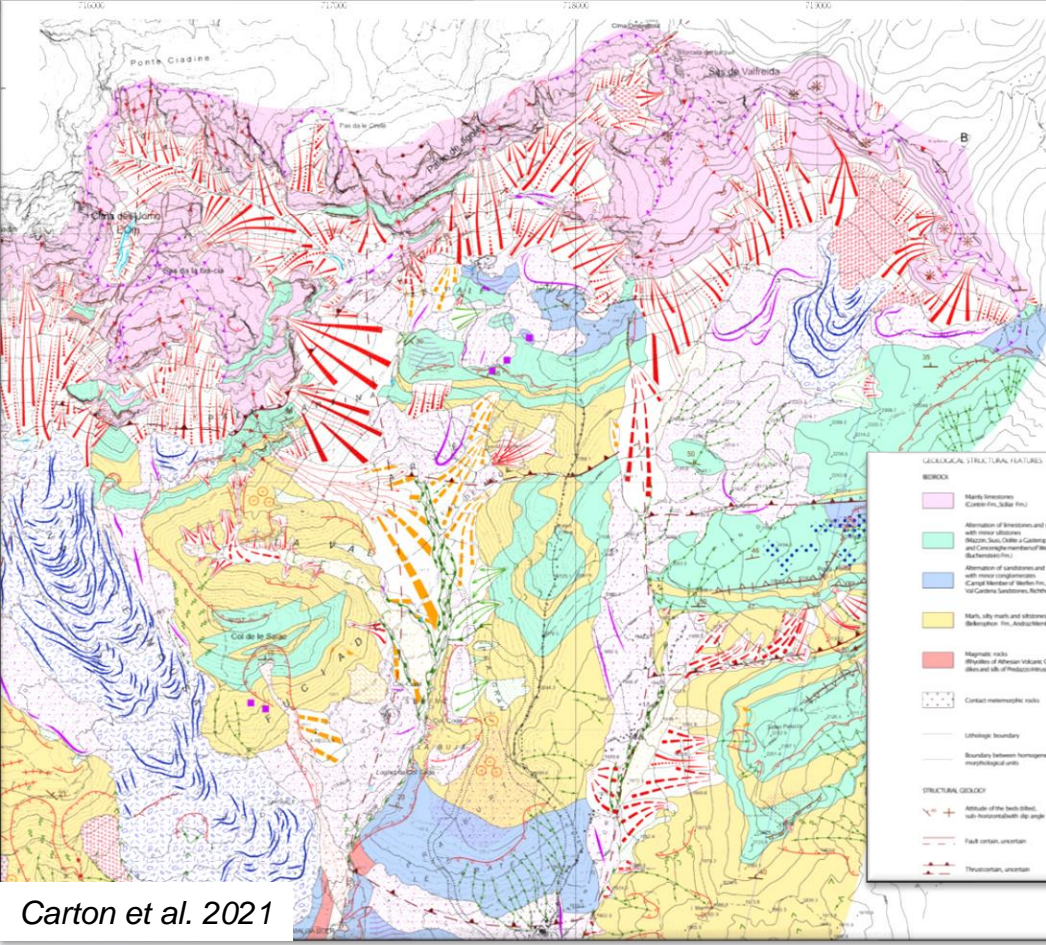
 Attitude of the beds,
with dip angle



It deforms: Geological structures



It shapes: Geomorphological maps



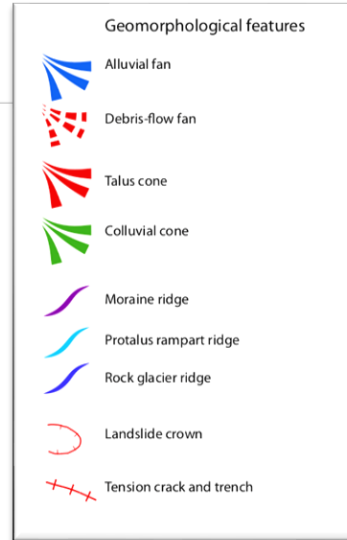
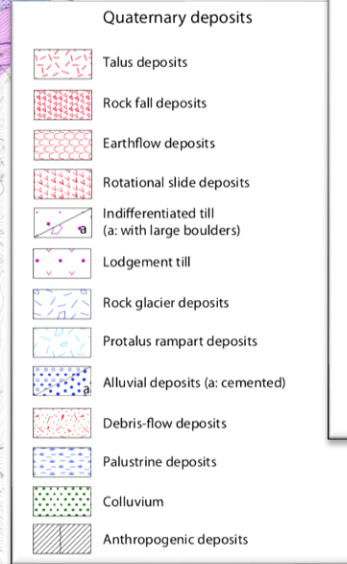
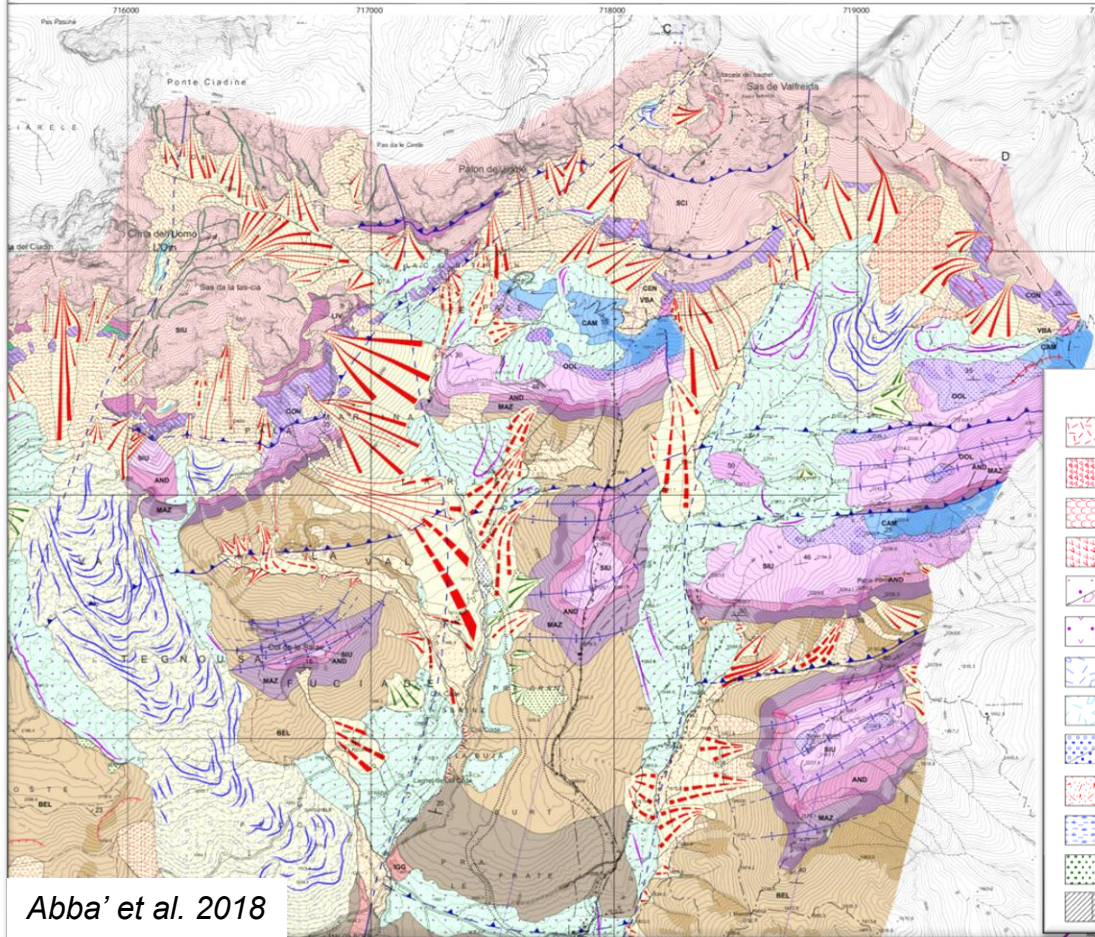
GEOMORPHOLOGICAL STRUCTURAL FEATURES	HYDROGRAPHY	LANDFORMS AND DEPOSITS (DUE TO GRAVITY)	LANDFORMS AND DEPOSITS (DUE TO SURFICIAL WATER)	GLACIAL LANDFORM AND DEPOSITS
BEDROCK <ul style="list-style-type: none"> Marks, lineations (Carton et al. 2021) Alteration of bedrocks and marks lineations with minor alluviums (Miguelas, San Celler, Gombau, Val Balle and Cervera members of Iberian Fm., Llandegai, Bactonensis) Alteration of sandstones and shales with minor conglomerates (Carnal Member of Iberian Fm., Val Carles, Santones, Richelieu Conglomerate) Marks, ally marks and shales (Bactonensis Fm., Andujar Member of Iberian Fm.) Migmatite rocks (Miguelas, San Celler, Gombau, Val Balle and Cervera members of Iberian Fm., Llandegai, Bactonensis, and all of Pre-Cambrian Complex) Contact metamorphic rocks Lithologic boundary Boundary between homometric morphological units 	<ul style="list-style-type: none"> Spring Lake Fluvial deposit 	<ul style="list-style-type: none"> active valley SEDIMENTAL LANDFORMS Landslide crown Val of earth debris flow of rotational slide Degradational scarp Collar with debris discharge Degradational slope CONSTRUCTIONAL LANDFORMS AND DEPOSITS Landslide deposit Earth flow Rotational landslide Debris-flown-out flowpaths Scree slope Talus cone Debris-flown-out fan Debris flow Terraced/slopes/land spreading breach 	<ul style="list-style-type: none"> active valley LANDFORMS AND DEPOSITS (DUE TO SURFICIAL WATER) Gully / Barren V-shaped valley Through-erosional valley Flat bottomed small valley Incising channel Fluvial erosion scarp Surface affected by sheet erosion Surface affected by debris erosion Stream deposit with texture from leader to head Complement Alluvial fan Colluvial deposit Colluvial fan CYTICZIC AND NATIVATION LANDFORMS Profilat transport Risk glacier Surface with earth hummocks 	<ul style="list-style-type: none"> active valley SEDIMENTAL LANDFORMS Edge of tongue Step of through-barrier Smoothed surface Radial moraines CONSTRUCTIONAL LANDFORMS AND DEPOSITS Musky ridge Clacial deposit Big boulder glacial deposit Small boulder MAN-MADE LANDFORMS Excavation surface Embankment Sea bank GEOMORPHOLOGY °C day
STRUCTURAL GEOLOGY <ul style="list-style-type: none"> Attitude of the fault-related, sub-horizontal (dip angle) Fault-scarp, orientation Thrust-scarp, orientation 	<ul style="list-style-type: none"> STRUCTURAL LANDFORMS Edge of scarp Structurally controlled steep slope Ridge Hogback Peak Strike-slip KARST LANDFORMS Edge of doline Doline or doline field (over scale) 	<ul style="list-style-type: none"> SEDIMENTAL LANDFORMS Landslide crown Val of earth debris flow of rotational slide Degradational scarp Collar with debris discharge Degradational slope CONSTRUCTIONAL LANDFORMS AND DEPOSITS Landslide deposit Earth flow Rotational landslide Debris-flown-out flowpaths Scree slope Talus cone Debris-flown-out fan Debris flow Terraced/slopes/land spreading breach 	<ul style="list-style-type: none"> LANDFORMS AND DEPOSITS (DUE TO SURFICIAL WATER) Gully / Barren V-shaped valley Through-erosional valley Flat bottomed small valley Incising channel Fluvial erosion scarp Surface affected by sheet erosion Surface affected by debris erosion Stream deposit with texture from leader to head Complement Alluvial fan Colluvial deposit Colluvial fan CYTICZIC AND NATIVATION LANDFORMS Profilat transport Risk glacier Surface with earth hummocks 	<ul style="list-style-type: none"> GLACIAL LANDFORM AND DEPOSITS Edge of tongue Step of through-barrier Smoothed surface Radial moraines CONSTRUCTIONAL LANDFORMS AND DEPOSITS Musky ridge Clacial deposit Big boulder glacial deposit Small boulder MAN-MADE LANDFORMS Excavation surface Embankment Sea bank GEOMORPHOLOGY °C day

Sample: Depth from lake bottom | Type of material | Radiocarbon age (years BP) | Calibrated age (see lab notes BP)
 Area 000712 | 2.00 m | Fine silts | 16,310 ± 710
 Area 000713 | 2.00 m | Fine silts | 11,200 ± 600
 Radiocarbon dates from the center of Camporruig. Age calibrated through the software CALIB 8.2 (Stuiver et al., 2023) (see the central table 000712 and 000713).

