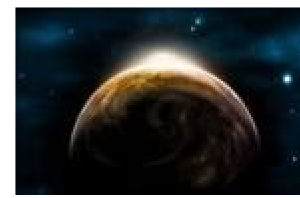
Nuclear Power in Space Exploration

and the

Associated Environmental Safeguards: A Preliminary Overview

by



Michael D. Campbell, P.G., P.H.

Chair, Uranium Committee
Energy Minerals Division, AAPG and
Member of the Astrogeology Committee, AAPG
and
Managing Partner

M. D. Campbell and Associates, L.P.
Houston and Seattle

Presented as Featured Speaker at the Houston Geological Society,
Environmental and Engineering Geology Group Dinner.
Houston, Texas
January 20, 2009

Investigation Participants

A Report of the Uranium Committee of the Energy Minerals Division, AAPG

by

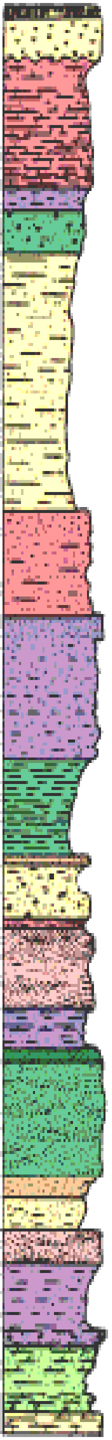
Michael D. Campbell, P.G., P.H., (Chair)
Houston

Jeffery D. King, P.G. (Associate)
Seattle

Henry M. Wise, P.G. (Member)
Houston

Bruce N. Handley, P.G. (Member)
Houston

M. David Campbell, P.G. (Associate)
Houston

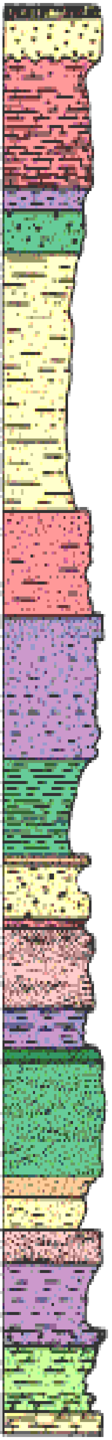


Uranium Committee Report* Outline

* Note: The full report will be released after the [2009 AAPG-EMD Conference](#) in Denver, Co., dated: June 7-10

Outline for this Presentation

- **Spacecraft Propulsion**
  - ❑ Planet-Based Power Systems
  - ❑ Earth-Based Power Systems
- **Environmental Safeguards in Orbit**
- **International Development: The Nuclear Genie is Out of the Bottle**
- **World Uranium Occurrences**
- **Dual Objectives: Using Nuclear Power also to Explore for Uranium, Thorium, and Special Commodities**

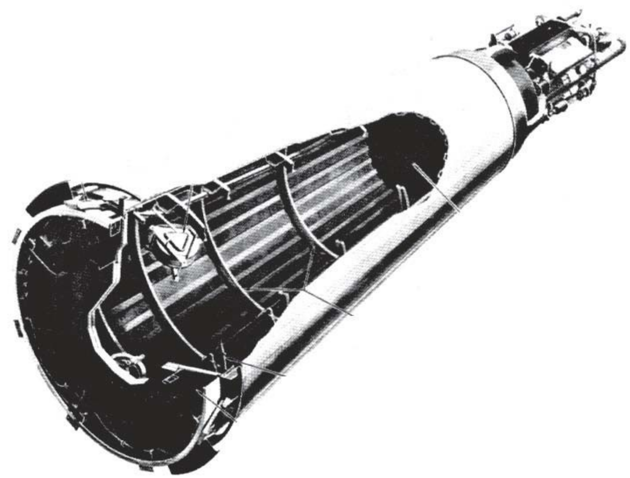


Outline for this Presentation

- **Off-World Mining**
  - ❑ **The Debate on Lunar Mining**
  - ❑ **Mining Asteroids**
  - ❑ **The “Space Elevator”**
  - ❑ **The “Space Tractor”**
- **Earth-Based Spin Off from Space Research**

Source of Energy in Space

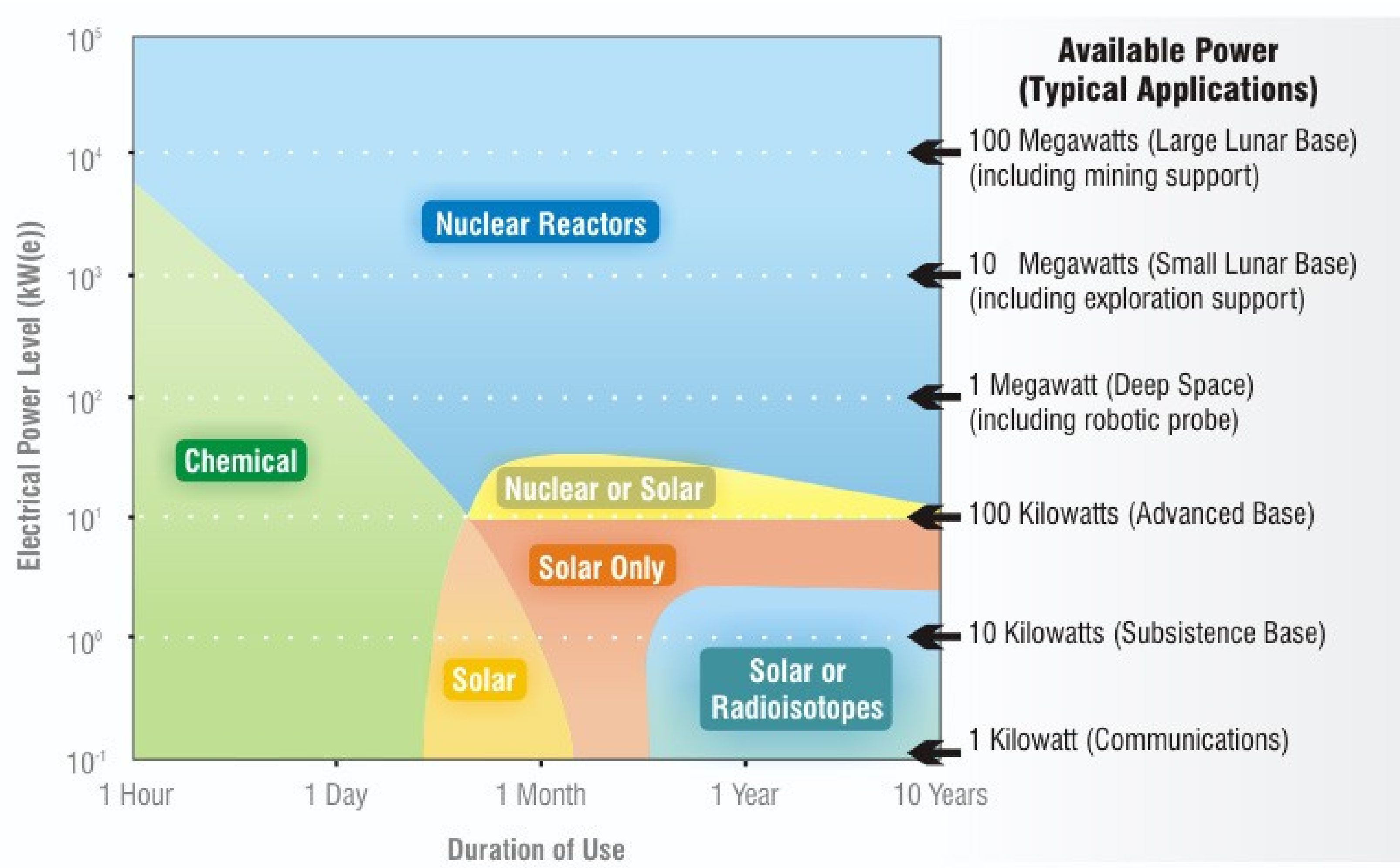
- **Spacecraft Propulsion**
  - ❑ **Planet-Based Power Systems**
  - ❑ **Earth-Based Power Systems**



Electrical Systems

- Batteries
- Solar Cells
- Nuclear Power
  - Radioisotope Thermoelectric Generators
  - Thermoelectric Generators
  - Radioisotope Heater Units

Source of Energy in Space



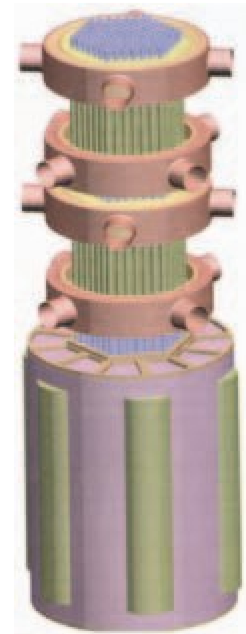
After: IAEA (2005)

Propulsion in Space

- **Chemical (Standard Rocket Propulsion)**
  - Solid
  - Liquid
    - Kerosene/Oxygen
    - Hydrogen/Oxygen
    - Hydrozene/Oxygen

Propulsion in Space

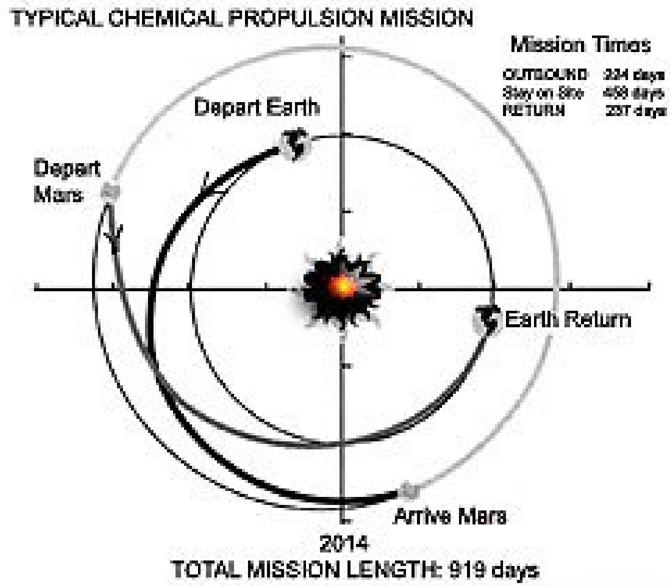
- **Electrical (Ion Propulsion)**
  - Chemical
    - Batteries
    - Fuel Cell
  - Solar
  - Nuclear
    - Radioisotope Thermoelectric Generators
    - Thermoelectric Generators

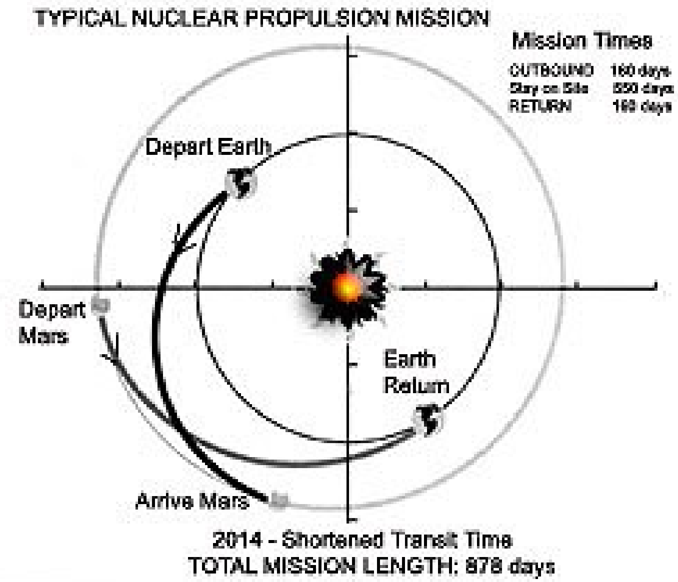


Homer

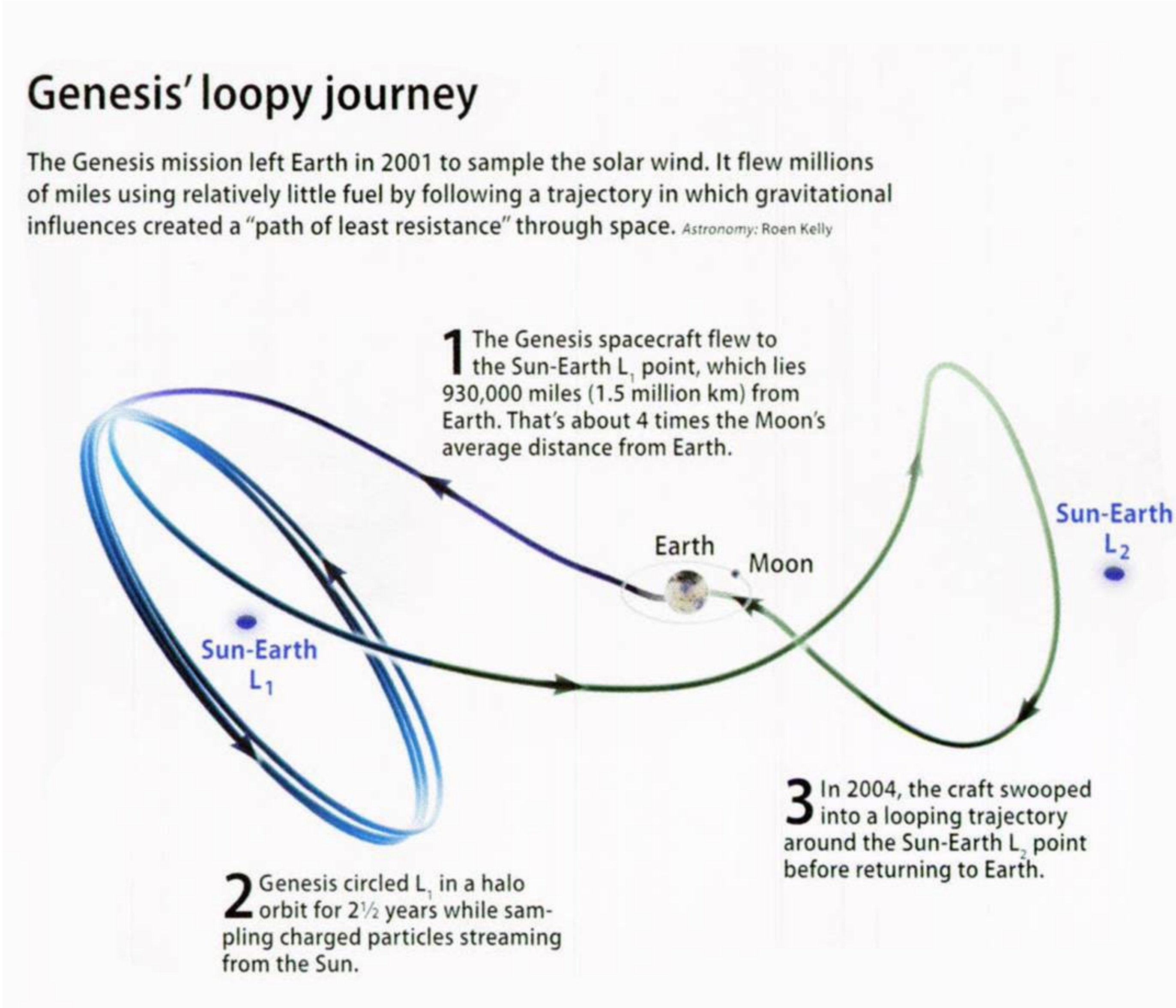
- The higher the electrical output, the higher the thrust

Chemical Propulsion vs. Nuclear Propulsion





(after IAEA 2005)


Genesis' loopy journey
The Genesis mission left Earth in 2001 to sample the solar wind. It flew millions of miles using relatively little fuel by following a trajectory in which gravitational influences created a "path of least resistance" through space. Astronomy: Roen Kelly
1 The Genesis spacecraft flew to the Sun-Earth L_1 point, which lies 930,000 miles (1.5 million km) from Earth. That's about 4 times the Moon's average distance from Earth.
Earth
Moon
Sun-Earth L_2
Sun-Earth L_1
2 Genesis circled L_1 in a halo orbit for 2½ years while sampling charged particles streaming from the Sun.
3 In 2004, the craft swooped into a looping trajectory around the Sun-Earth L_2 point before returning to Earth.