Carton et al. 2021

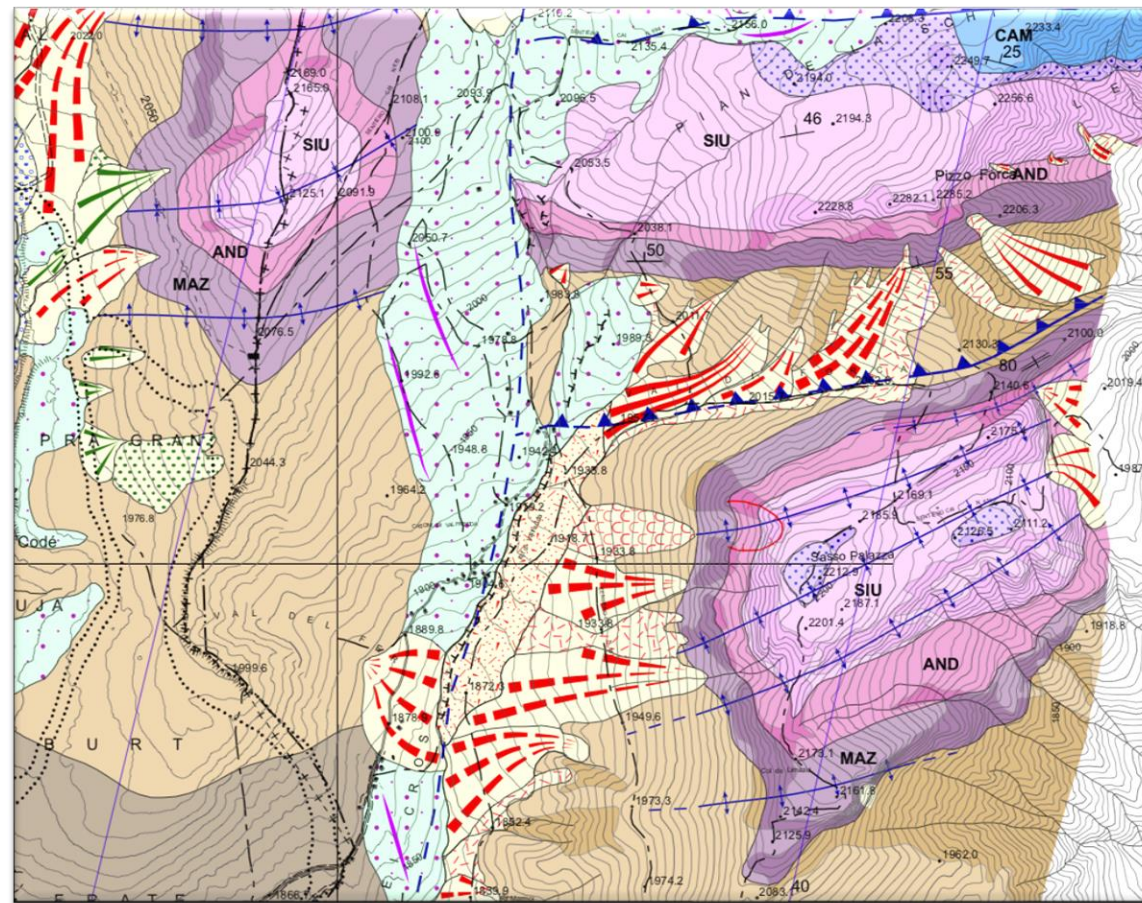


It shapes: Deposits and Geomorphology



Abba' et al. 2018

From details to the overall synthesis



- SIU - Siusi Member**
 Lower part: red and gray limestones and silty limestones in dm-thick beds, with common bivalve pavements (e.g., *Claria claria*). 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 (*Diplocatation*), and intercalated horizons of poorly sorted intrastriatic 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

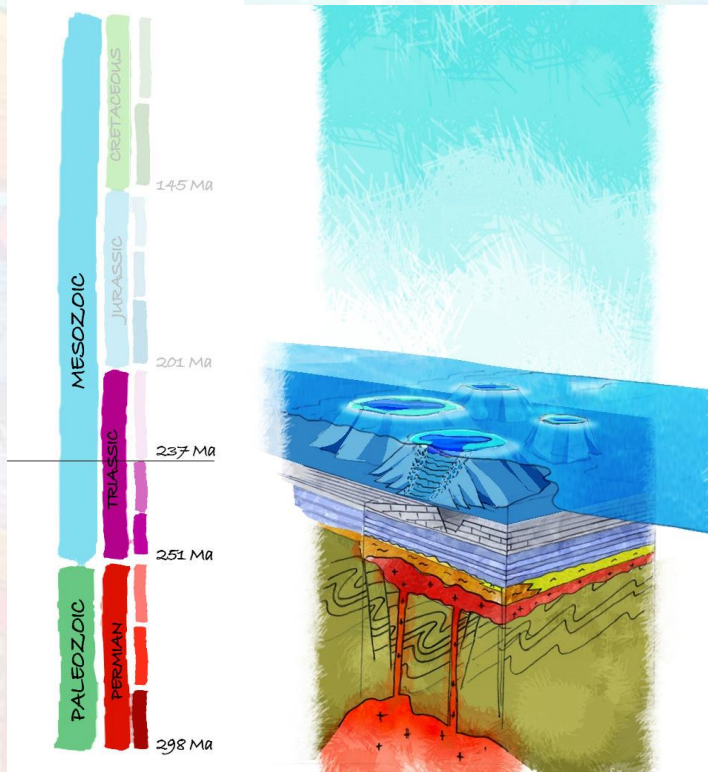
- MAZ - Tesero and Mazzin members**
 Light gray oolitic grainstones in dm-thick beds (Tesero member), gray laminated and micromnodular marly limestones with rare bivalve moulds and phosphatic brachiopods, in dm-thick beds to some m-thick banks, separated by marl layers. Oolites of the Tesero member occur 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 - Belleophon 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 ("fiasc fumazza"). 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 ("fiasc badotta"). The lower boundary is transitional with AVG.
 Depositional environment(s): sabkha and coastal mudflat (lower part), epicritic 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.



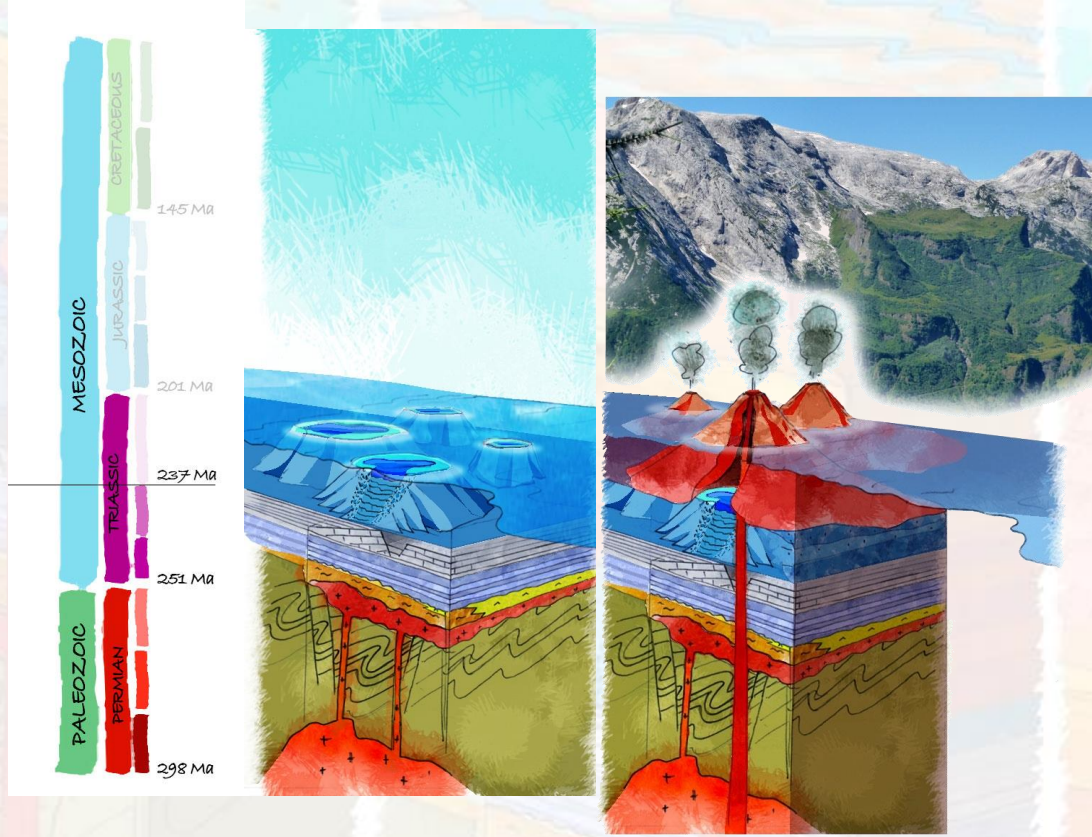
Reading the geological evolution from a stratigraphic scheme



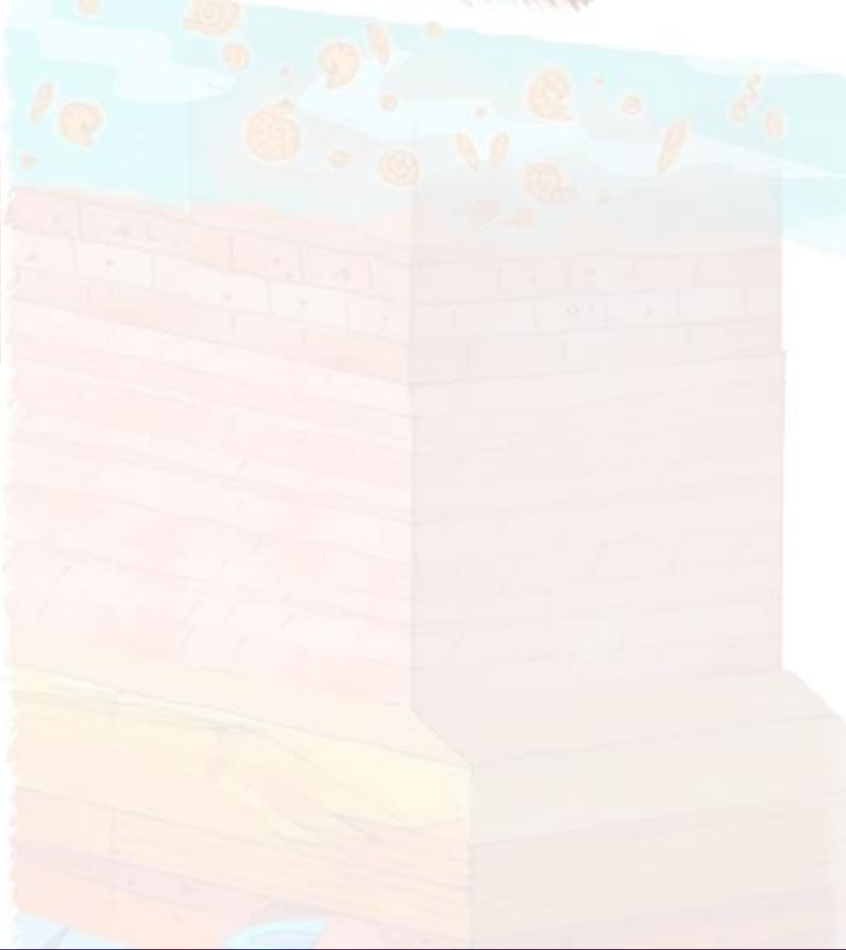
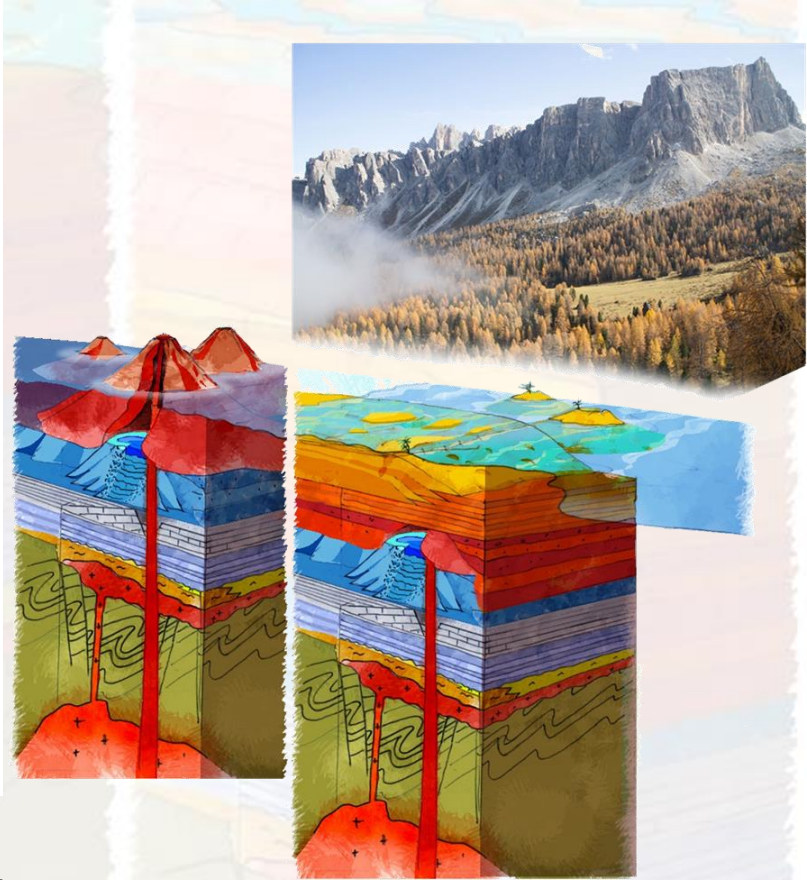
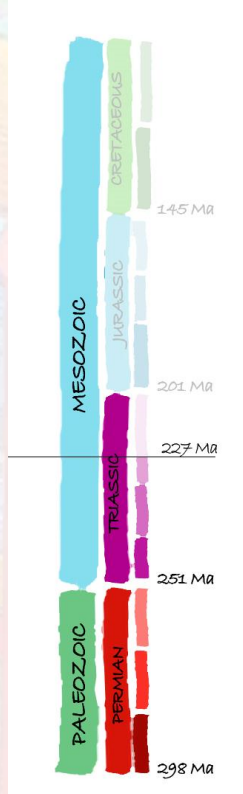
Colorata stratigrafica realizzata utilizzando i passaggi presenti in Dolomiti milioni di anni fa.

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

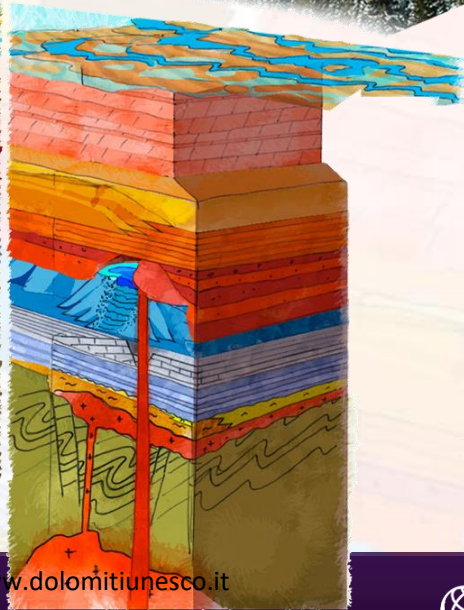
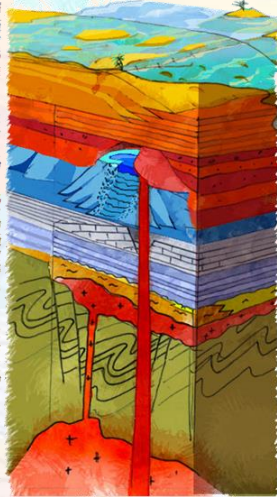
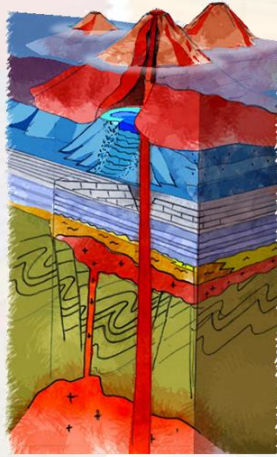
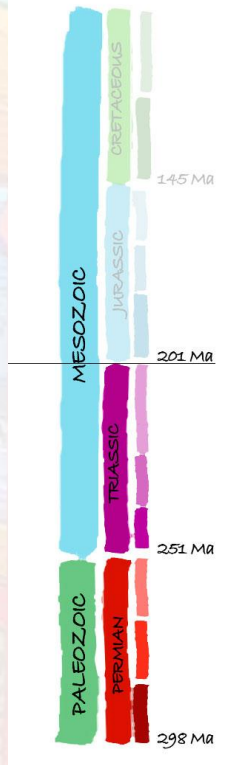
Credits: E.Manfré
Fondazione Dolomiti Unesco www.dolomitiunesco.it



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

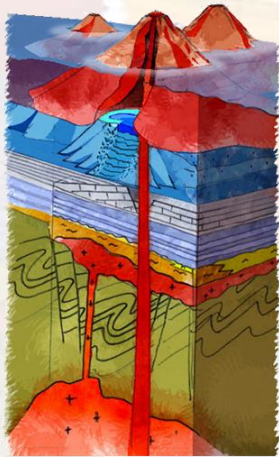
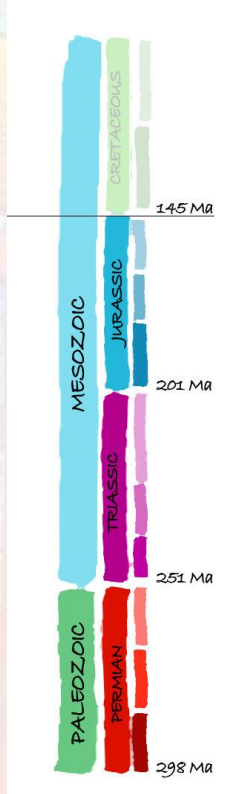


Credits: E.Manfré
 Fondazione Dolomiti Unesco www.dolomitiunesco.it

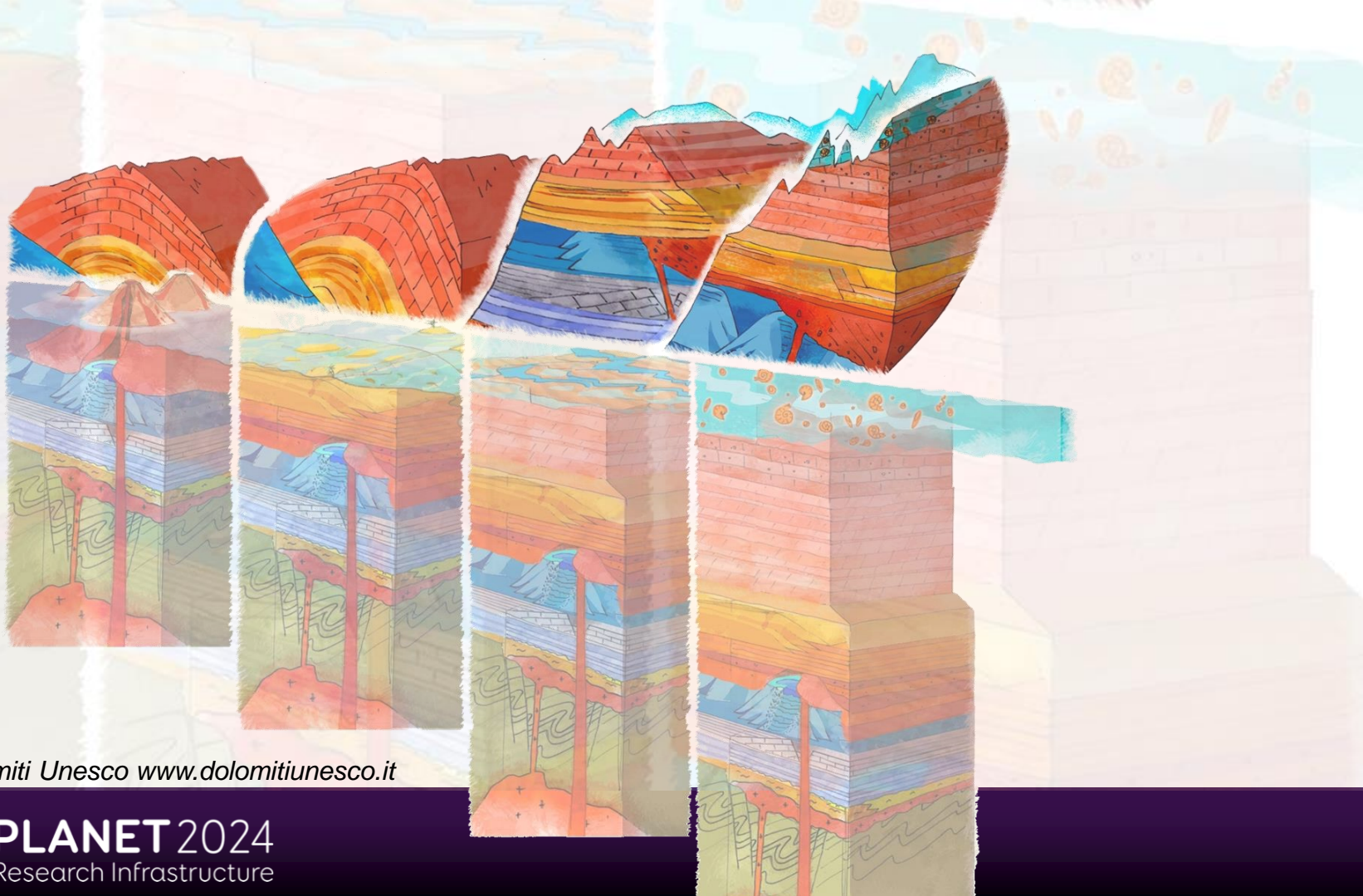
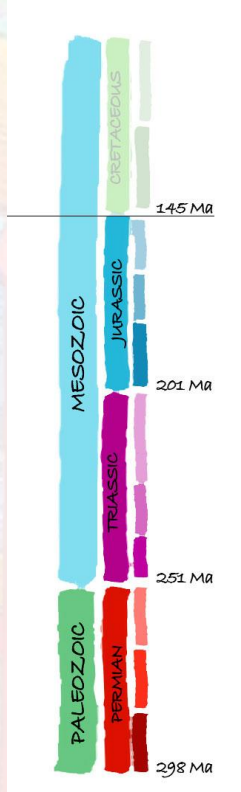