(Reddy, 2008)

Environmental Safeguards

- **Nuclear power to be used only in a stable orbit or in interplanetary space ….recent developments.**

- **Fuel is heat-resistant ceramic plutonium oxide:**

  - **Reduces chances of vaporization by fire or re-entry**
  - **Highly insoluble**
  - **Fractures into large pieces**

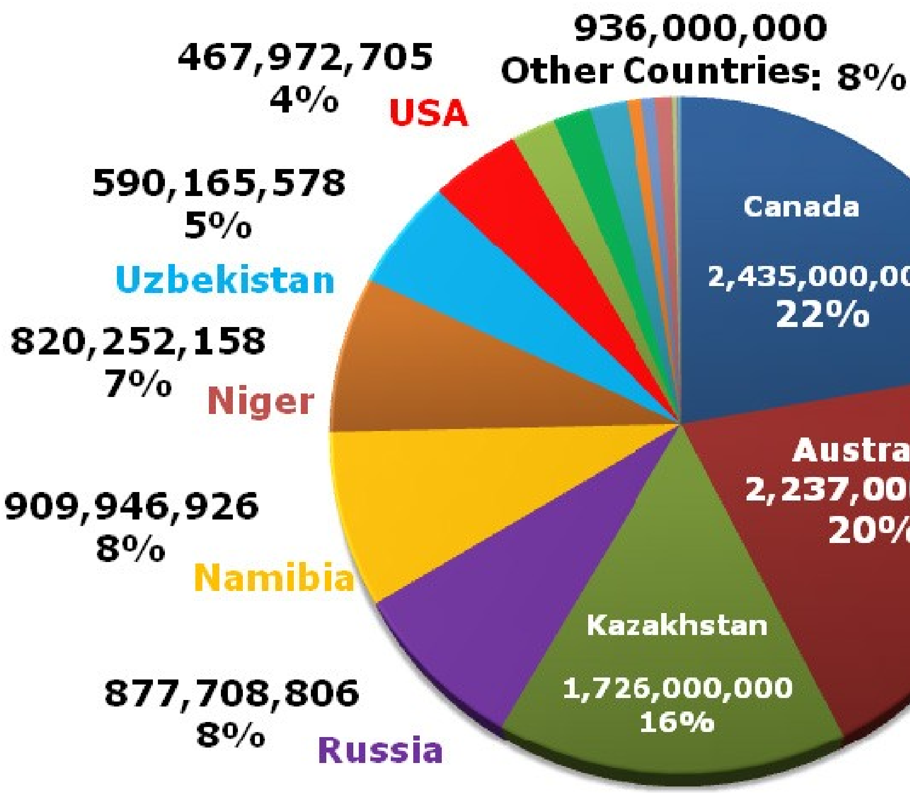
- **Fuel has its own heat shield and impact casing to reduce chance of release in case of accident.**

- **Reactor will remain subcritical if immersed in fluids such as water or fuel.**

- **Two independent systems to reduce reactivity to a subcritical state and not subject to a common failure mode.**

International Development

- **The genie is out of the bottle**
- **Space programs in 20 countries and the European Union:**
  - Solar and fuel cells are sufficient for earth orbit and the inner planets
  - Nuclear power needed for the outer planets
- **Most programs are communication, weather and surveillance**
- **U.S., Russia, and China have manned space programs**
- **China is planning to establish a mining base on the Moon**
- **India, Korea, and others have space programs under way**
- **Lunar bases will utilize nuclear power for long-term use and**
- **Solar power may also play a significant role.**



IAEA (2008)

World Uranium Reserves 2007

11 Billion Pounds U_3O_8

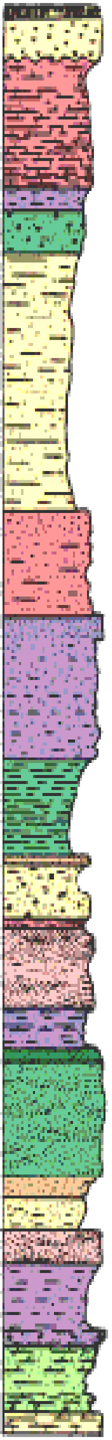
Life Time of Present Reserves 66 Years

Future Requirements:
788 Reactors
36 Years

2008
World Fuel Requirements/YeaR
439 Reactors
168,000,000 lbs. Yellowcake/YR

Exploration Objectives in the Solar System: 1st – The Moon

- **Uranium**
- **Thorium**
- **Special Commodities**
    - Rare Earths
    - Metals
    - Helium-3



Primary Nuclear-Fuel Resources on Earth

Cenozoic Deposits

Wyoming	(Roll-Fronts- Developed by In Situ Methods)
Nebraska	(Roll-Fronts – Developed by In Situ Methods)
South Dakota	(Roll-Fronts – Developed by In-Situ Methods)
Texas	(Roll-Fronts- Developed by In Situ Methods)
Kazakhstan	**(**Roll-Fronts- Developed by In Situ Methods)
Uzbekistan	(Roll-Fronts- Developed by In Situ Methods)
Australia	(Roll-Fronts- Developed by In Situ Methods)

Mesozoic Deposits

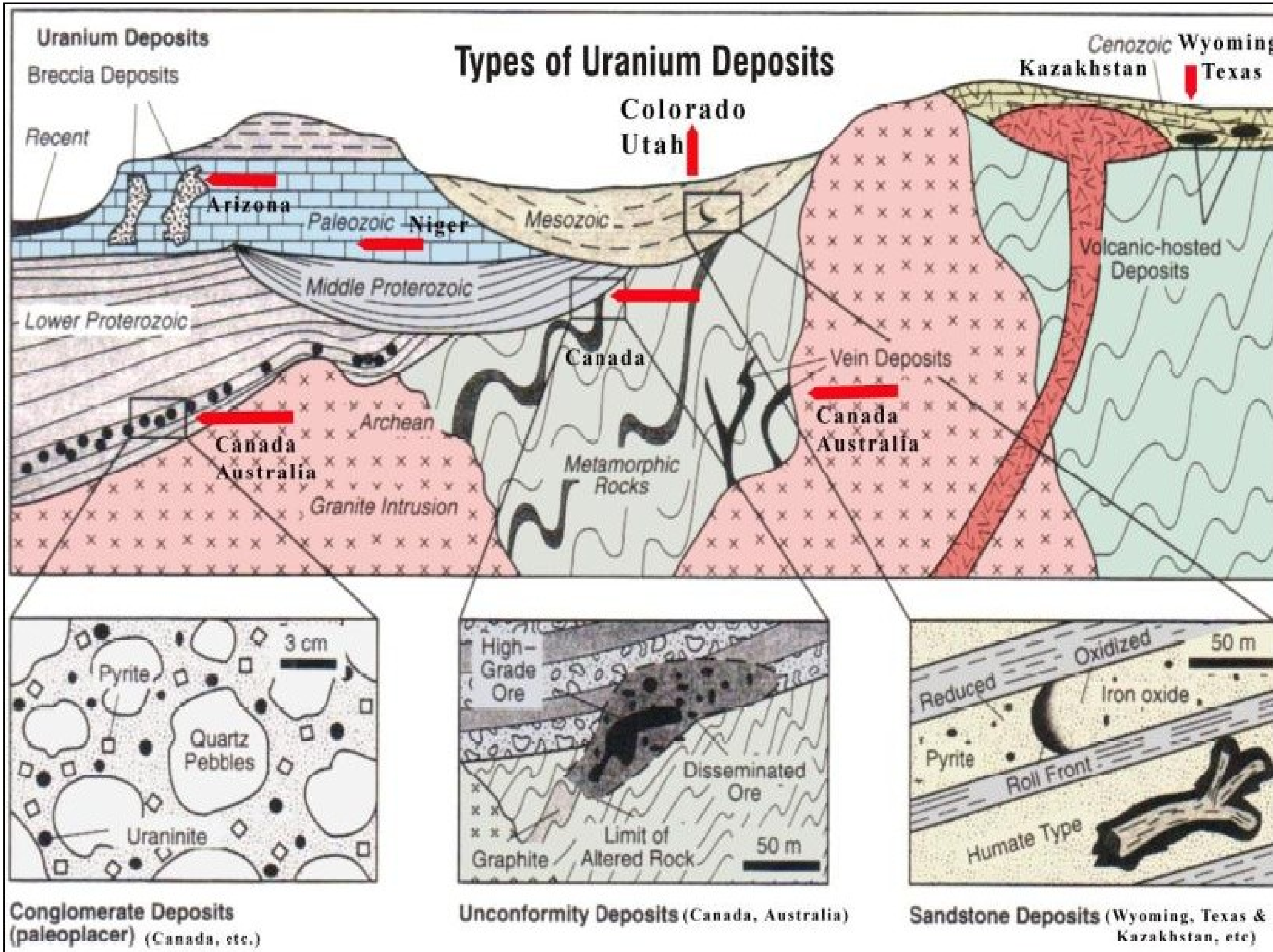
Canada	Western (Mining Only)
Canada	Eastern (In Situ and Surface Mining Methods)
Colorado	Redistributed Roll-Fronts – In Situ Methods & Surface Mining Methods)
New Mexico	Redistributed Roll-Fronts – In Situ & Surface & Underground Mining Methods)

Paleozoic Deposits

Arizona	(Developed by Surface Mining Methods)
Niger	(Surface Mining)

Proterozoic Deposits

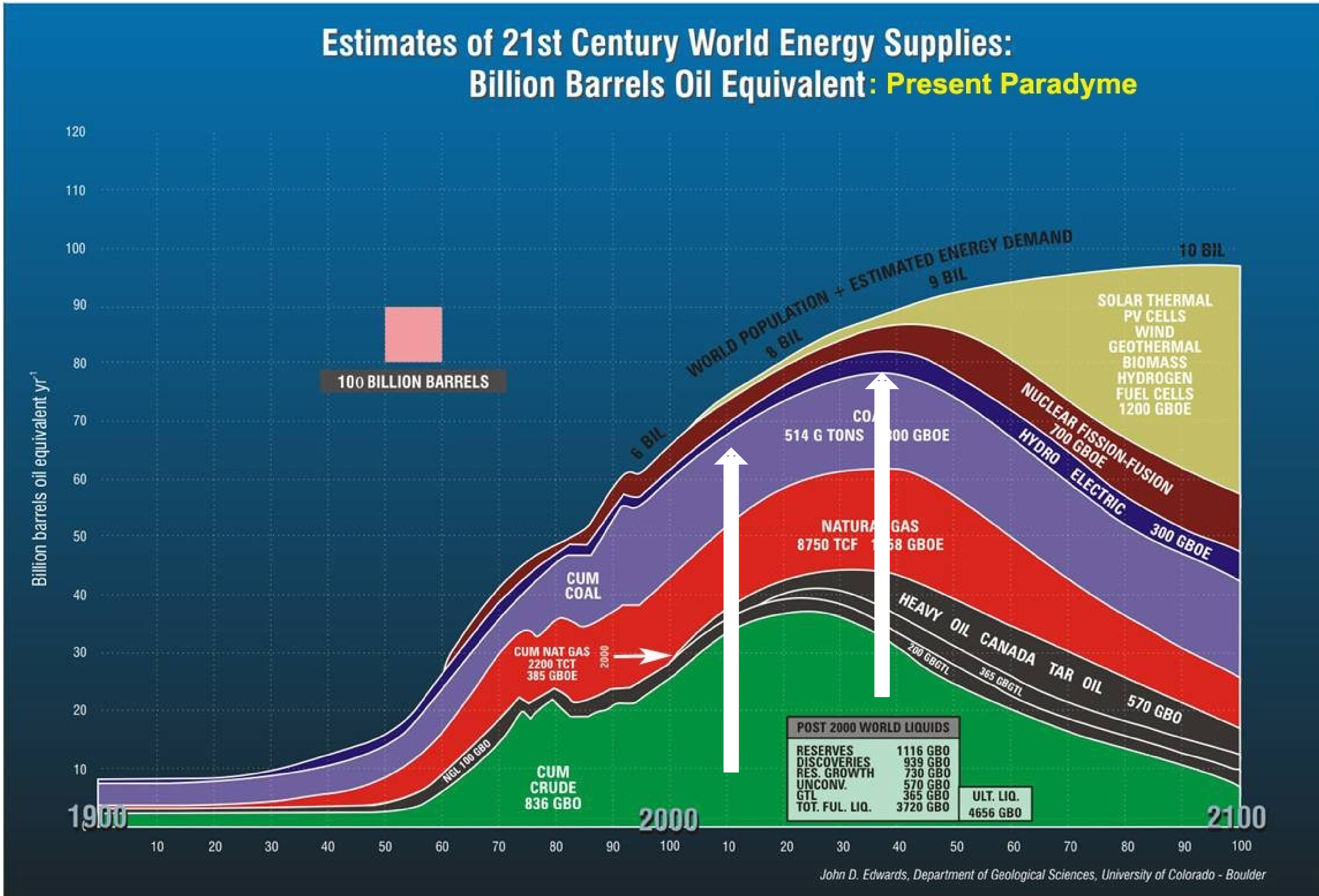
Canada	(Surface and Underground Mining)
Australia	(Surface Mining)
Guyana	(Surface and Underground Mining)
Gabon	(Surface and Underground Mining)
Namibia	(Surface and Underground Mining)



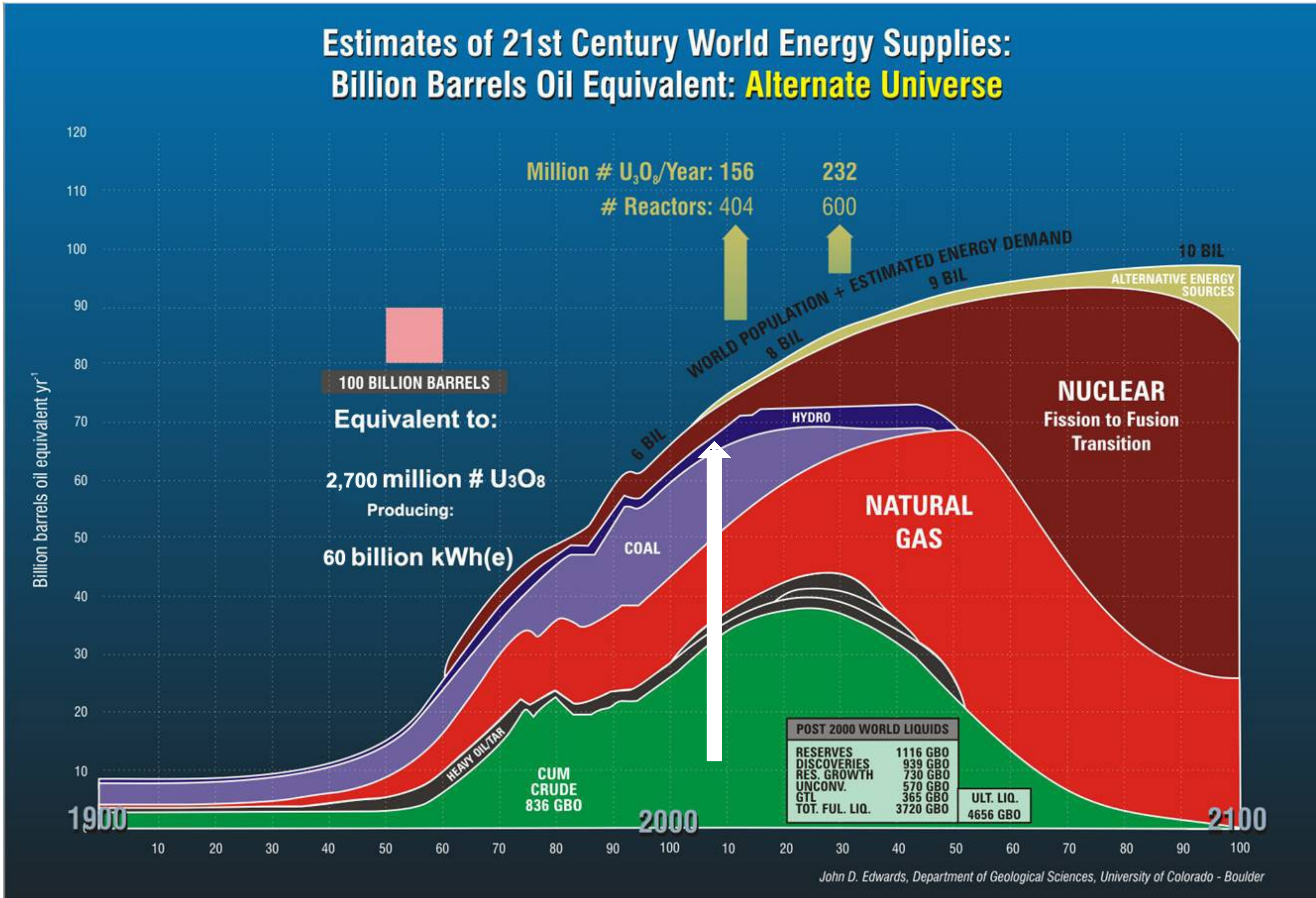
(After Kesler, 1994)

World Uranium Resources
2007

IAEA (2008)



Estimates of 21st Century World Energy Supplies:
Billion Barrels Oil Equivalent: Present Paradyme
Billion barrels oil equivalent yr-1
120
110
100
90
80
70
60
50
40
30
20
10
100 BILLION BARRELS
WORLD POPULATION + ESTIMATED ENERGY DEMAND
6 BIL
8 BIL
9 BIL
10 BIL
SOLAR THERMAL
PV CELLS
WIND
GEOTHERMAL
BIOMASS
HYDROGEN
FUEL CELLS
1200 GBOE
NUCLEAR FISSION-FUSION
700 GBOE
HYDRO ELECTRIC
300 GBOE
CO
514 G TONS
00 GBOE
CUM COAL
NATURA GAS
8750 TCF
58 GBOE
CUM NAT GAS
2200 TCT
385 GBOE
2000
HEAVY OIL CANADA TAR OIL 570 GBO
200 GBGTL
365 GBGTL
NGL 100 GBO
CUM CRUDE
836 GBO
POST 2000 WORLD LIQUIDS
RESERVES 1116 GBO
DISCOVERIES 939 GBO
RES. GROWTH 730 GBO
UNCONV. 570 GBO
GTL 365 GBO
TOT. FUL. LIQ. 3720 GBO
ULT. LIQ.
4656 GBO
1900
2000
2100
10
20
30
40
50
60
70
80
90
100
John D. Edwards, Department of Geological Sciences, University of Colorado - Boulder



Estimates of 21st Century World Energy Supplies:
Billion Barrels Oil Equivalent: Alternate Universe
Million # U_3O_8/Year: 156 232
Reactors: 404 600
100 BILLION BARRELS
Equivalent to:
2,700 million # U_3O_8
Producing:
60 billion kWh(e)
WORLD POPULATION + ESTIMATED ENERGY DEMAND
6 BIL
8 BIL
9 BIL
10 BIL
ALTERNATIVE ENERGY SOURCES
NUCLEAR
Fission to Fusion Transition
HYDRO
COAL
NATURAL GAS
HEAVY OIL/TAR
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ULT. LIQ. 4656 GBO
Billion barrels oil equivalent yr⁻¹
120
110
100
90
80
70
60
50
40
30
20
10
1900
2000
2100
10 20 30 40 50 60 70 80 90 100 10 20 30 40 50 60 70 80 90 100
John D. Edwards, Department of Geological Sciences, University of Colorado - Boulder

Commodities Presently Imported to U.S.

Commodity	Percent	Major Import Sources (2003-06)[1]
ARSENIC (trioxide)	100	China, Morocco, Hong Kong, Chile
ASBESTOS	100	Canada
BAUXITE and ALUMINA	100	Guinea, Jamaica, Australia, Brazil
CESIUM	100	Canada
FLUORSPAR	100	China, Mexico, South Africa, Mongolia
GRAPHITE (natural)	100	China, Mexico, Canada, Brazil
INDIUM	100	China, Japan, Canada, Belgium
MANGANESE	100	South Africa, Gabon, Australia, China
MICA, sheet (natural)	100	India, Belgium, China, Brazil
NIOBIUM (columbium)	100	Brazil, Canada, Estonia, Germany
QUARTZ CRYSTAL (industrial)	100	Brazil, Germany, Madagascar, Canada
RARE EARTHS	100	China, France, Japan, Russia
RUBIDIUM	100	Canada
STRONTIUM	100	Mexico, Germany
TANTALUM	100	Australia, Brazil, China, Germany
THALLIUM	100	Russia, Netherlands, Belgium
THORIUM	100	United Kingdom, France
VANADIUM	100	Czech Republic, Swaziland, Canada,
YTTRIUM	100	China, Japan, France, Austria
GALLIUM	99	China, Ukraine, Japan, Hungary
GEMSTONES	99	Israel, India, Belgium, South Africa
BISMUTH	95	Belgium, Mexico, China, United Kingdor
PLATINUM	94	South Africa, United Kingdom, Germany
STONE (dimension)	90	Italy, Turkey, China, Mexico
DIAMOND (natural industrial stone)	88	Botswana, Ireland, Namibia, South Afric
ANTIMONY	86	China, Mexico, Belgium
RHENIUM	86	Chile, Germany
BARITE	83	China, India
TITANIUM MINERAL CONCENTRATES	82	South Africa, Australia, Canada, Ukrain
POTASH	81	Canada, Belarus, Russia, Germany
TIN	79	Peru, Bolivia, China, Indonesia
COBALT	78	Norway, Russia, Finland, China
PALLADIUM	73	Russia, South Africa, United Kingdom,
TUNGSTEN	70	China, Canada, Germany, Portugal
TITANIUM (sponge)	64	Kazakhstan, Japan, Russia, Ukraine
CHROMIUM	62	South Africa, Kazakhstan, Russia, Zimb
PEAT	60	Canada
ZINC	58	Canada, Peru, Mexico, Australia
MAGNESIUM COMPOUNDS	57	China, Canada, Austria, Australia
GARNET (industrial)	56	Australia, India, China, Canada
SILICON (ferrosilicon)	56	China, Venezuela, Russia, Norway
SILVER	55	Mexico, Canada, Peru, Chile
MAGNESIUM METAL	54	Canada, Russia, Israel, China
DIAMOND (dust, grit and powder)	52	China, Ireland, Russia, Ukraine
NITROGEN (fixed), AMMONIA	44	Trinidad and Tobago, Canada, Russia,
VERMICULITE	40	South Africa, China
COPPER	37	Chile, Canada, Peru, Mexico
MICA, scrap and flake (natural)	32	Canada, China, India, Finland
PERLITE	30	Greece
ALUMINUM	26	Canada, Russia, Brazil, Venezuela
GYPSUM	26	Canada, Mexico, Spain, Dominican Republic
SULFUR	24	Canada, Mexico, Venezuela
PUMICE	20	Greece, Italy, Turkey
SALT	18	Canada, Chile, The Bahamas, Mexico
CEMENT	17	Canada, China, Thailand, Republic of
NICKEL	17	Canada, Russia, Norway, Australia
PHOSPHATE ROCK	14	Morocco
BROMINE	13	Israel, United Kingdom
IRON and STEEL	12	Canada, European Union, Mexico, Brazil
IRON and STEEL SLAG	7	Canada, Italy, France, Japan
LIME	1	Canada, Mexico

[1] In descending order of import share

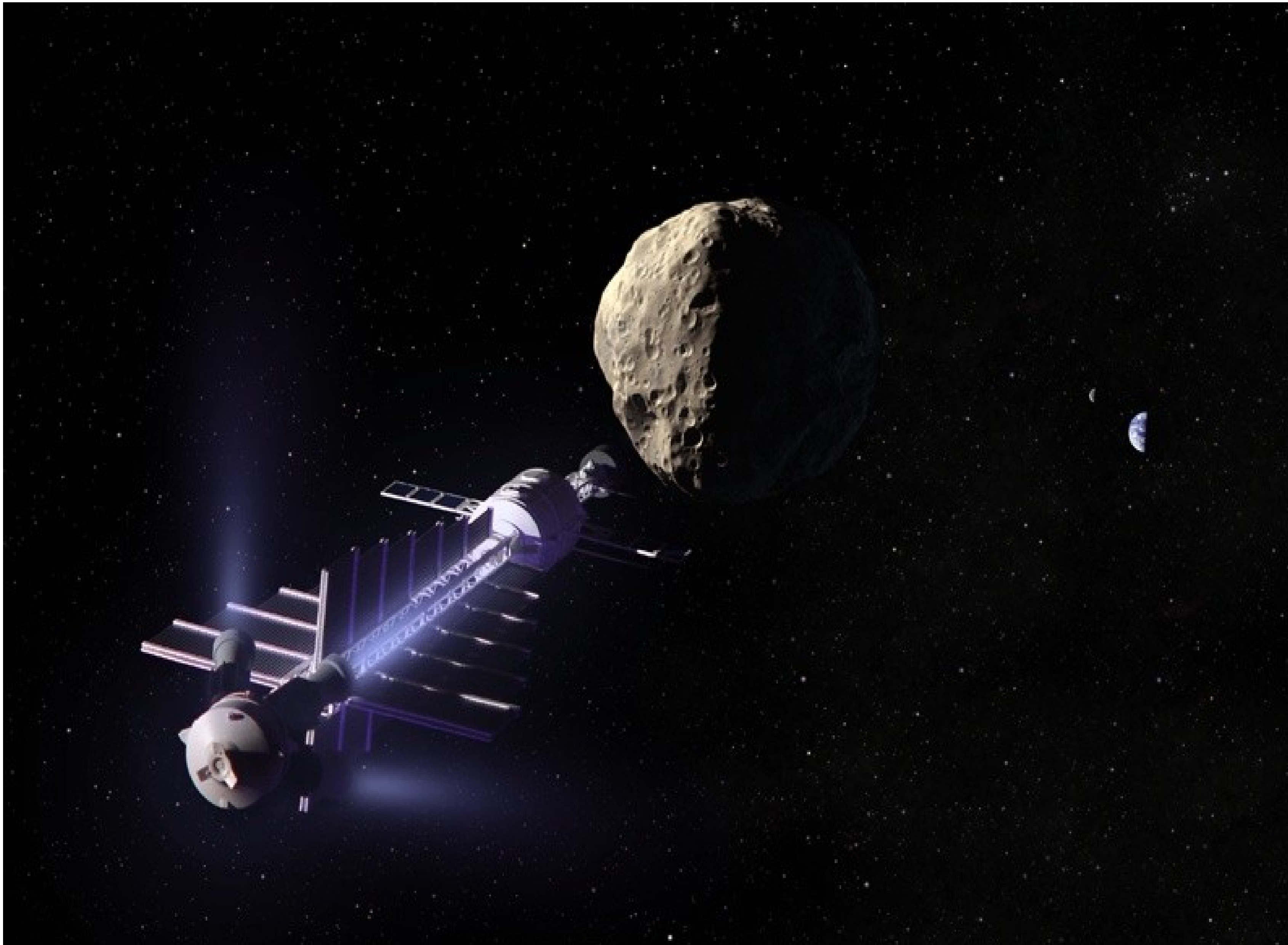
Near-Earth Asteroids and Comets

- **Monitoring Near-Earth Asteroids (NEAs) and Comets**
- **The Moon can be a base for monitoring NEAs**
- **Remote sensing satellites inside Venus's orbit**
- **Ways to move NEAs away from collisions with earth**
- **Nuclear power will be used to power most of these**

Defense of Earth ?

- **Improved Monitoring NEAs,**
- **Telescopes on Moon or in Orbit.**
- **Respond with Robotics: "Gravity Tractor" or other Equipment.**

“Gravity Tractor”

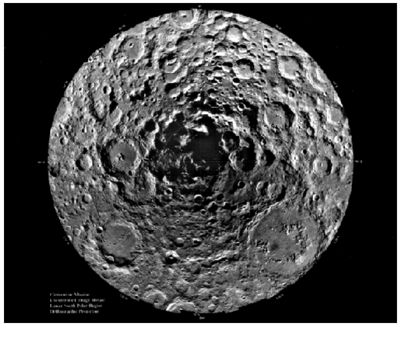


Off-World Mining

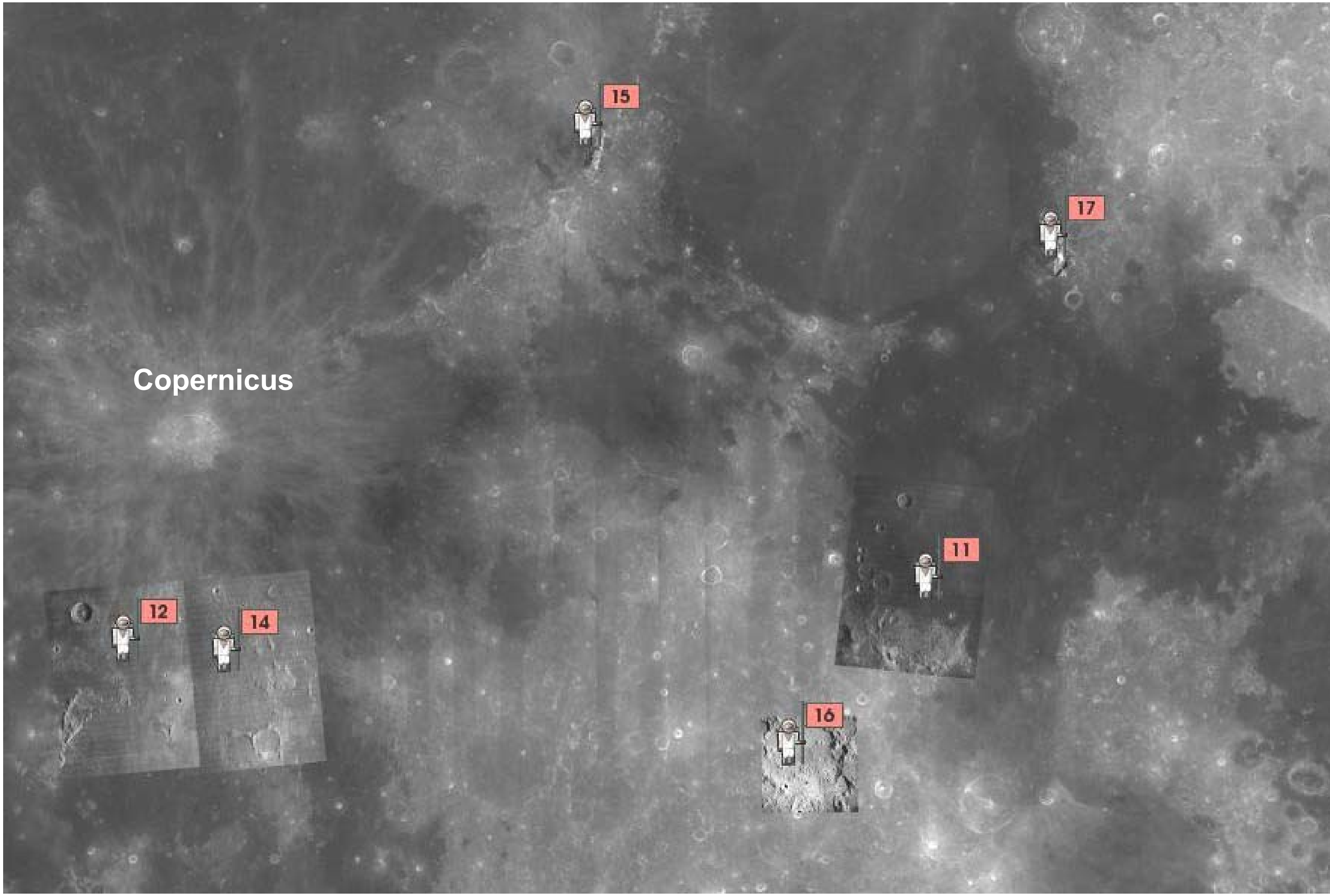
- Mining on Moon, Mars, etc.
- Mining Near-Earth Asteroids and Comets
- The “Space Tractor” (Manages Threats to Earth)
- The Space Elevator (Reduces “Lifting” Costs)
- Off-World Mining Preferable to Mining on Earth?
- When Will it Make Sense?

Lunar Exploration

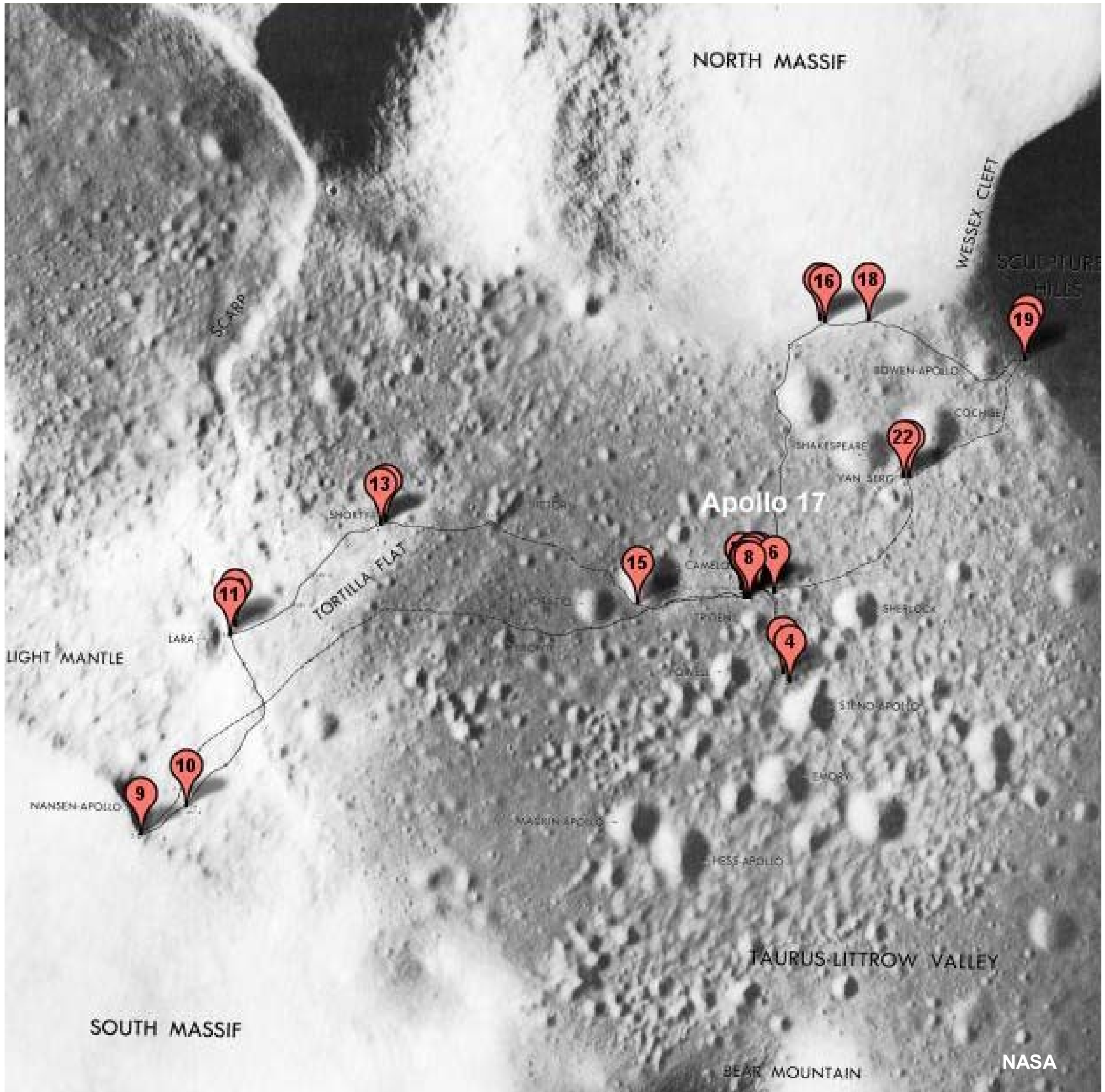
- **Lunar Prospector (1998)**
  - **Mapped surface Indications of key elements**
    - H, U, Th, K, O, Si, Mg, Fe, Ti, Al, Ca, H_2O
- **Additional mapping to be conducted**
  - Ni, Co, Samarium, other rare-earth elements
  - Structural geology
  - Confirmation of earlier aerial photography, aerial geophysical, and remote sensing