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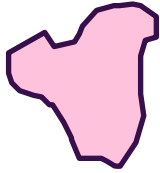
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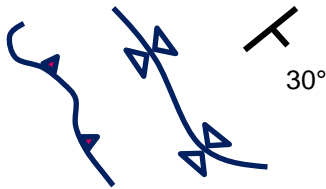
In Summary Earth Geological Maps

Polygons



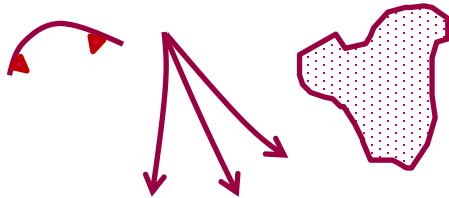
It forms – Geology –Lithostratigraphy
Chronostratigraphy

Lines
Points



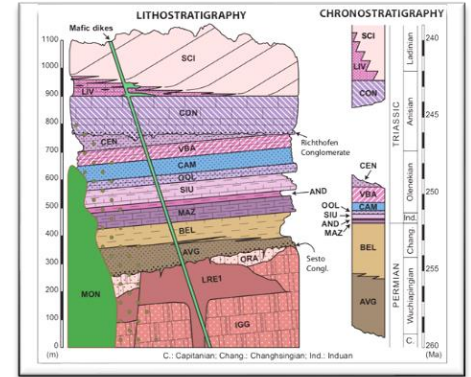
It deforms – Geological structures
and strata attitudes

Lines
Polygons

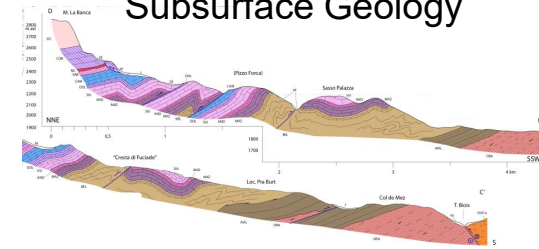


It shapes – Geomorphology
and loose deposits

Geological Evolution



Subsurface Geology



Does it hold for Planetary surfaces?

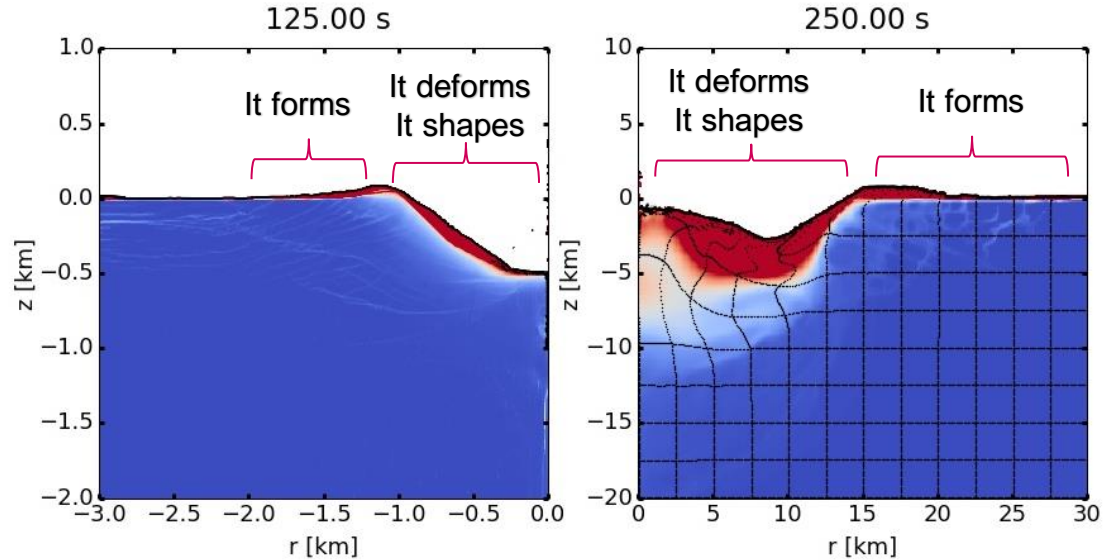
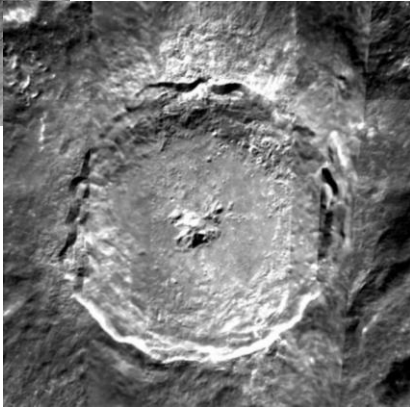


Does it hold for planetary surfaces? The Impact cratering problem



Linné (D: 2km)

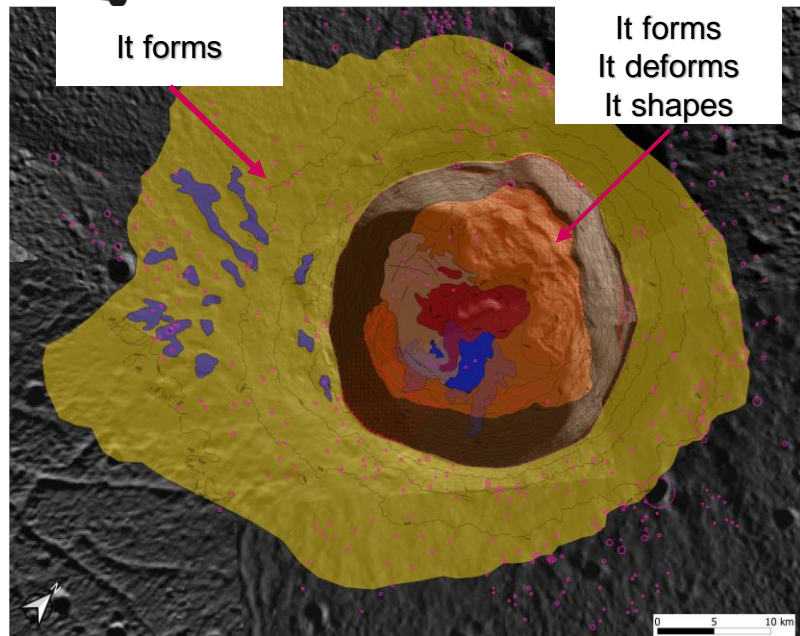
Thyco (D: 85km)



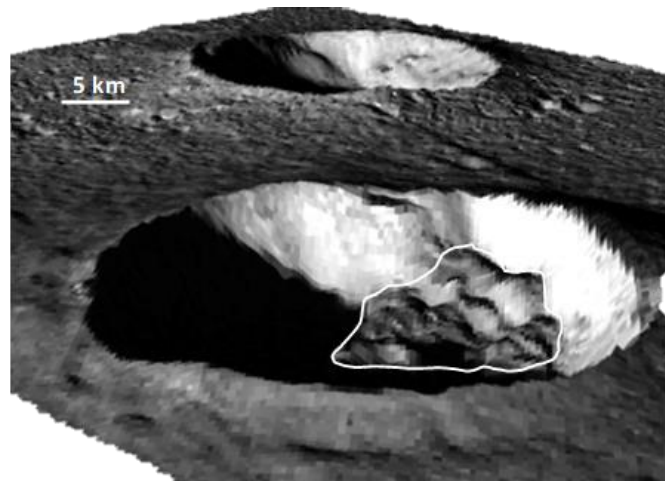
Courtesy: Elena Martellato

Does it hold for planetary surfaces? the Impact cratering problem

Fuller crater (Mercury)



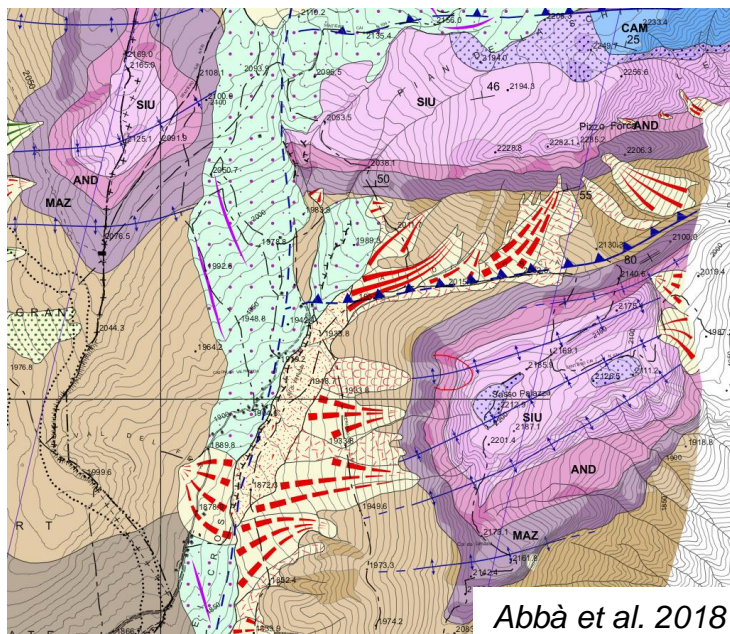
- Legend**
- Contacts**
- Approximate
 - Defined
- Gravity induced landforms**
- ▨ Landslide
 - Edge of terrace
 - Trench
 - Crown
- Impact landforms**
- Crater rim
 - Ejecta
 - Melt pool
- Uncertain origin landforms**
- Fracture
- Crater Wall Units**
- Terraced material
 - Wall
- Crater Floor Units**
- Central peak
 - Smooth Floor material
 - Hummocky Floor Material
 - Radar bright material



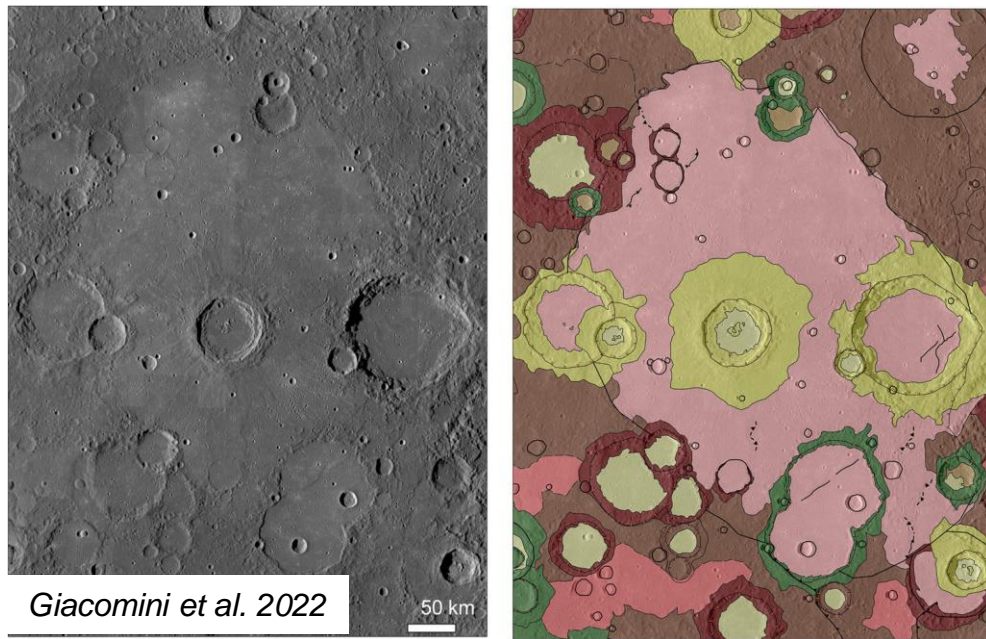
Bertioli et al. submitted

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

Earth
(Dolomites - San Pellegrino Pass)



Planet Mercury
(Keuper Quadrangle)



Does it hold for Planetary surfaces?