Lunar Apollo Exploration – Phase I – 1960s-1970s



Lunar Apollo Exploration – Phase I – 1960s-1970s



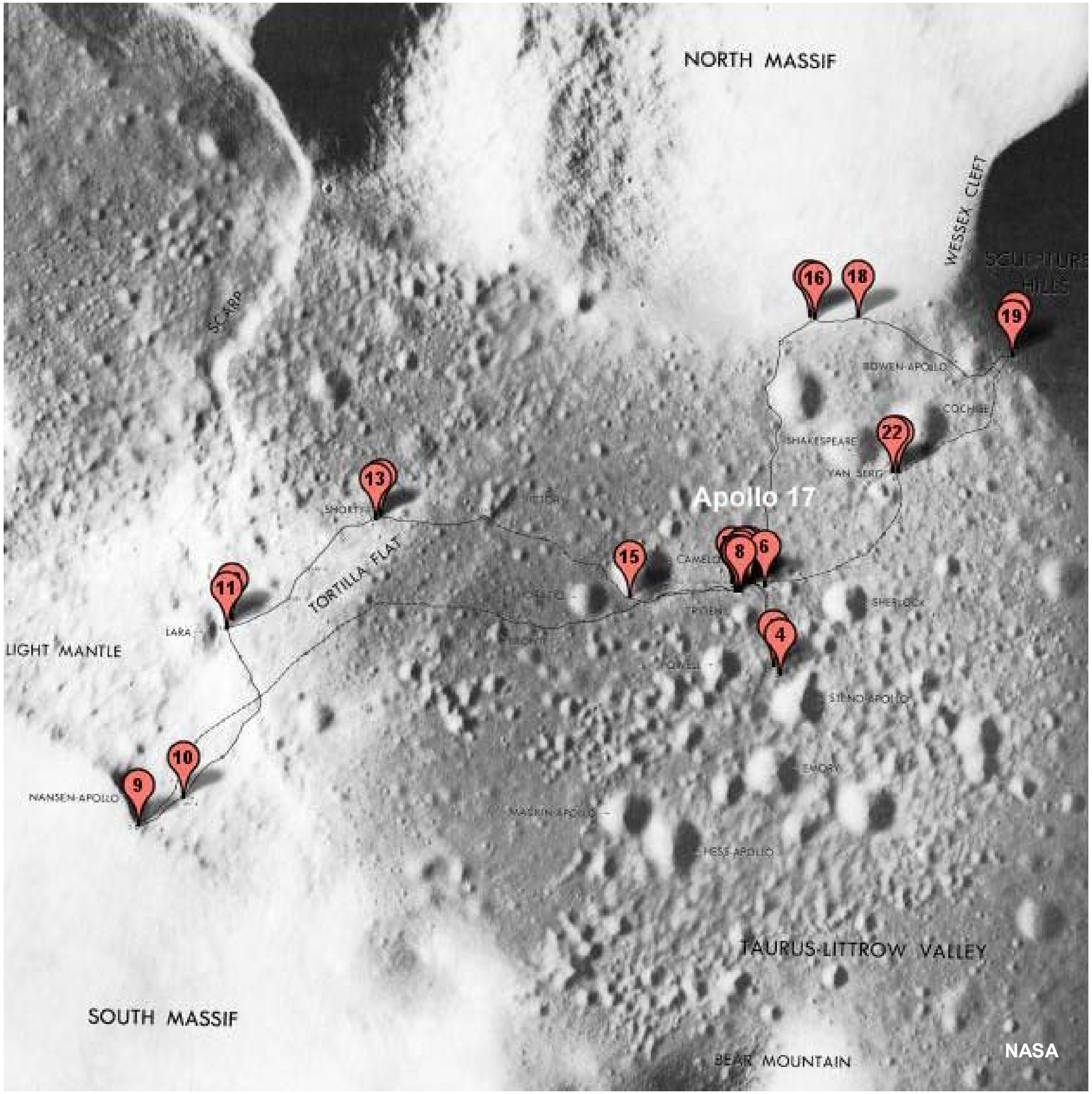
Lunar Sampling

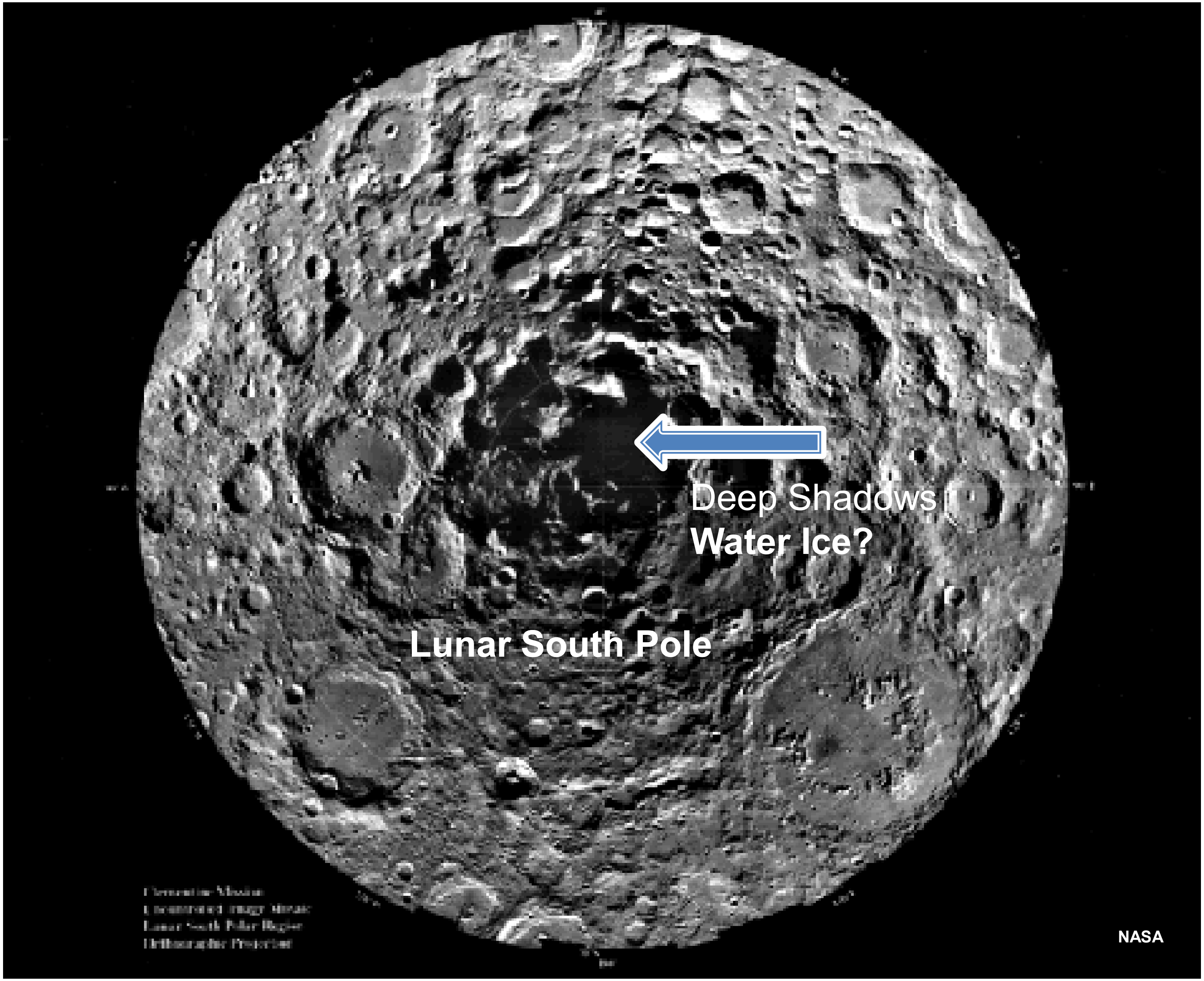
Apollo 17 - Reconnaissance Site 16

Lunar Apollo Exploration – Phase I – 1960s-1970s

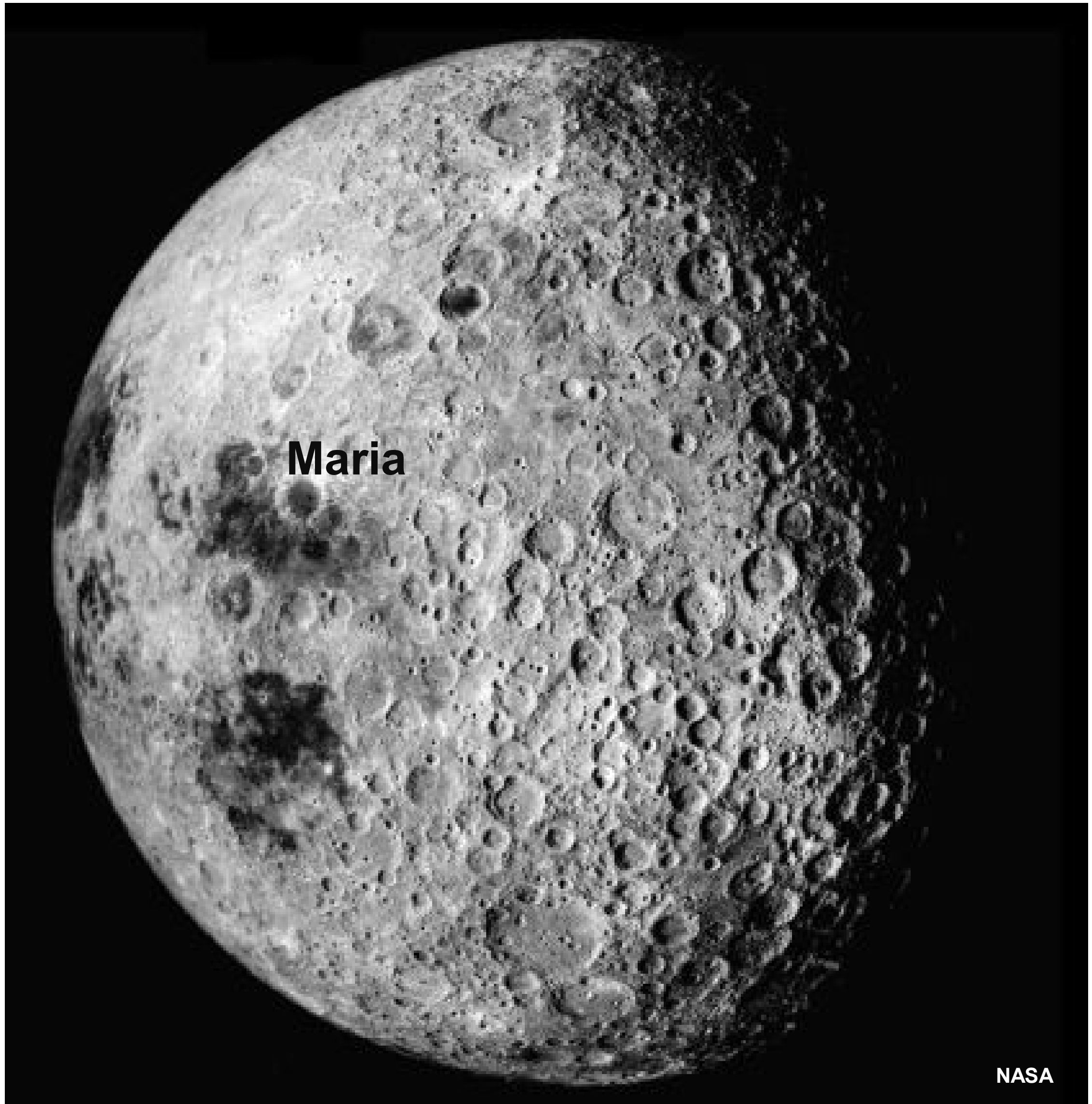
Apollo 17 - Reconnaissance Site 13

Lunar Exploration – Phase I – 1960s-1970s

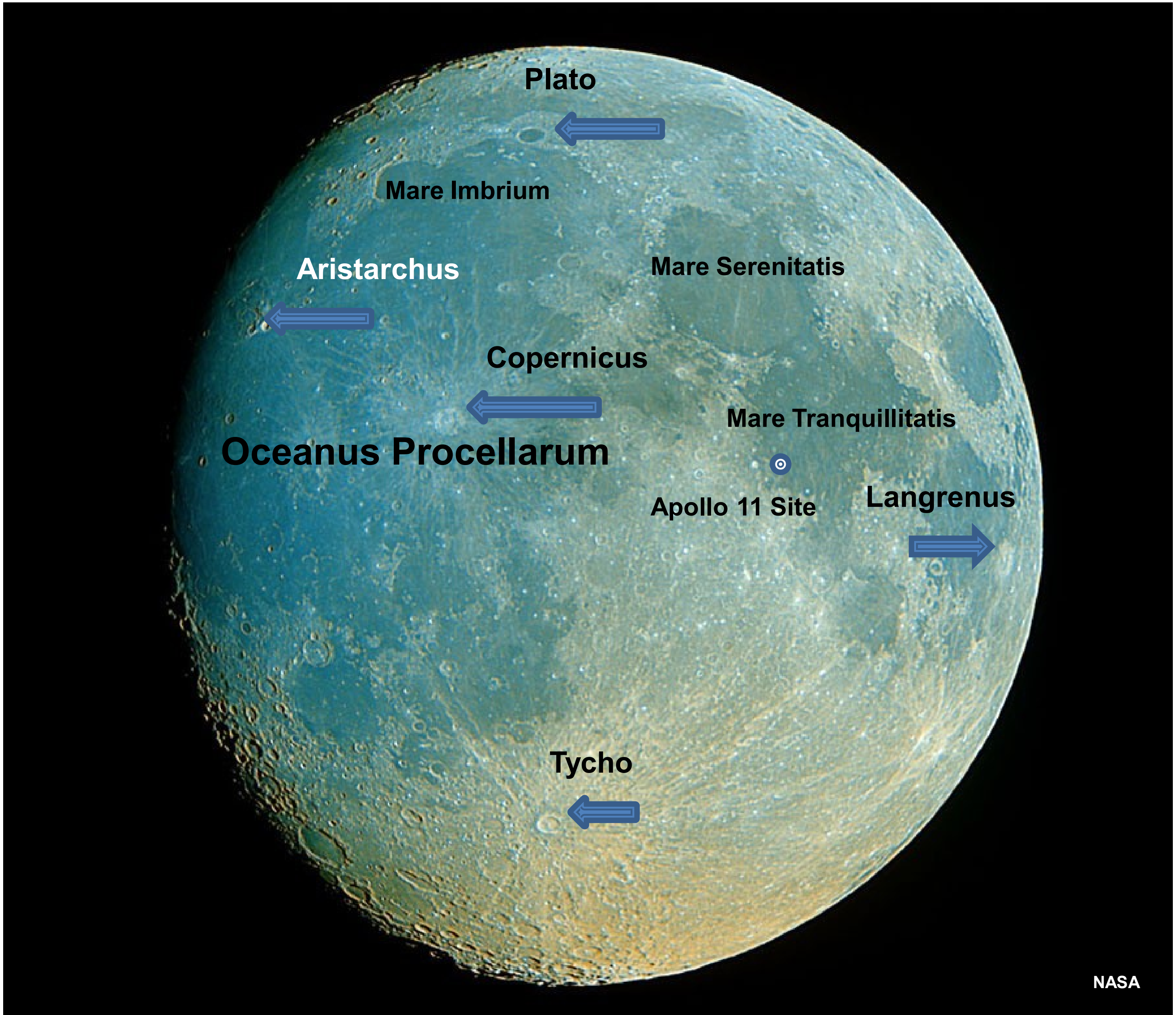


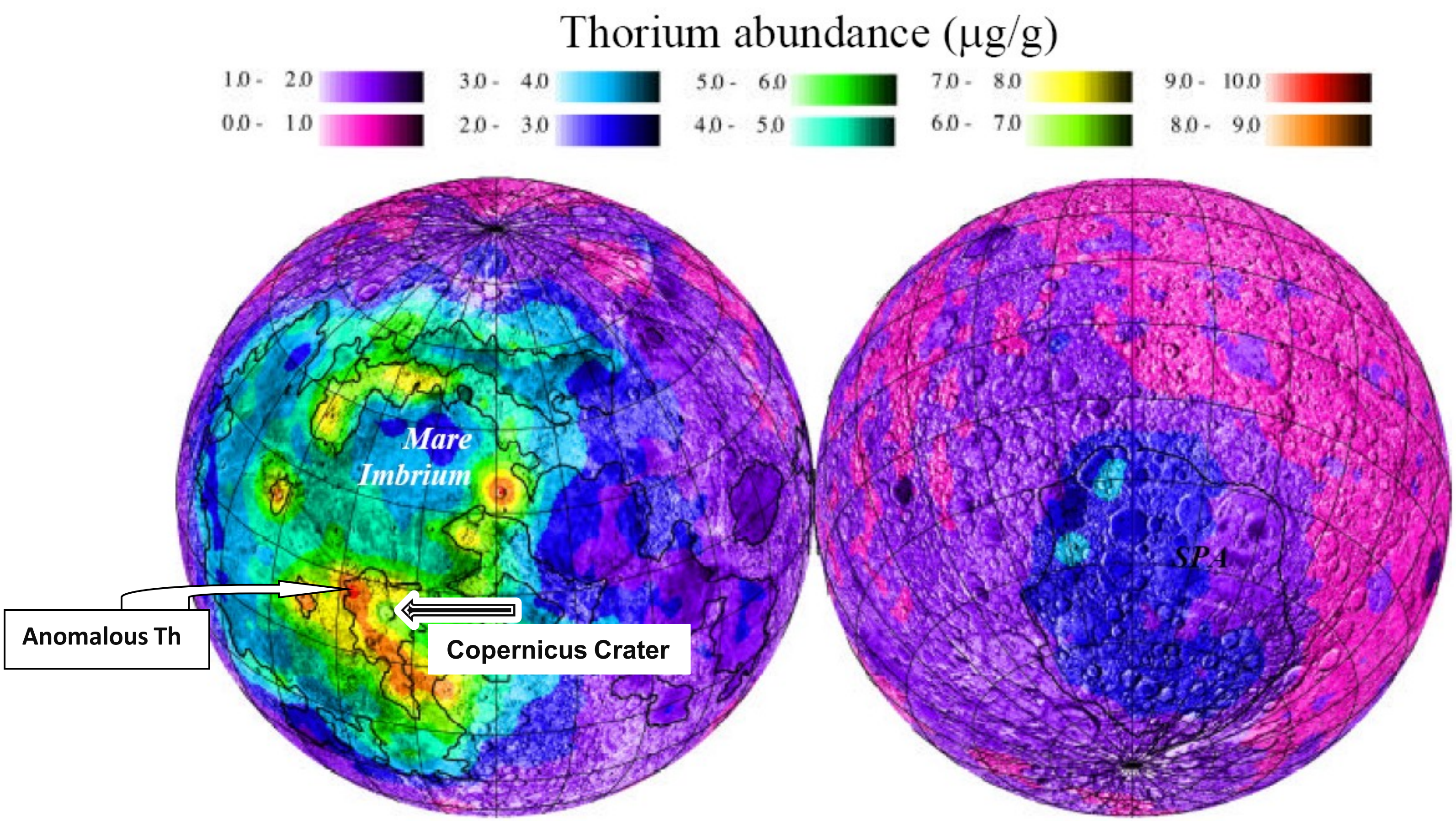

Deep Shadows
Water Ice?
Lunar South Pole
NASA

Back Side of Moon

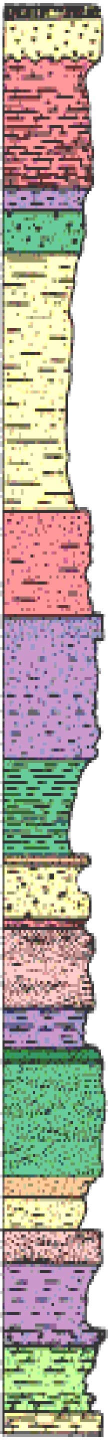


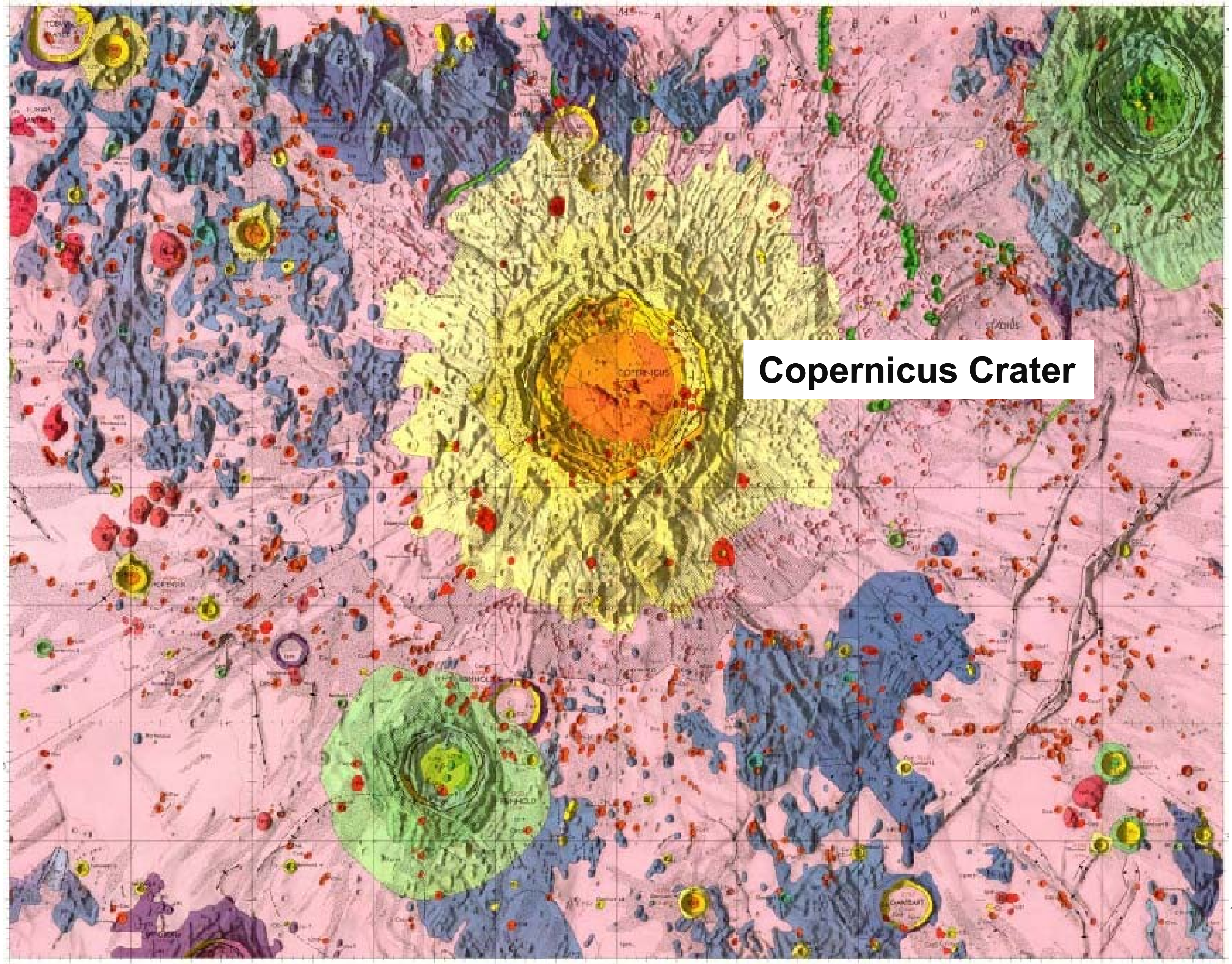
Common Lunar Sites





From Elphic, *et al.*, 2000.



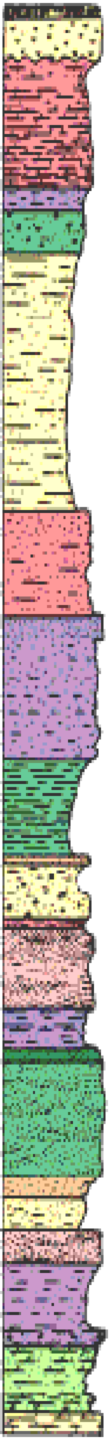


USGS Geologic Map of the Moon
I-515 – Aristarchus – 1967 – Schmitt, Trask, and Shoemaker

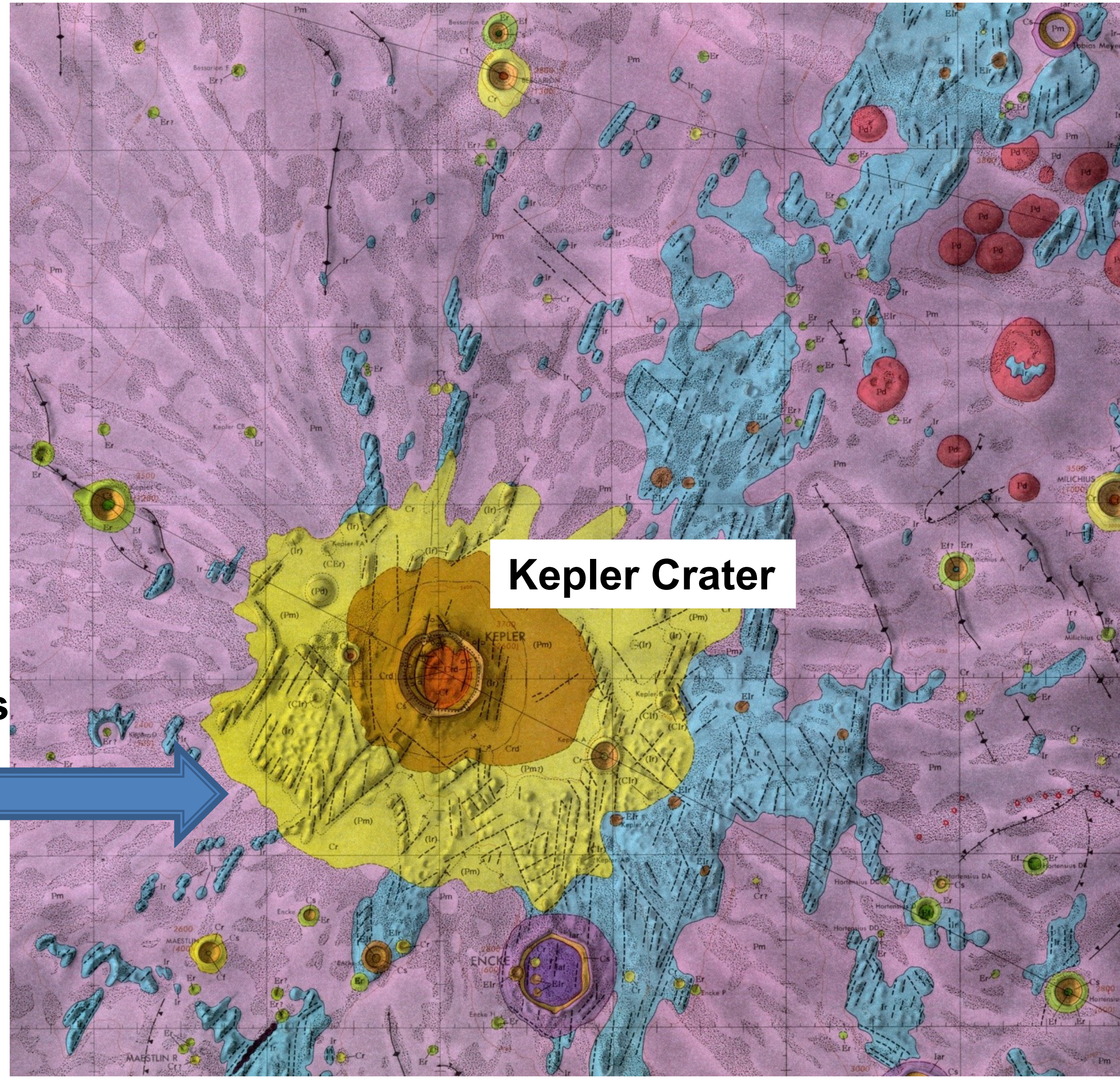
(Skinner and Gadis, 2008)

N

Approx. 30 miles



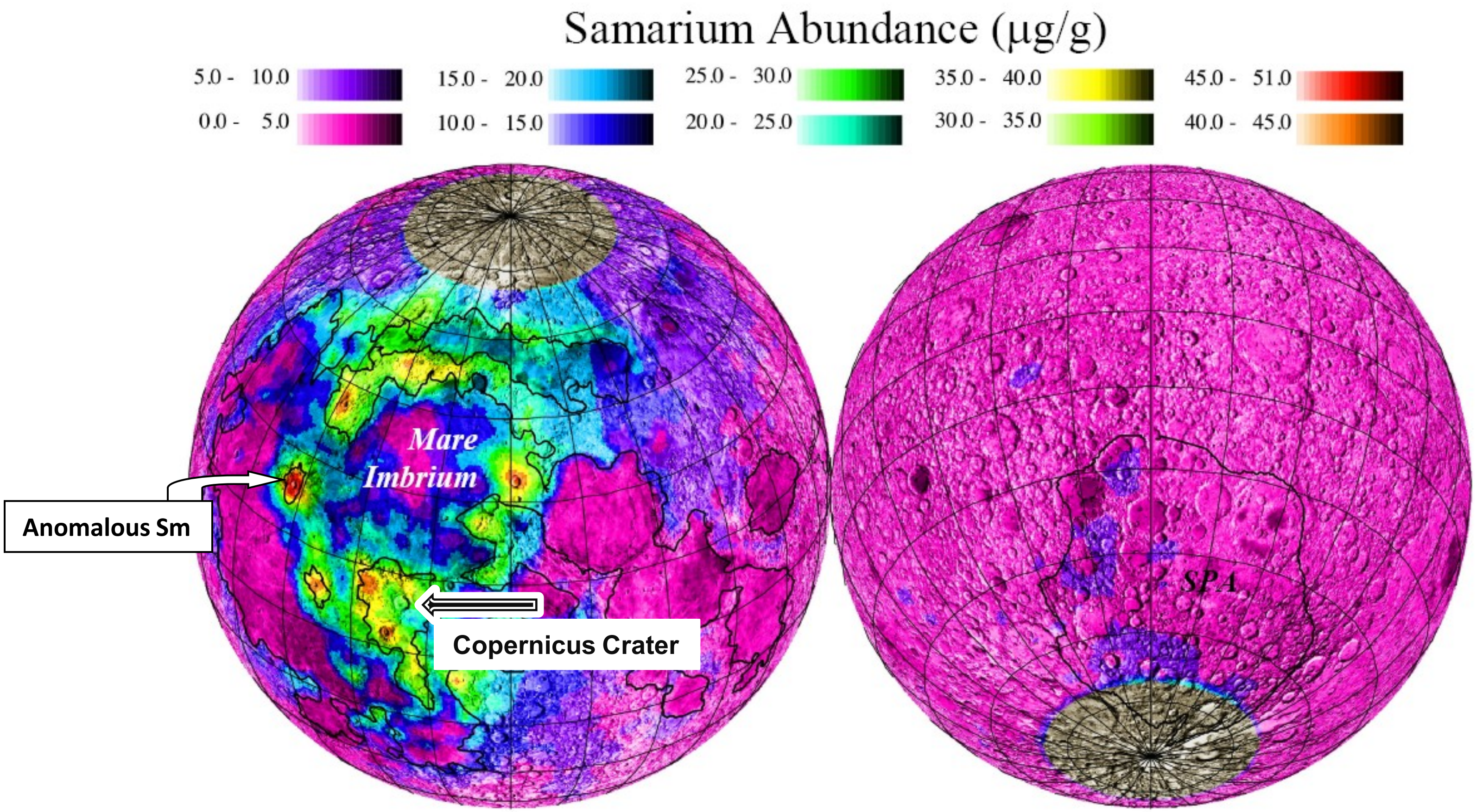
Highland Area
of
Thorium Anomalies



USGS Geologic Map of the Moon
I-355 Kepler -1962 - Hackman

Approx. 30 miles

N



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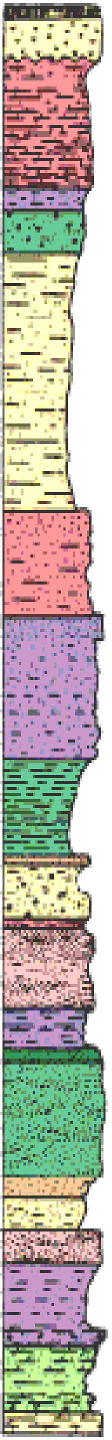
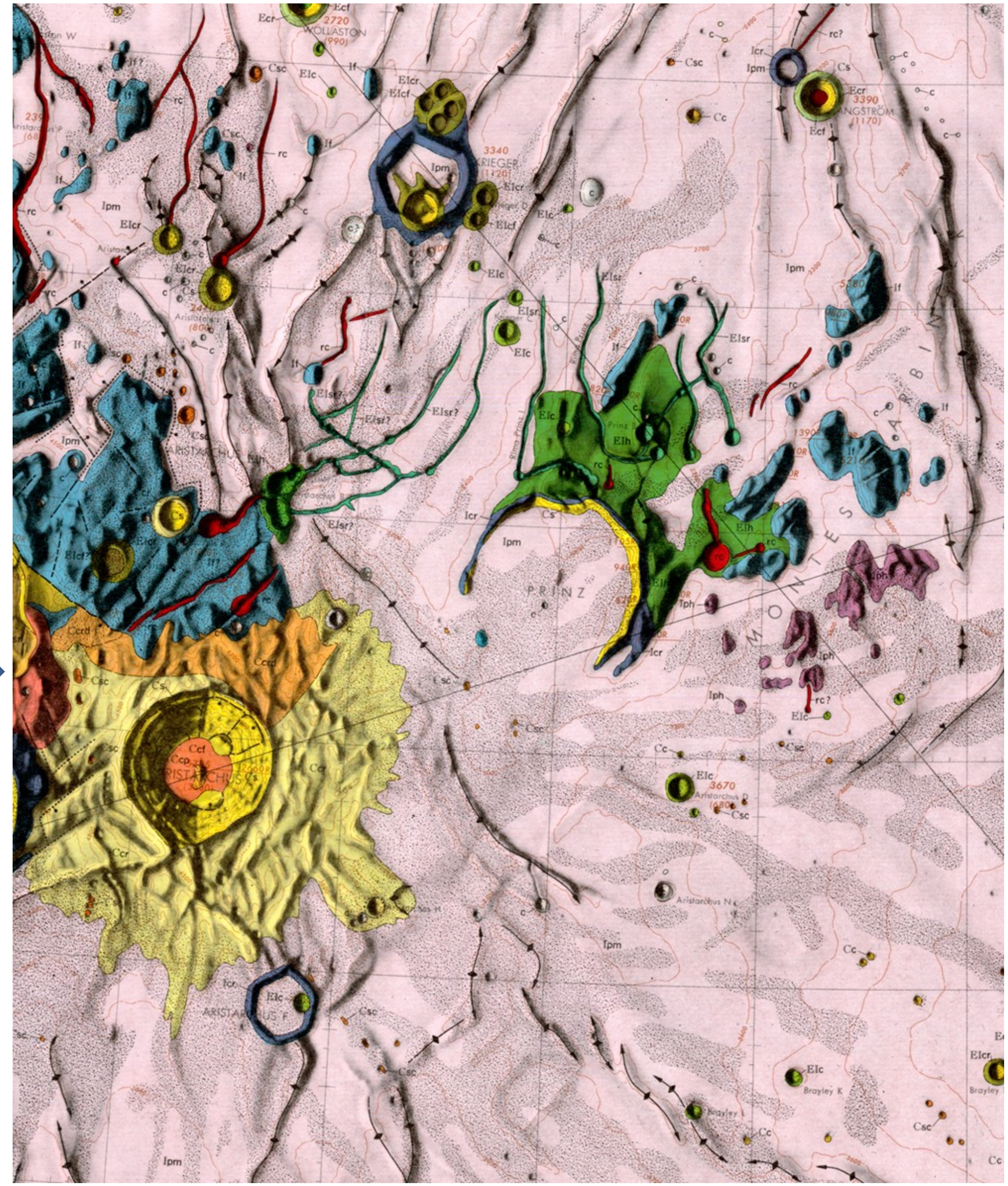