Lithostratigraphic unit vs Morphostratigraphic unit

Lithostratigraphic and Chronostratigraphic units

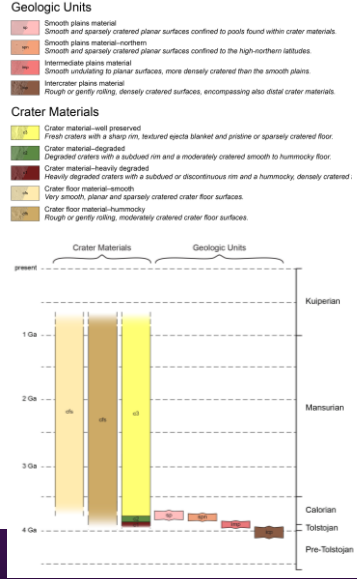
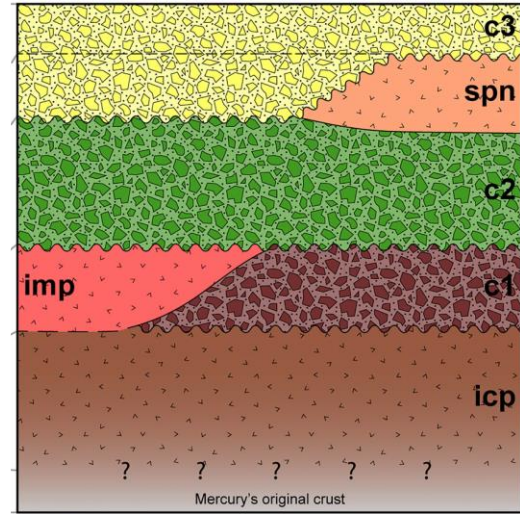
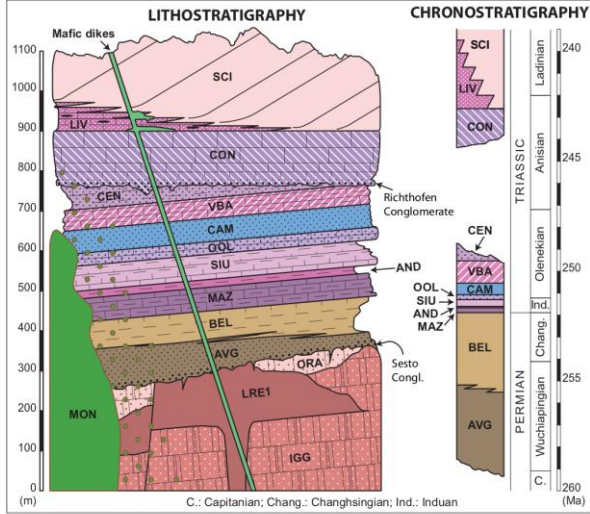
SIU - Siusi Member
Lower part: red and gray limestones and silty limestones in dm-thick beds, with common bivalve pavements (e.g. *Clarea clara*). Cm- to dm-thick oolitic or bacillate beds also occur. Middle part: red and gray silty limestones with bivalves and red siltstones in m-scale alternations. 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 environments: 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 aphanitic white dolomites. This unit forms recessive furrows on exposed walls. The lower boundary is sharp on MAZ.
Depositional environments: 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 environments: carbonate ramp
Thickness: 30- 60 m. Age: Lower Induan

UPPER PERMIAN (Lopingian)
BEL - Belleophon Formation
Aphanitic, 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 fiammazzà"). 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 badota"). The lower boundary is transitional with AVG.
Depositional environments: sabkha and coastal mudflat (lower part), epicritic carbonate platform (upper part).
Thickness: 70- 200 m. Age: Wuchiapingian - Changhsingian

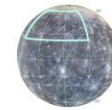
AVG - Val Gardena Sandstones
Red sandstones and siltstones in dm- to m-thick beds, commonly with cross bedding. A conglomerate (Sesto Conglomerate) can be present at the base, locally made up of pebbles from the Athesian Volcanic Complex. Horizons of carbonate nodules occur mostly within siltstones. 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 environments: fluvial channels and alluvial plains of a dryland river system.



Geologic Map of the Victoria Quadrangle (H02), Mercury

Galluzzi V.¹, Guzzetta L.¹, Feranti L.², Di Achille G.³, Rothery D.A.⁴, Palumbo P.^{5,6}

¹ INFN, Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy;
² DISTAR, Università degli Studi di Napoli "Federico II", Naples, Italy;
³ INFN, Osservatorio Astronomico di Teramo, Teramo, Italy;
⁴ Department of Physical Sciences, The Open University, Milton Keynes, UK;
⁵ Dipartimento di Scienza e Tecnologia, Università degli Studi di Napoli "Parthenope", Naples, Italy



H01 - Basins			
H01 - Imbrium Archaic	H01 - Beethoven Early	H01 - Shakespeare Intermediate	H01 - Victoria Recent
H02 - Craters			
H02 - Small Small	H02 - Encke-like Small-to-medium	H02 - Volcanic Medium	H02 - Ejecta Recent
H02 - Subvolcanic Large	H02 - Mercurial Global Protrusion	H02 - Intermediate Global Protrusion	H02 - Shakespeare Global Protrusion

- Geologic Units**
- Smooth plains material
 - Smooth and sparsely cratered plains surfaces conform to local floor within crater networks
 - Smooth plains material-southwest
 - Smooth and sparsely cratered plains surfaces conform to the high northern latitudes
 - Intermediate plains material
 - Smooth and sparsely cratered plains surfaces, more densely cratered than the smooth plains
 - Intermediate plains material
 - Smooth and sparsely cratered plains surfaces, conforming to local floor within crater networks
 - Crater floor material
 - Highly or gently rolling, sparsely cratered surfaces, conforming to local floor within crater networks
- Crater Materials**
- Crater material used preserved
 - Plain crater with a deep rim, isolated spatio-temporally and pristine or sparsely cratered floor
 - Crater material-irregular
 - Deposited crater with a shallow rim and a moderately cratered smooth to hummocky floor
 - Crater material-rough irregular
 - Crater material-rough irregular
 - Crater material-rough irregular
 - Crater floor material-smooth
 - Highly or gently rolling, sparsely cratered crater floor surfaces
 - Crater floor material-irregular
 - Rough or gently rolling, moderately cratered crater floor surfaces

Surface Features

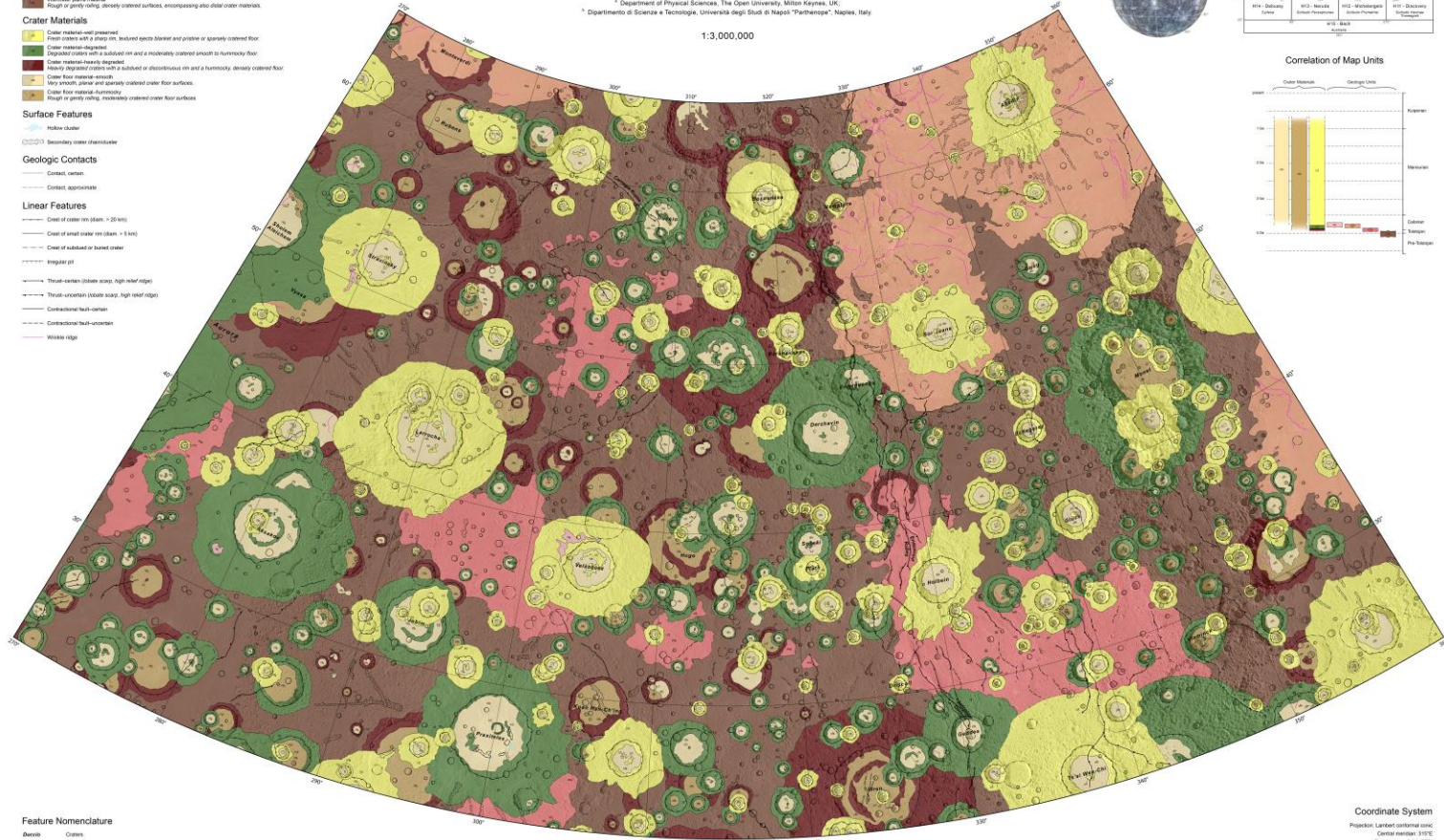
- Radial crater
- Interaxial crater characteristic

Geologic Contacts

- Contact, certain
- Contact, approximate

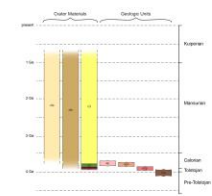
Linear Features

- Crack of crater rim (depth > 20 km)
- Crack of small crater rim (depth > 3 km)
- Crack of subvolcanic or basalt crater
- Irregular pit
- Thrust scarps (dip-slip strike, high relief ridges)
- Thrust scarps (dip-slip strike, high relief ridges)
- Contractional fault-cosine
- Contractional fault-cosine
- Wrinkle ridge



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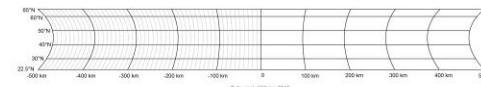
Correlation of Map Units



Feature Nomenclature

Basins Craters
 A large α Albedo features
 Victoria Region Locals (small impact and high-relief ridges lobes)
 From the Glossary of Planetary Nomenclature of the International Astronomical Union (IAU)

Basemaps



Coordinate System

Projection: Lambert conformal conic
 Central meridian: 310°E
 Standard parallel: 30°N
 Standard parallel: 2.58°N
 Sphere radius: 2440 km



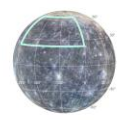
Galluzzi et al. 2016



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 INFN, Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy
² DITAR, Università degli Studi di Napoli "Federico II", Naples, Italy
³ INFN, Osservatorio Astronomico di Teramo, Teramo, Italy
⁴ Department of Physical Sciences, The Open University, Milton Keynes, UK
⁵ Dipartimento di Scienza e Tecnologia, Università degli Studi di Napoli "Parthenope", Naples, Italy



- Geologic Units**
- Smooth plains material
 - Smooth and sparsely cratered older surfaces confined to plate floor and other features
 - Smooth plains material, smooth
 - Smooth and sparsely cratered older surfaces confined to the high northern interior
 - Intermediate plains material
 - Smooth and sparsely cratered older surfaces, more densely cratered than the smooth plains
 - Intermediate plains material
 - Rough or gravelly outcrop, densely cratered surfaces, encompassing also older crater materials

- Crater Materials**
- Crater material well preserved
 - From impact with a steep rim, retained spurs beyond and proximal to sparsely cratered floor
 - Crater material degraded
 - Cratered craters with a subdued rim and a moderately cratered smooth to hummocky floor
 - Crater material heavily degraded
 - Highly degraded craters with a subdued or discontinuous rim and a hummocky, densely cratered floor
 - Crater floor material - smooth
 - Highly degraded craters and sparsely cratered older floor surfaces
 - Crater floor material - hummocky
 - Rough or gravelly outcrop, moderately cratered older floor surfaces

- Surface Features**
- Water vapor
 - Secondary crater chain/cluster

- Geologic Contacts**
- Contact, approximate

- Linear Features**
- Crack of small rim (diam. < 1-2 km)
 - Crack of small crater rim (diam. < 1 km)
 - Crack of substantial or normal crater
 - Impagite pit
 - Thrust scarps (dipole steep, high-relief ridge)
 - Thrust scarps (dipole steep, high-relief ridge)
 - Contractional neck scarps
 - Contractional neck scarps
 - Walled ridge

- Feature Nomenclature**
- Boreas Crater
 - Arara Albia features
 - Victoria Regio - Lower sector (sparsely and high-relief ridges) (H02)

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

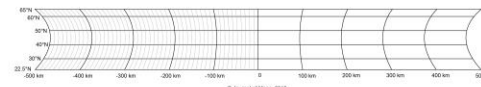
Basemaps

Top-light Mercury globe: mda_h1_color_1000_430_430_60ppp
 Central map: mda_h1_750m_250ppp

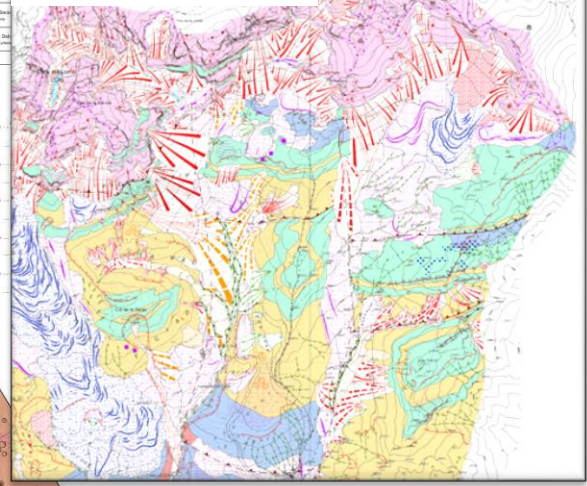
Basemap credits: NASA/JPL/Arizona State University Applied Physics Laboratory/Carnegie Institution of Washington



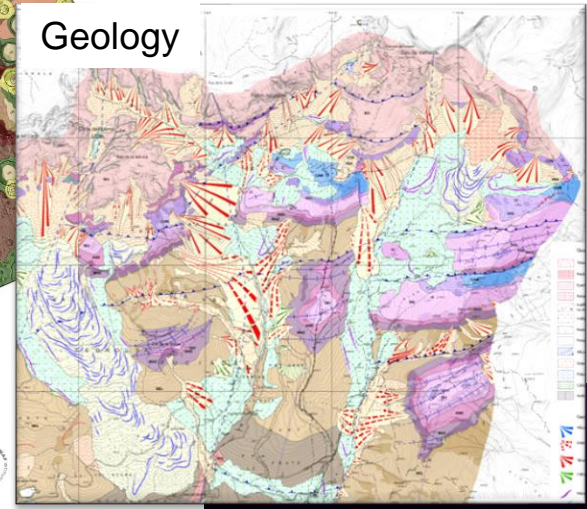
Morphostratigraphy



Geomorphology



Geology



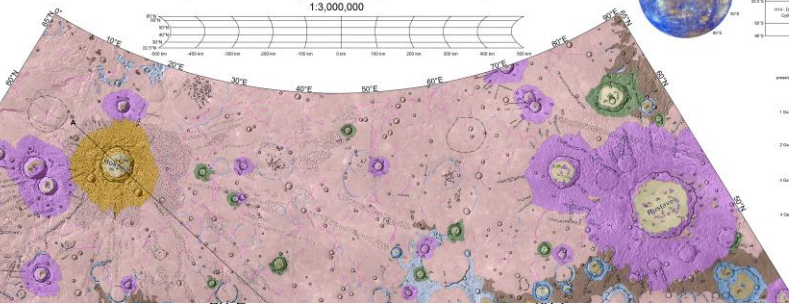
Geological map of the Hokusai Quadrangle (H05), Mercury

Wright J. J., Rothery D. A., Balme M. R., Conway S. J.²

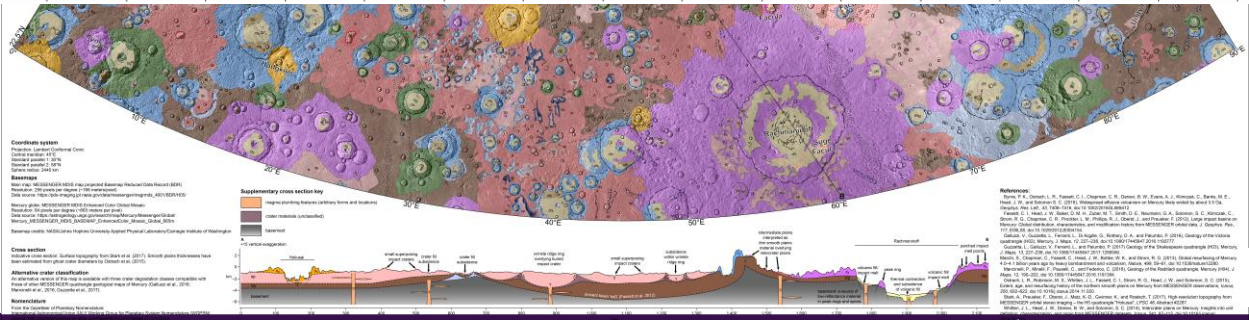
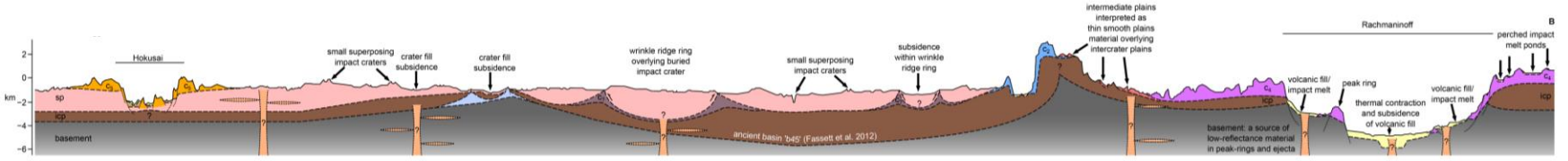
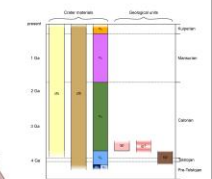
¹School of Physical Sciences, The Open University, Milton Keynes, MK7 6AA, United Kingdom
²CNRS, Laboratoire de Planétologie et Géodynamique, Université de Nantes, France

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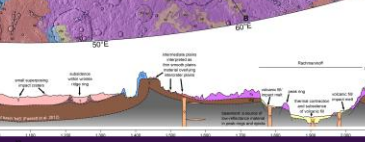
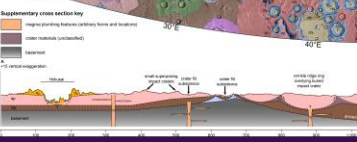
- Geological units**
- Interplanetary plains. Probably volcanic and/or impact ejecta
 - Small patches associated with impact craters beneath primary impact melt
 - Intermediate plains
 - Plains of smooth material overlain by high-albedo glass sheralites or spherules between smooth and intermediate plains
 - Primary intercrater plains. Flat but has small pits. Associated to smooth material of volcanic origin
 - Intermediate plains
 - Primary intercrater plains with a rhyolite columnar texture
- Crater materials (five degradation classes)**
- Class 1 - Smooth
 - Class 2 - Deep rims and central peaks. Textured ejecta blankets. Albedo rays present
 - Class 3 - Rims well preserved
 - Class 4 - Rims low and irregular peaks. Textured ejecta blankets. Albedo rays absent
 - Class 5 - Rims -nearly degraded
 - Class 6 - Rims -highly degraded
 - Class 7 - Rims -nearly completely, but subdued. Peaks and clear ejecta rims
 - Class 8 - Rims -extensively degraded
 - Class 9 - Rims -completely degraded
 - Class 10 - Rims -completely degraded
- Surface features**
- Plains
 - Craters
 - Secondary impact crater chains
 - Beams
 - Albedo rays
 - Albedo ray patterns
- Structures**
- Central
 - Peak within volcanic crater rim
 - High
 - Peak within volcanic crater rim
 - Shallow ridge
 - Contractional landform common within smooth plains
 - Shallow ridge
 - Contractional landform common within smooth plains
- Faults**
- Thrust-contract identification