Highland Area of

Samarium Anomalies

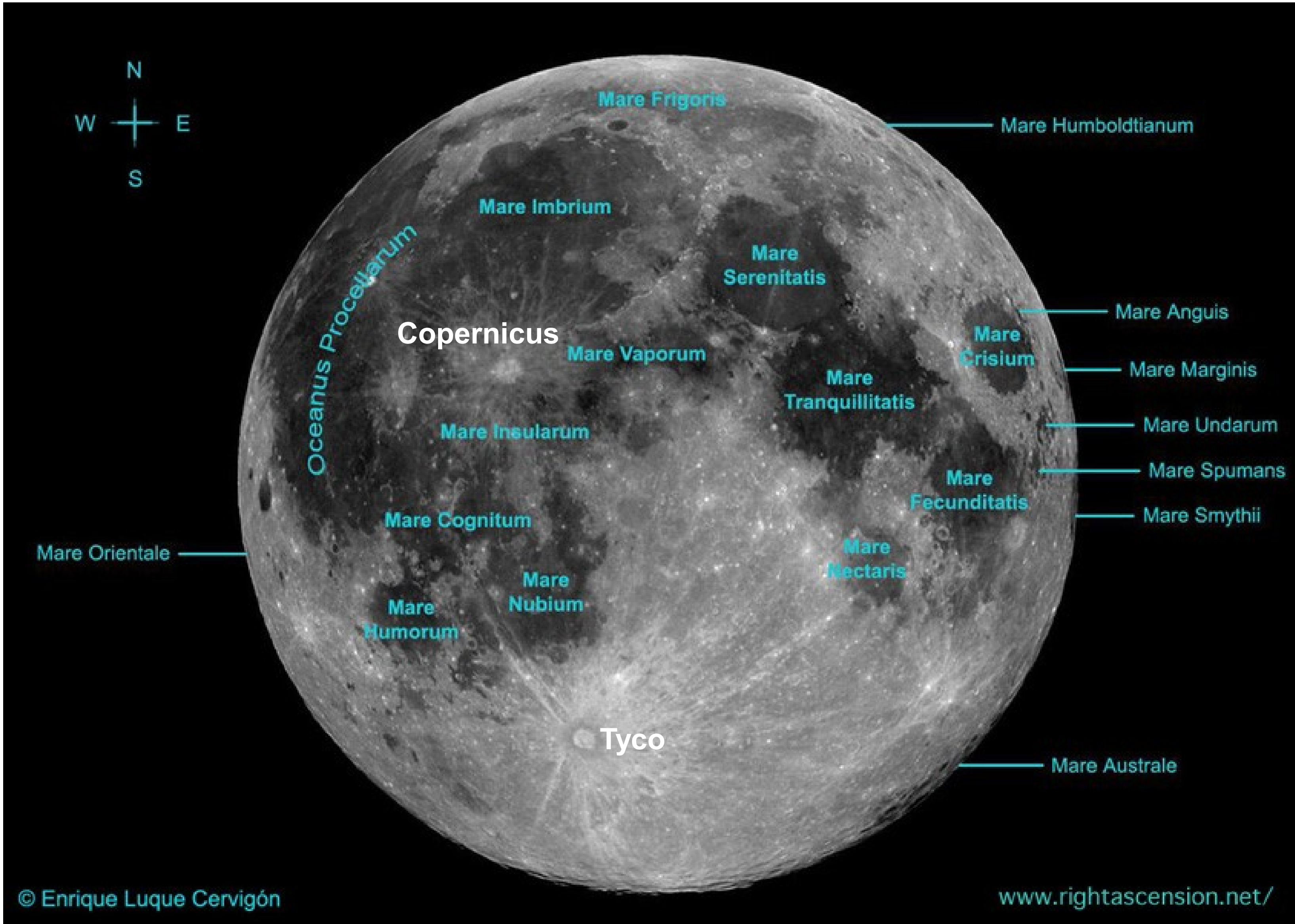


Approx. 30 miles

N

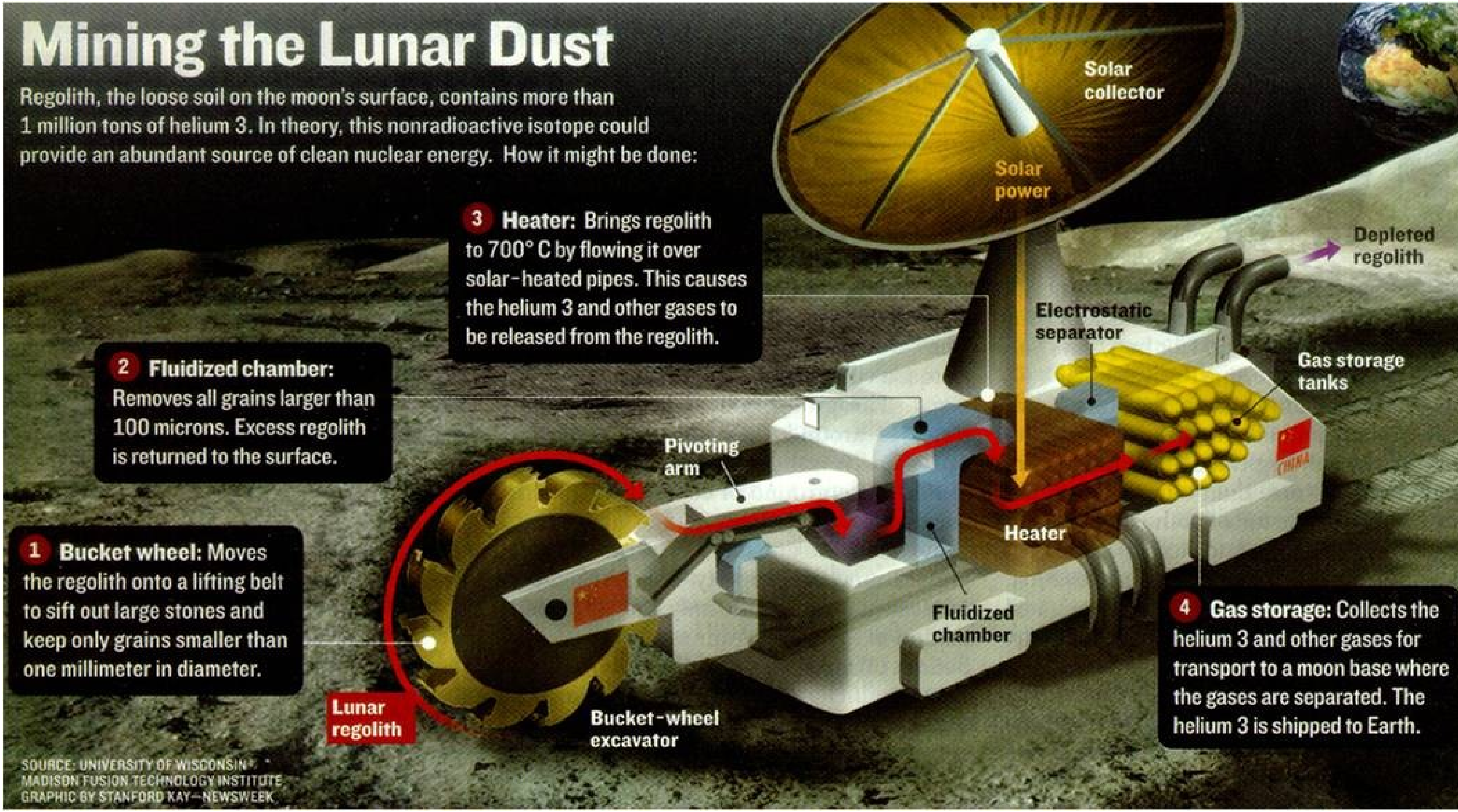
USGS Geologic Map of the Moon
I-465 – Aristarchus – 1965 - Moore

Helium-3 Resources in the Maria



Mining on the Moon

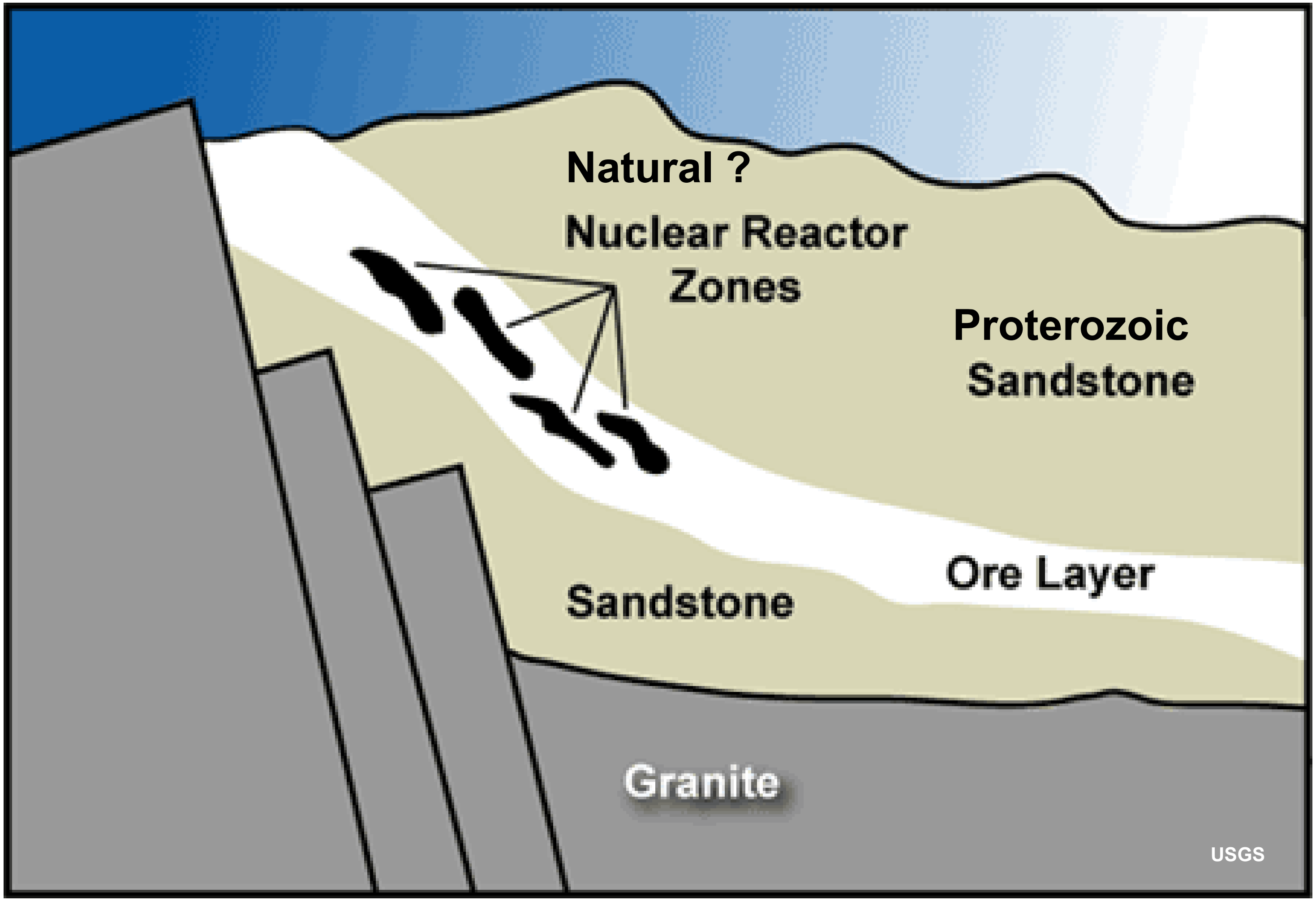
(Courtesy of *Popular Mechanics*)



Mining the Lunar Dust
Regolith, the loose soil on the moon's surface, contains more than 1 million tons of helium 3. In theory, this nonradioactive isotope could provide an abundant source of clean nuclear energy. How it might be done:
3 Heater: Brings regolith to 700° C by flowing it over solar-heated pipes. This causes the helium 3 and other gases to be released from the regolith.
2 Fluidized chamber: Removes all grains larger than 100 microns. Excess regolith is returned to the surface.
1 Bucket wheel: Moves the regolith onto a lifting belt to sift out large stones and keep only grains smaller than one millimeter in diameter.
4 Gas storage: Collects the helium 3 and other gases for transport to a moon base where the gases are separated. The helium 3 is shipped to Earth.
Solar collector
Solar power
Depleted regolith
Electrostatic separator
Gas storage tanks
Pivoting arm
Heater
Fluidized chamber
Lunar regolith
Bucket-wheel excavator
SOURCE: UNIVERSITY OF WISCONSIN-MADISON FUSION TECHNOLOGY INSTITUTE
GRAPHIC BY STANFORD KAY—NEWSWEEK

Analogues from Earth?

Oklo Deposit - Gabon



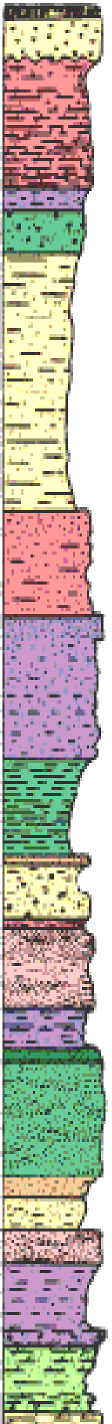
Reactions Dated at 1.6 Billion Years

Natural Nuclear Reactors ?

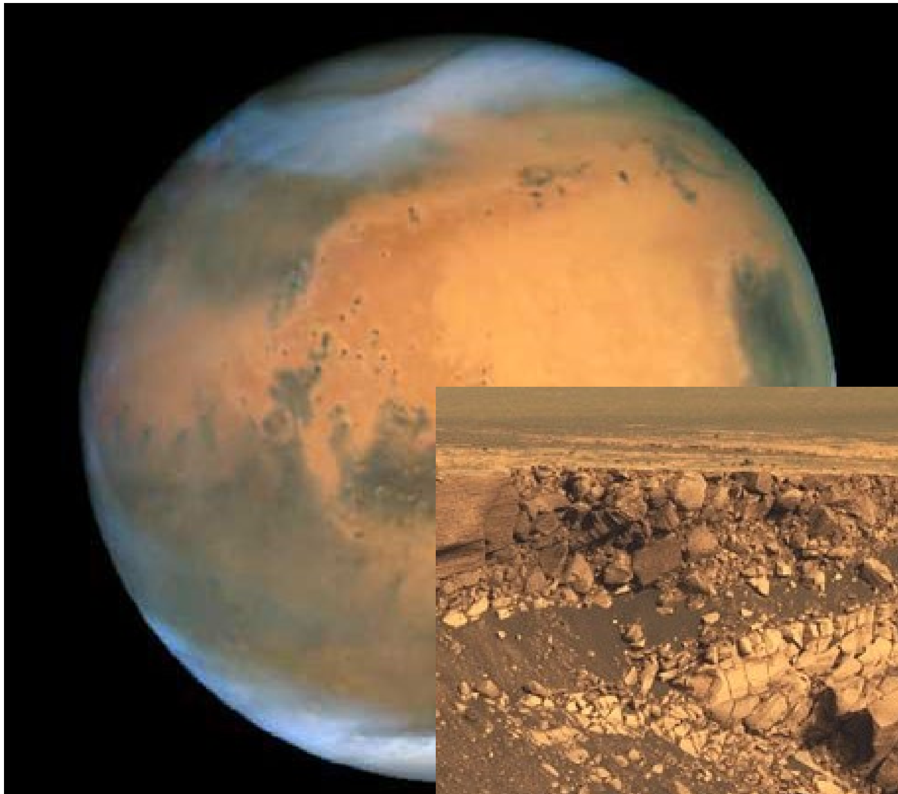
Oklo Deposit - Gabon

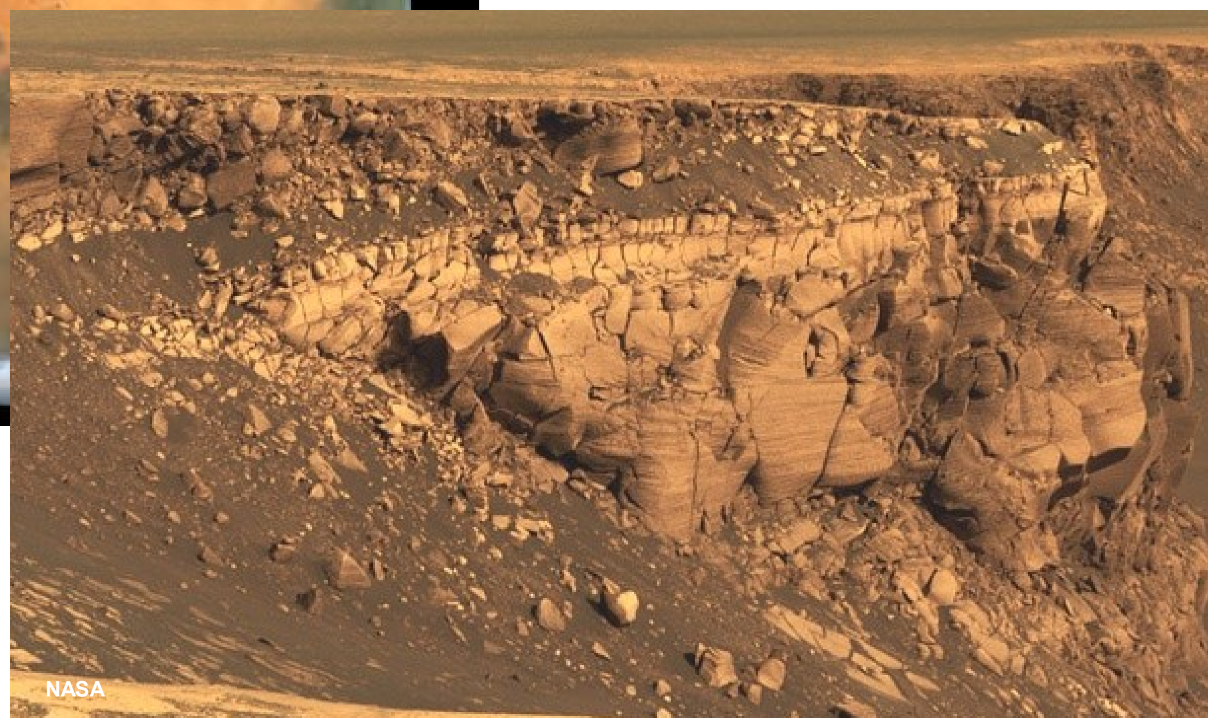
Significance?

- Mineralization may have analogues off-world.
- Would leave radioactivity behind…”breadcrumbs” to find in the Solar System.