H05: Hokusai		H06: Rachmannoff		H07: Perched	
Unit	Color	Unit	Color	Unit	Color
Interplanetary Plains	Yellow	Intermediate Plains	Light Green	Primary Intercrater Plains	Light Blue
Intermediate Plains	Light Green	Intermediate Plains	Light Green	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue
Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue	Primary Intercrater Plains	Light Blue



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 - Secondary impact crater chains
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- Structures**
- Central
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 - High
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 - Shallow ridge
 - Contractional landform common within smooth plains
 - Shallow ridge
 - Contractional landform common within smooth plains
- Faults**
- Thrust-contract identification



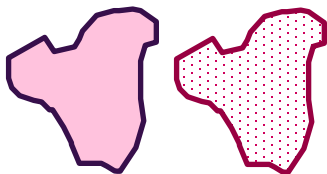
Wright et al. 2019





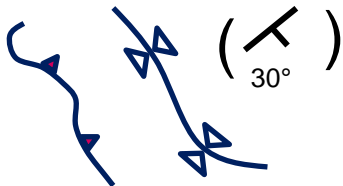
In Summary Planetary Morpho-stratigraphic Maps

Polygons



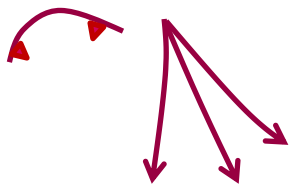
It forms – Morphostratigraphy

Lines
Points



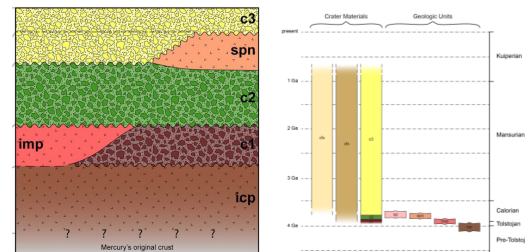
It deforms – Geological structures

Lines

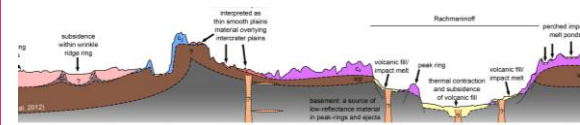


It shapes – Geomorphology

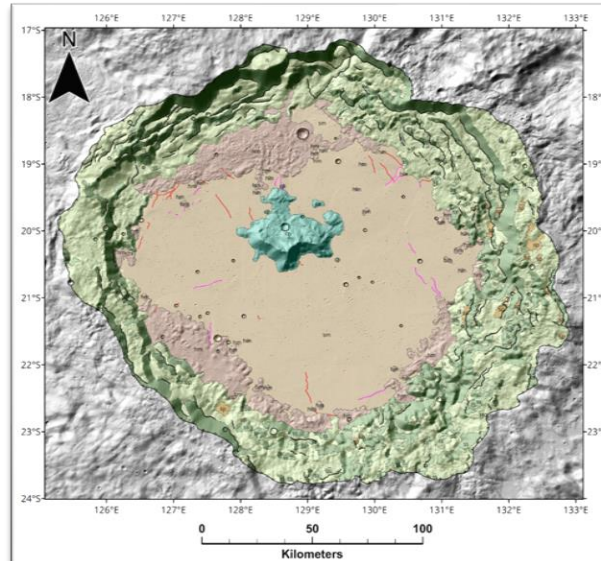
More Uncertain
Geological Evolution



Limited Subsurface Geology



Towards Earth-like Geological Maps Integrating colors and reflectance



Geologic units

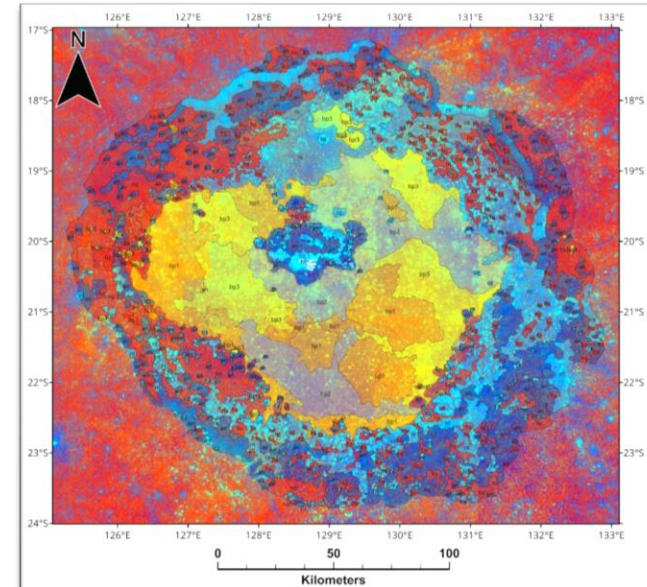
- Crater floor units
- sm Smooth material
 - hm Hummocky material
 - cp Central peak
- Crater wall units
- sp Smooth ponds
 - ss Steep scarps
 - is Inner slope

Geologic contacts

- Contact, certain
- ### Linear features
- Crest of small crater rim (diam. > 1 km)
 - Crest of crater rim (diam. > 20 km)
 - Mare rille

Tectonic features

- Fault, certain
- - Fault, uncertain
- Wrinkle ridge



Color-based spectral units

- bp1 Basaltic plain 1
- bp2 Basaltic plain 2
- bp3 Basaltic plain 3
- nt Noritic-anorthosite/troctolite
- an Anorthosite
- hs Mature and reworked highland soil

Spectral contacts

- Contact, certain
- - Contact, approximate



Tognon et al. 2021

Integrating morpho-stratigraphy with spectral index

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

J. Wright¹, F. Zambon², C. Carli², D. A. Rothery¹, M. R. Balme¹, S. J. Conway³

¹School of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

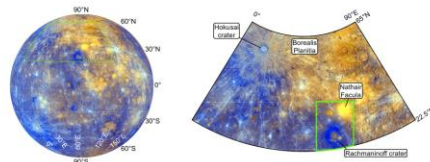
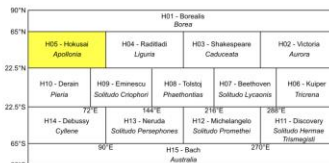
²INAF, Istituto di Astrofisica e Planetologia Spaziali (IAPS), Via del Fosso del Cavaliere, Rome 00133, Italy

³CNRS Laboratoire de Planétologie et Géodynamique de Nantes, Université de Nantes, 2 rue de la Houssinière, 44322, Nantes, France

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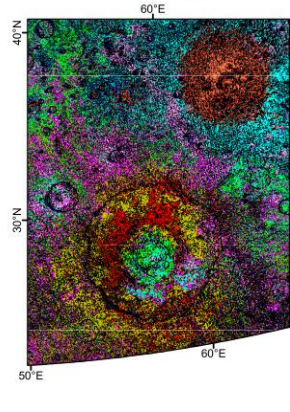
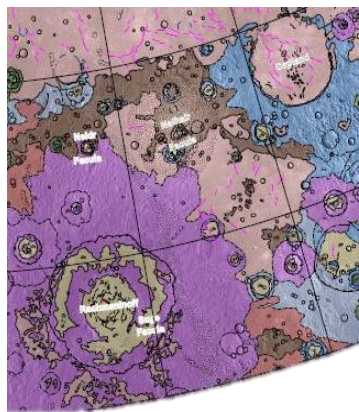
Introduction

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 the 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.

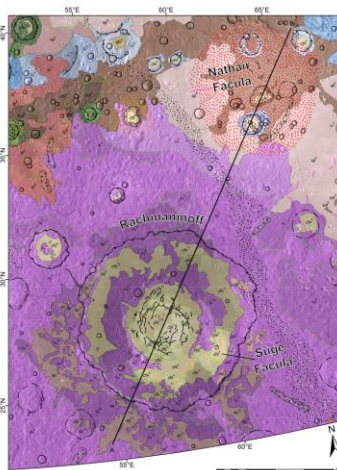


Morpho-stratigraphic map

Spectral Index map



Geostratigraphic map



Crater materials

c, craters

Well-preserved crater materials. Sharp rims and internal peaks. Textured ejecta blankets. Albedo rays absent. "c" is interpreted as Rachmaninoff ejecta mixed with melt. "c1" is low reflectance material excavated from Mercury's lower crust.

c, craters

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

c, craters

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

c, 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. cfa and cfa' are post-impact volcanic rills of Rachmaninoff.

Hummocky crater floor

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

Geostratigraphic units

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 geomorphological 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.

Plains materials

Smooth plains

Sparsely cratered plains. Probably volcanic where areally extensive. Small patches within impact crater terraces may probably impact melt. sp¹ is probably ponded Rachmaninoff impact melt.

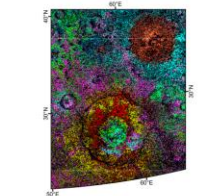
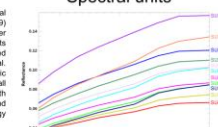
Intermediate plains

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 retreating-ramp origin.

Intercrater plains

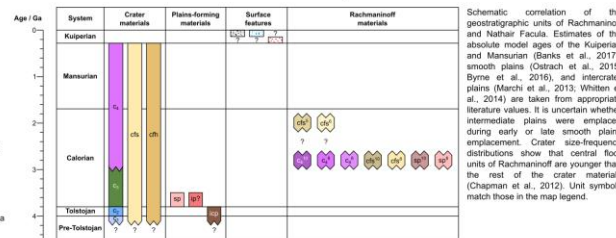
Heavily cratered plains with a rough, hummocky texture. Probably akin to smooth plains but older and thus more heavily cratered.

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 geostrophigraphic map.