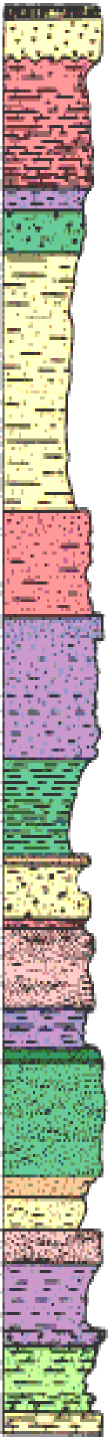
Mars is Beginning to Show Some Promise

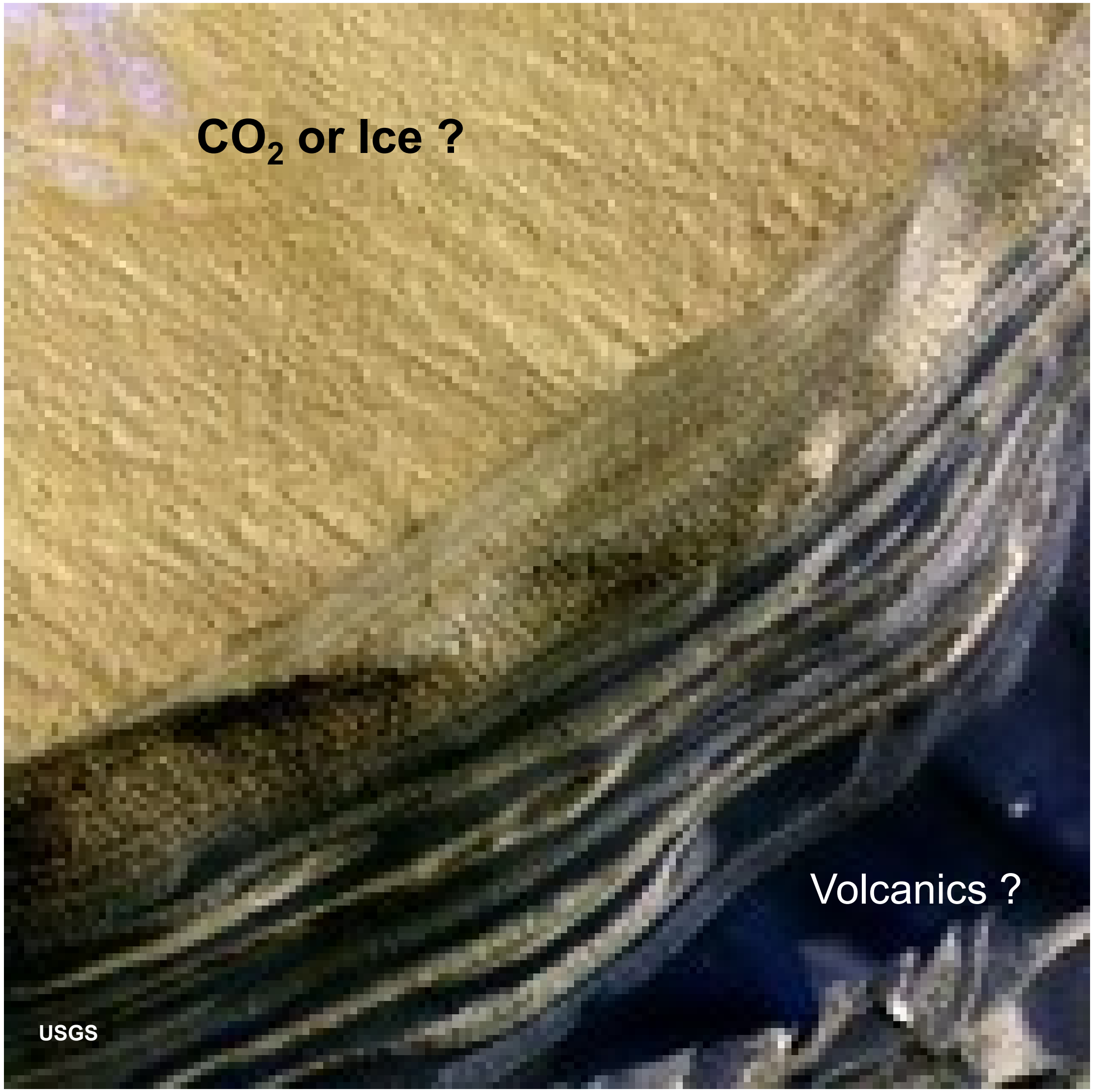




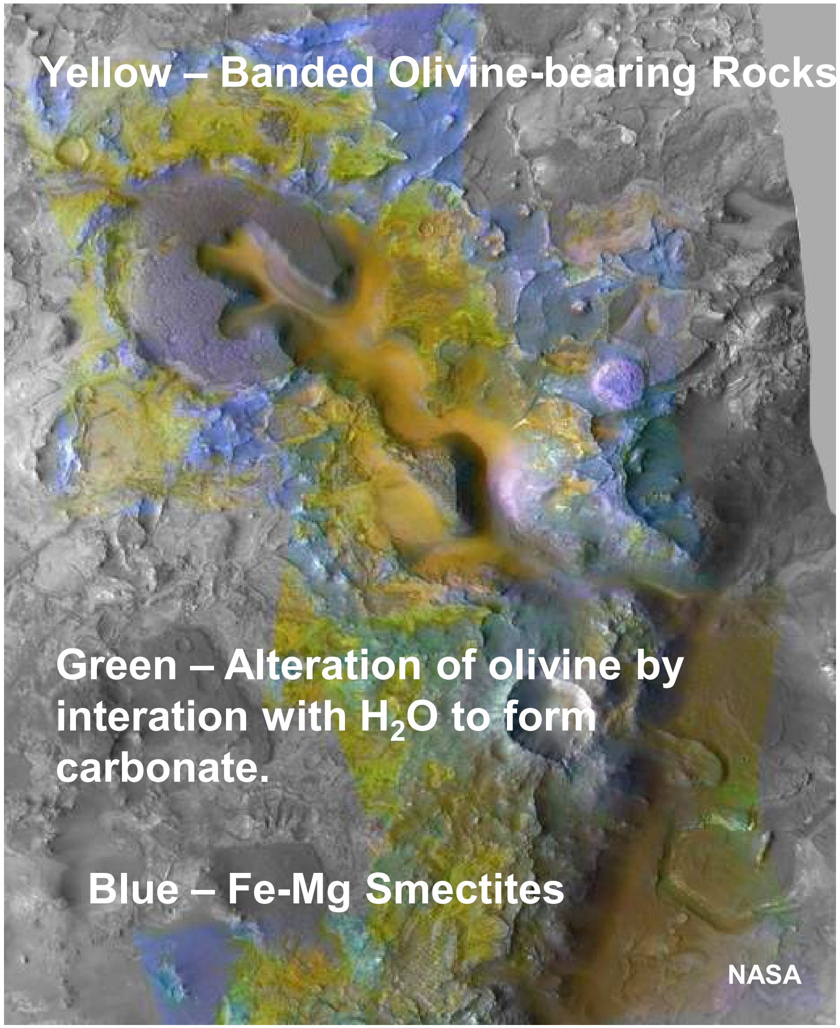
Angular Unconformity in *Victoria Crater*?