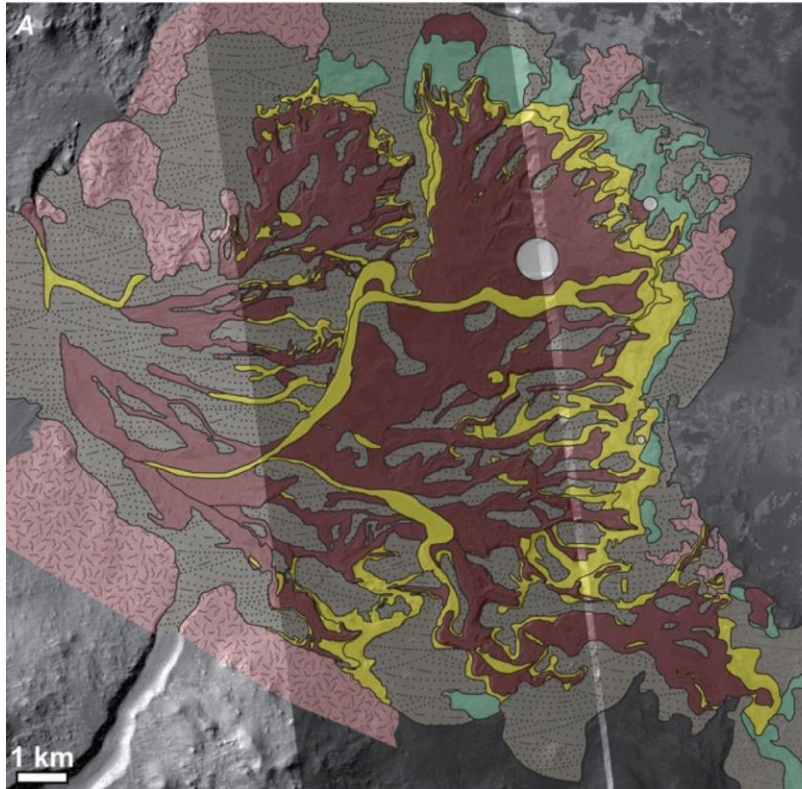
Correlation of Map Units








Linework and Ornaments

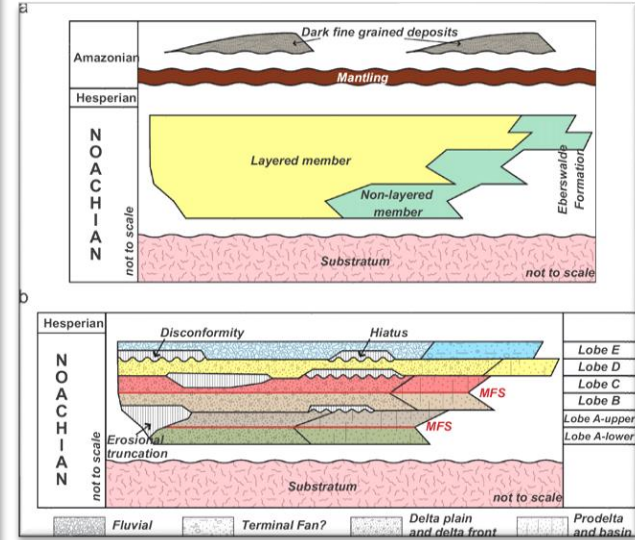


Towards Earth-like Geological Maps: Stratigraphy



Legenda

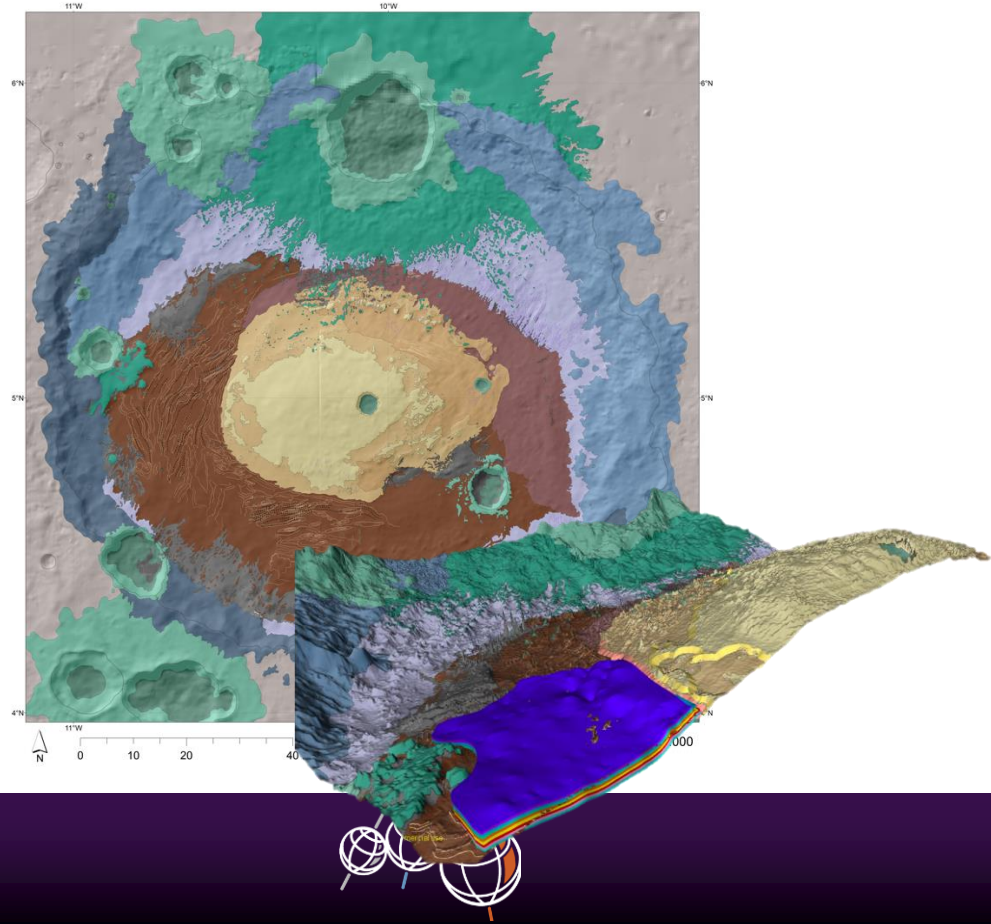
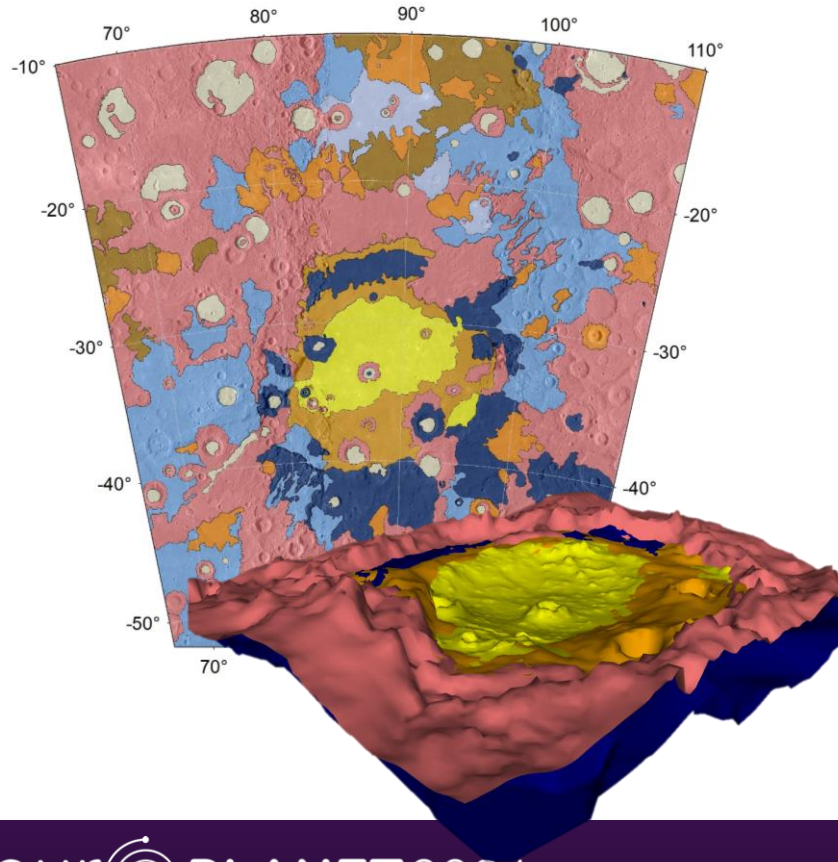
- 
Dark fine grained deposits
 Low albedo fine grained well sorted dunes and sand sheets. Present in patches up to few meters thick.
 Stratigraphic distribution: Noachian?-Recent?
- 
Mantling
 Low albedo smooth fine grained sedimentary deposits. Present in patches up to few meters thick.
 Stratigraphic distribution: Noachian?-Recent?
- Eberswalde Formation**
 High albedo sedimentary material subdivided in two members partly eteropic and partly overlapping.
 Stratigraphic distribution: Noachian?
- 
Layered Member
 Low and high albedo interlayered metric thick strata. Bright layers display coarse to breccia texture, sharp edges and polygonal fractures. Darker layers consist of fine grained, well sorted deposits. The overall thickness ranges from tens of meters to about 100 meters.
- 
Non-layered Member
 High albedo deposits with no or very fant stratification. It displays coarse texture, sharp edges and polygonal fractures. The overall thickness is estimated to be 10 to 20 meters.
- 
Substratum
 Massive to brecciated light-toned material
 Stratigraphic distribution: Noachian



Pondrelli et al. 2011

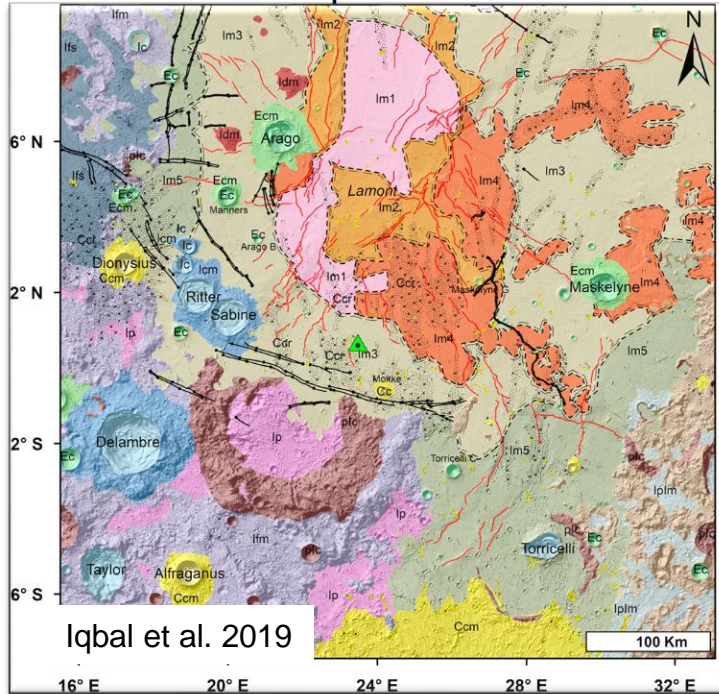


Towards Earth-like Geological Maps: Subsurface

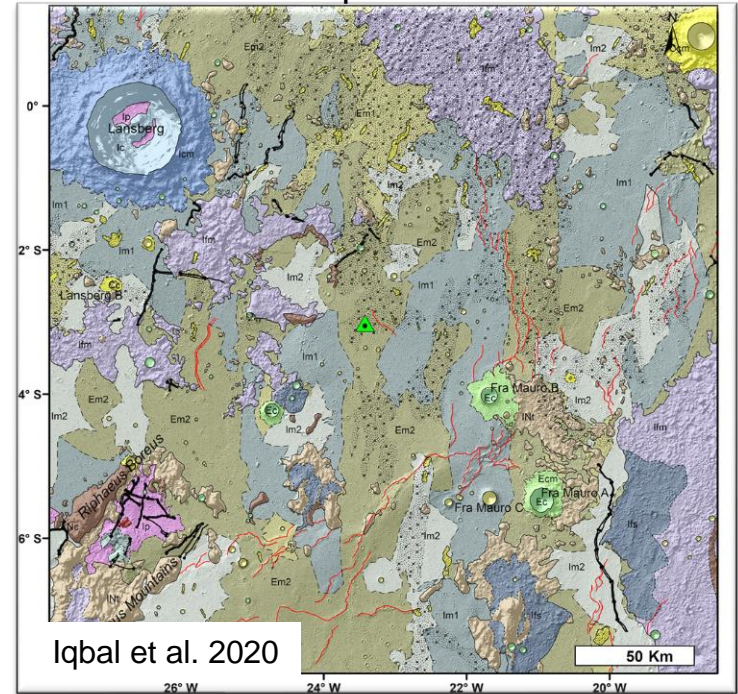


Towards Earth-like Geological Maps highly detailed maps

Apollo 11



Apollo 12



- 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).