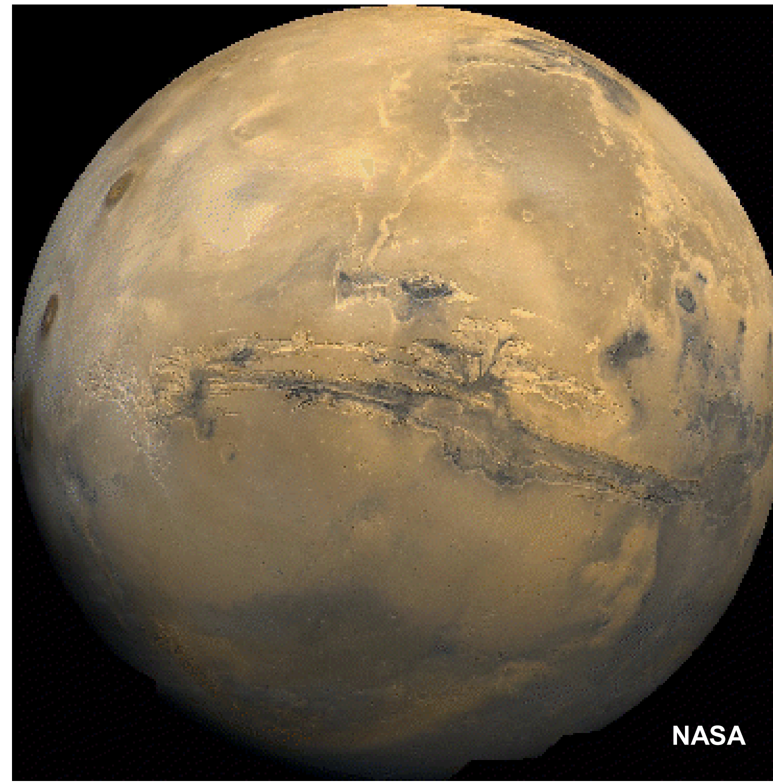
Bedding on Mars





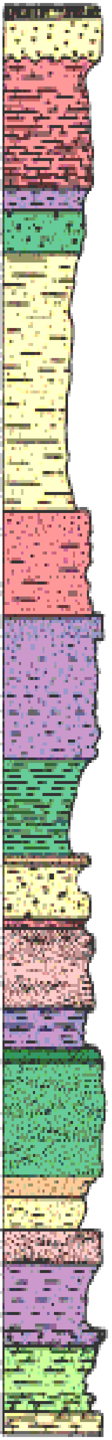
Mars is Beginning to Show Some Promise

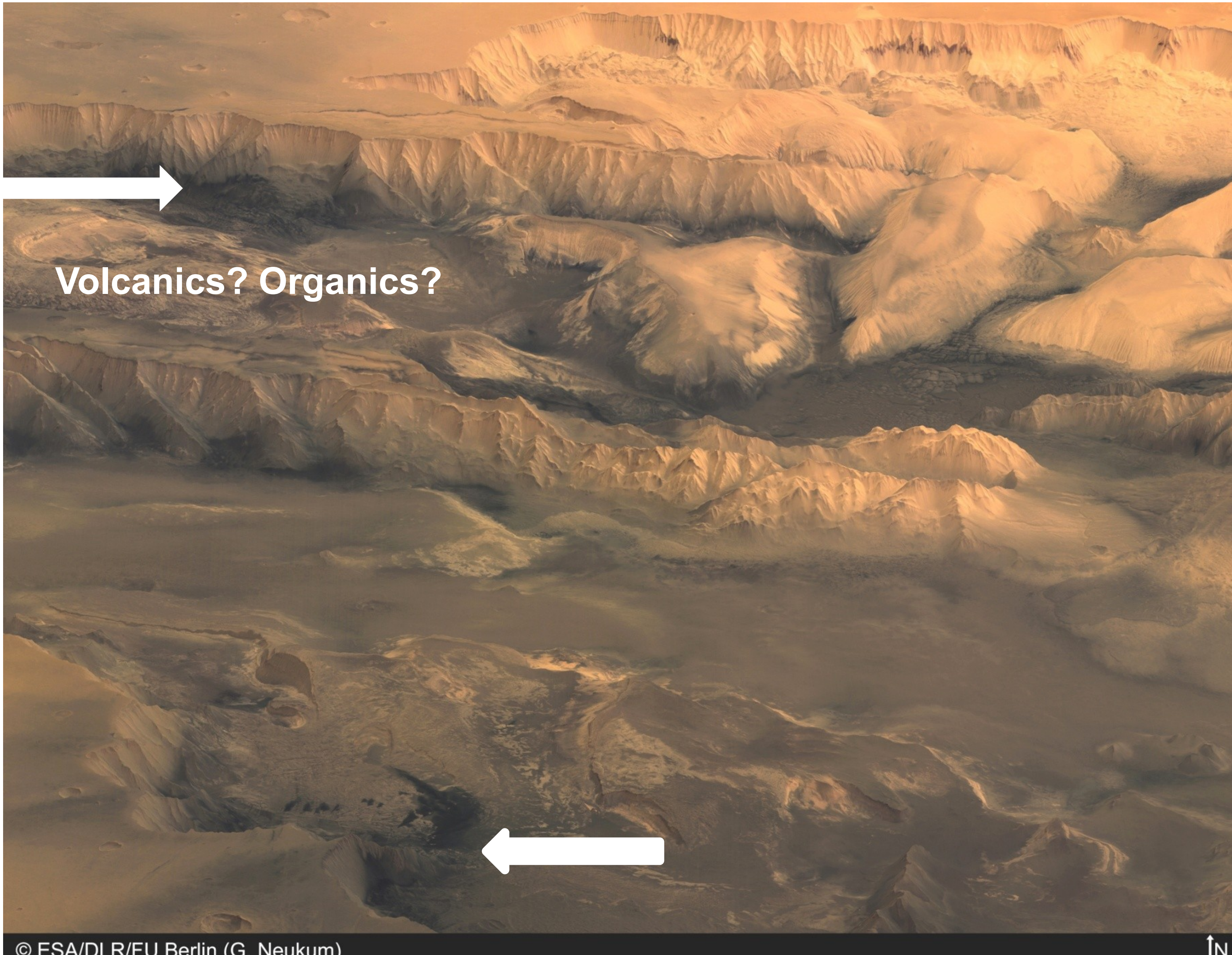




Carbonates mean H_20 may be present…

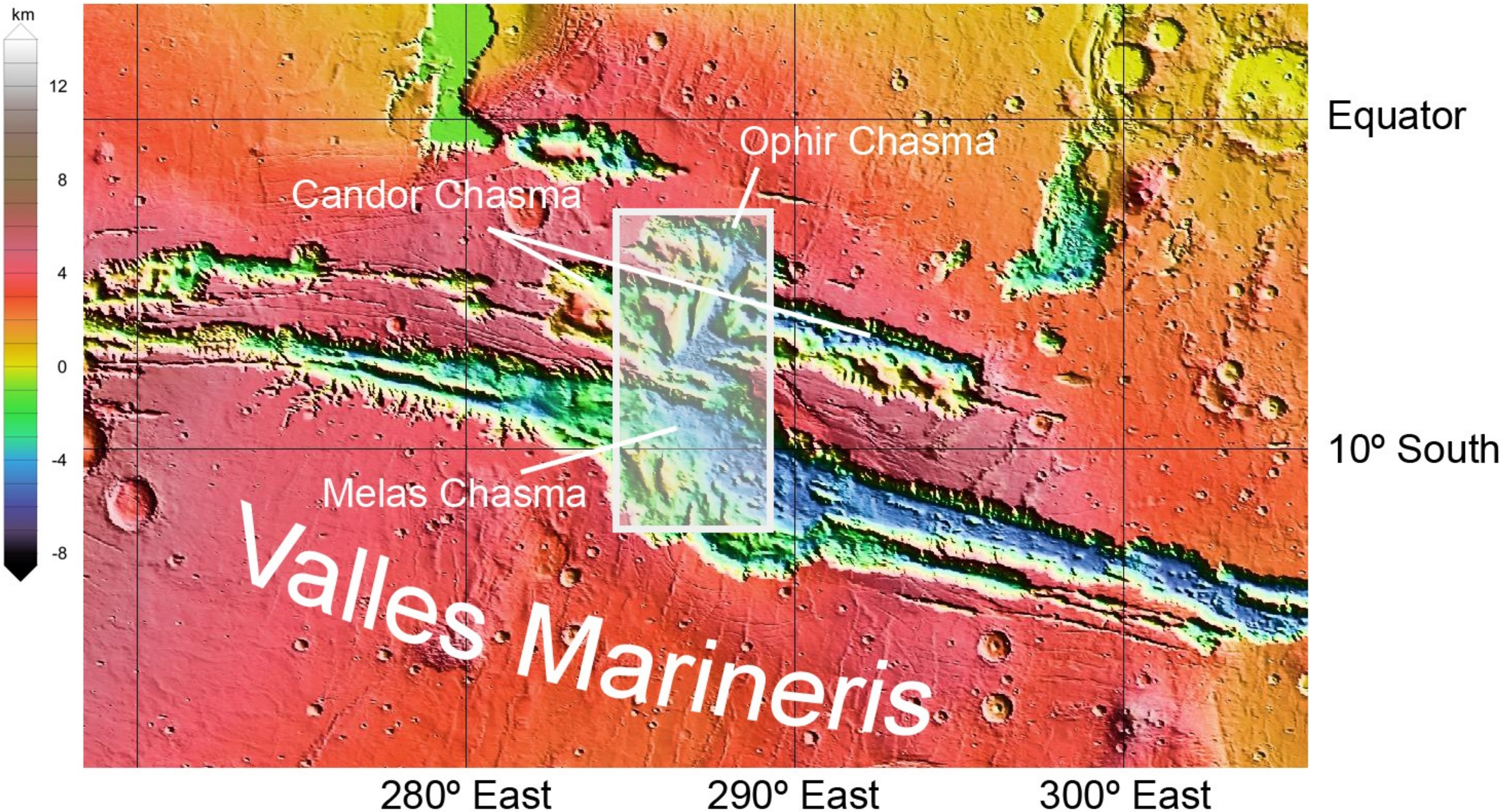
Valles Marineris



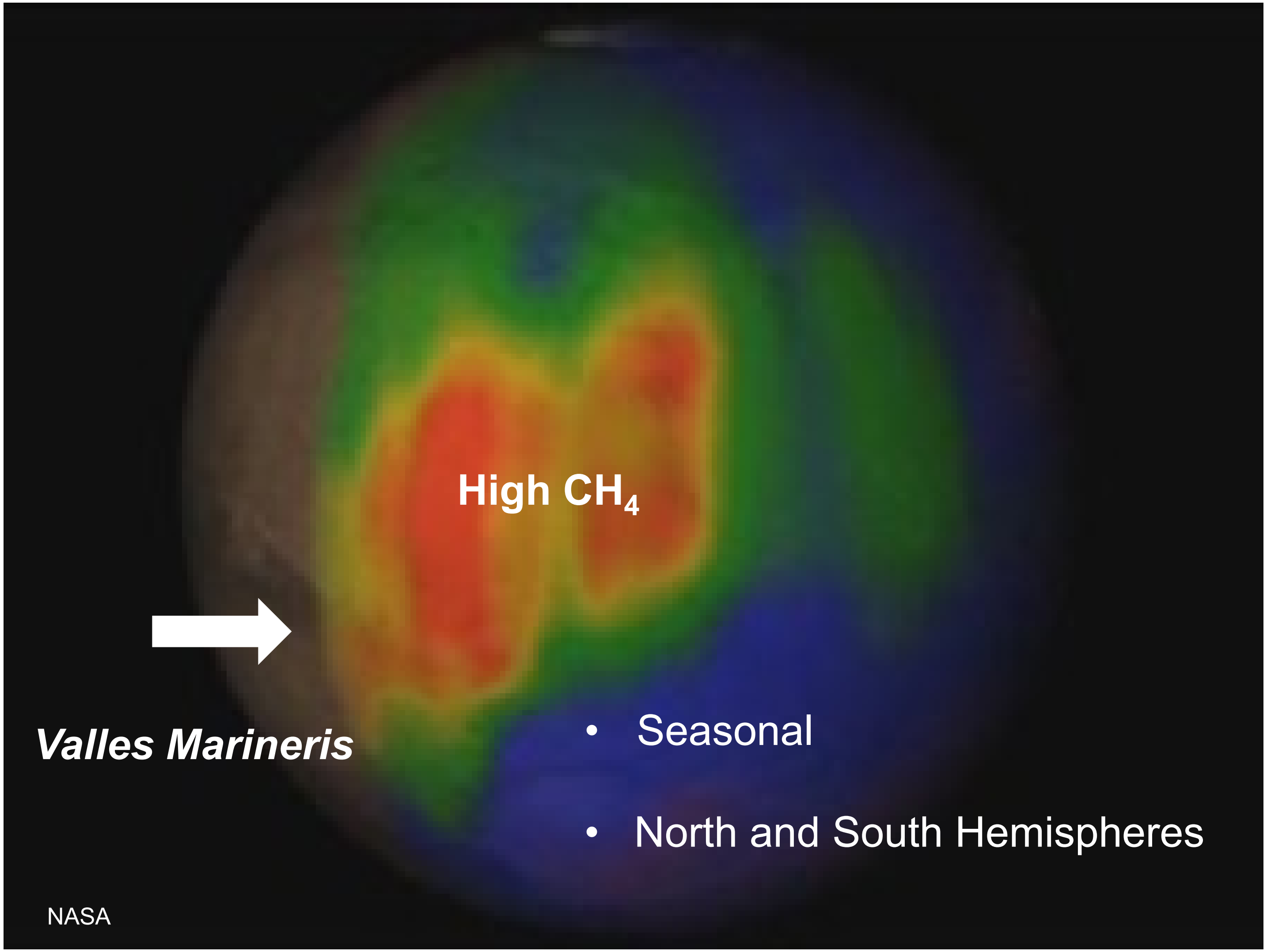


Mapping of Mars Improving

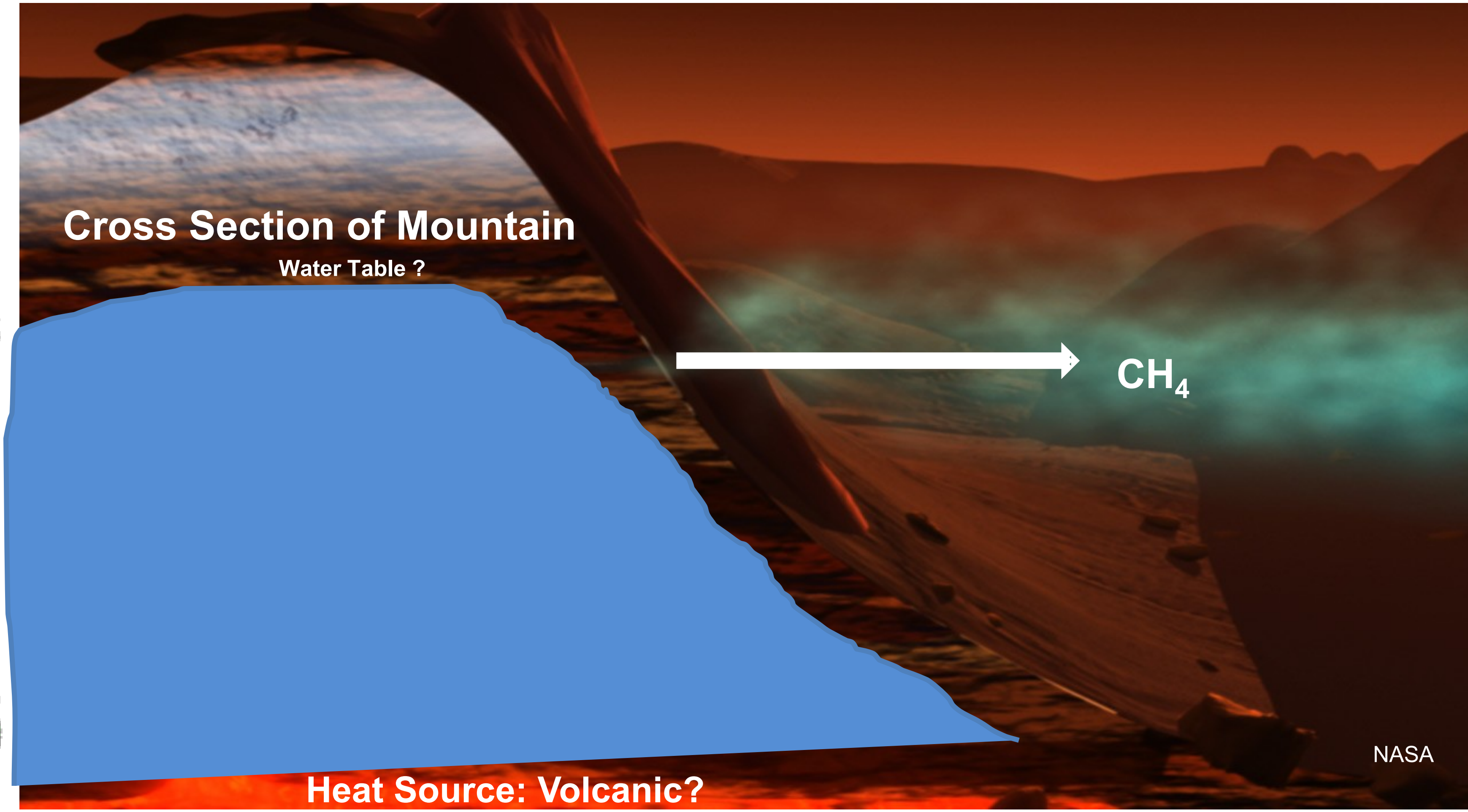
Mars Observer Laser Altimeter (MOLA)



Methane on Mars: Biological or Geochemical?

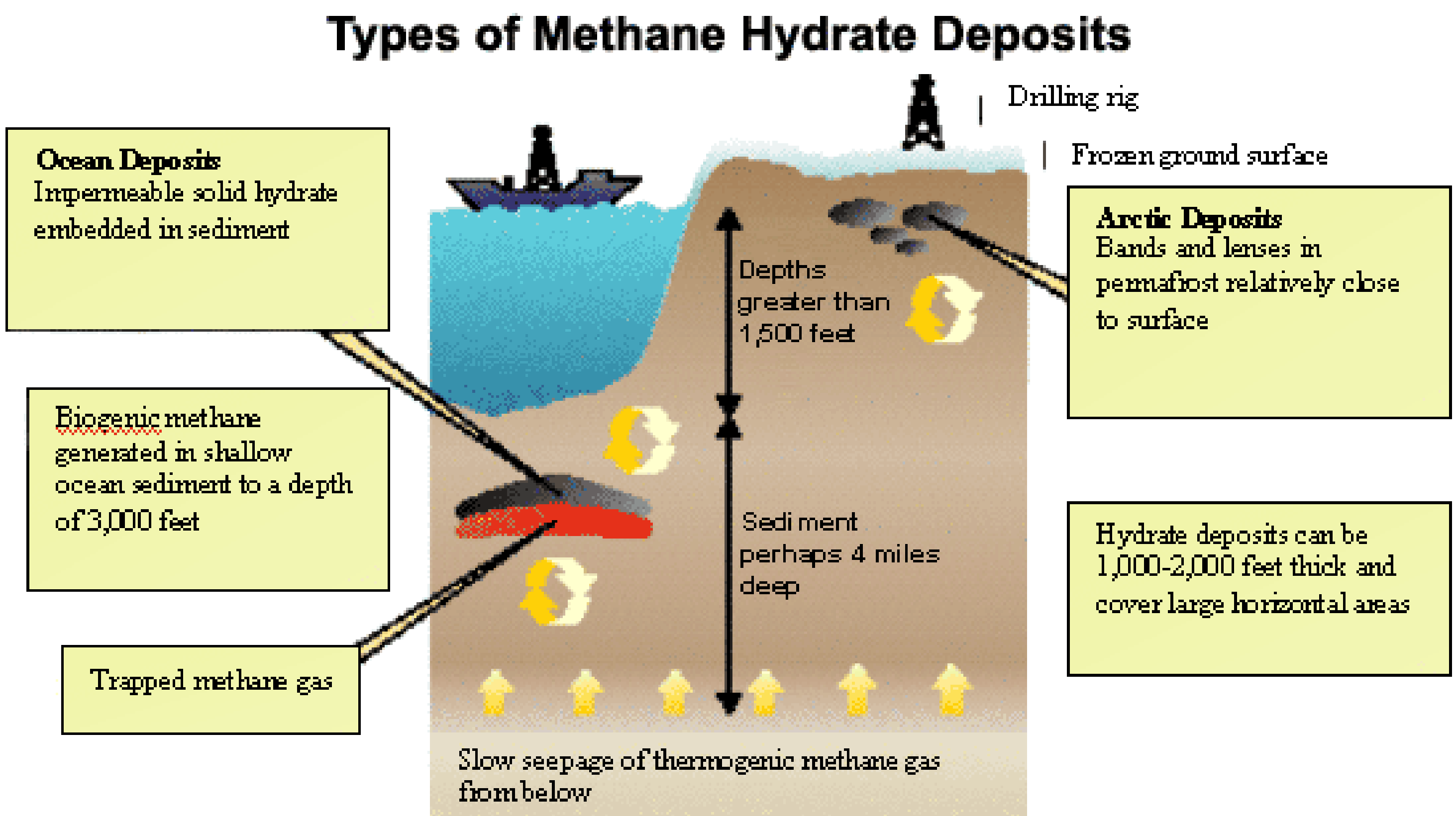


Methane on Mars: Biological or Geochemical?



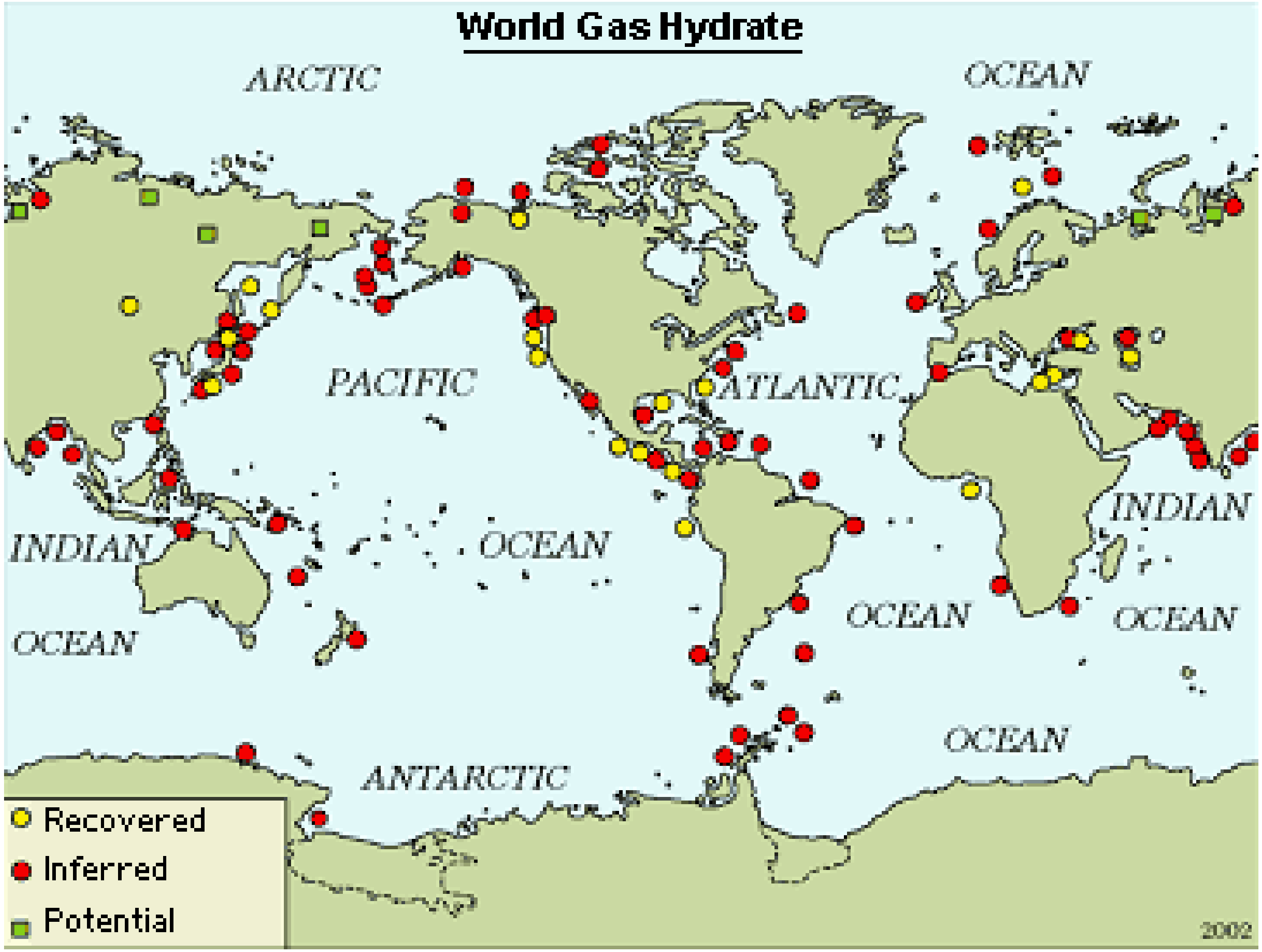
Significance? Could be indication that Earth-type mineralization is possible on Mars and on other bodies in Solar System.

Analogues from Earth?



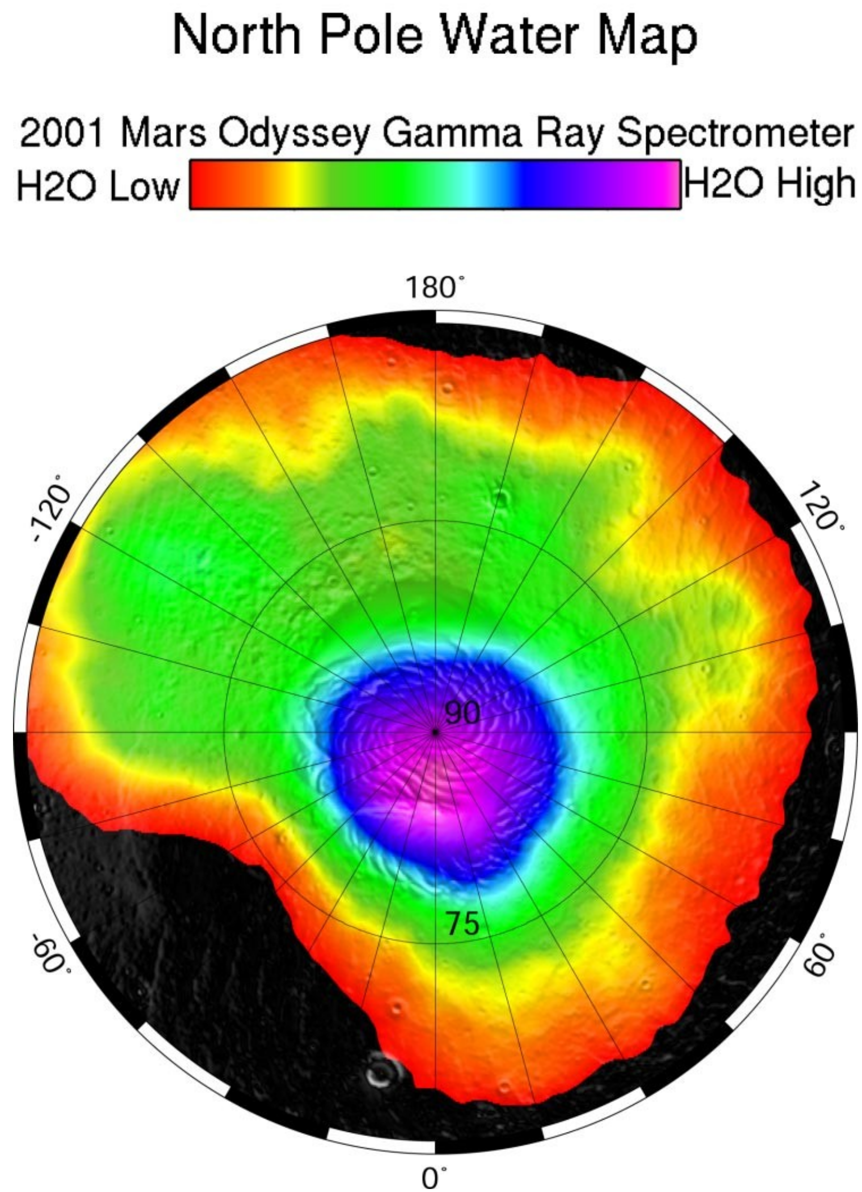
USGS Gas Hydrate Research

Analogues from Earth?



USGS Gas Hydrate Research

Even Water ?



NASA

Mining Asteroids

- **Asteroid Types**

  M – Metal Type

  - Iron, Nickel, Cobalt, Platinum-Group

  C – Carbonaceous Chondrite

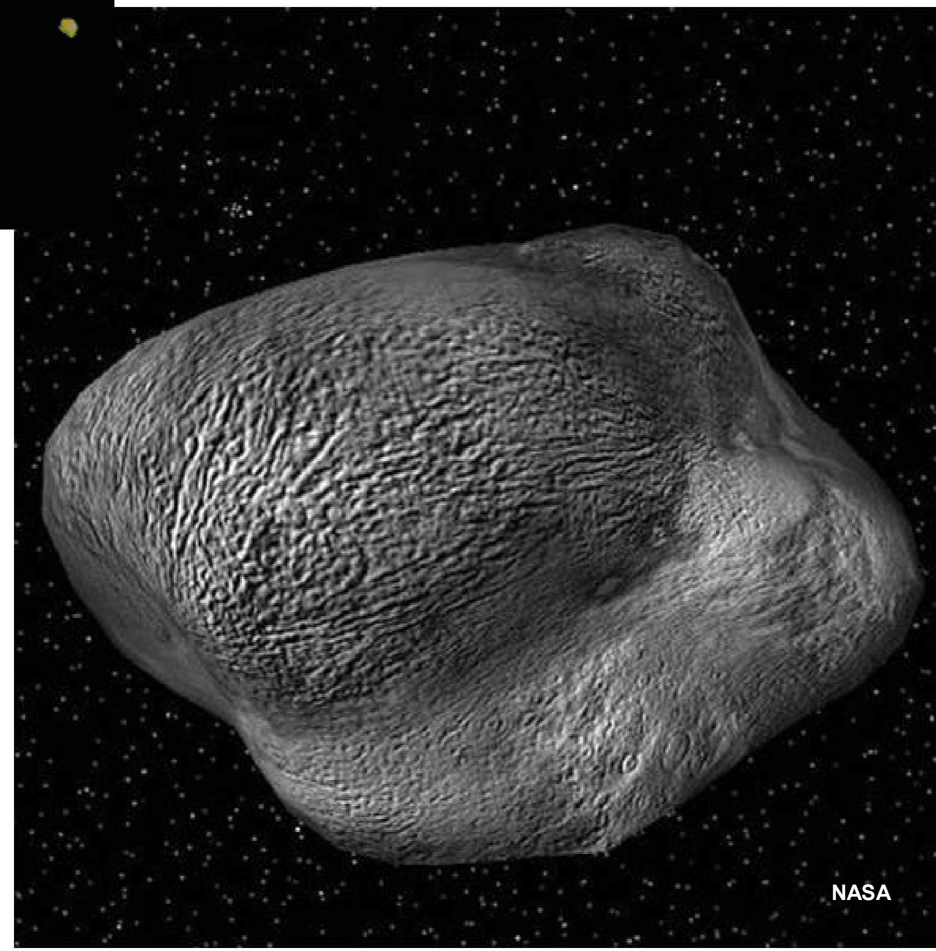
  - Hydrated Minerals

  S – Stony Type

  - Iron and Magnesium Silicates

S – Stony Type

Iron and Magnesium Silicates



M – Metal Type

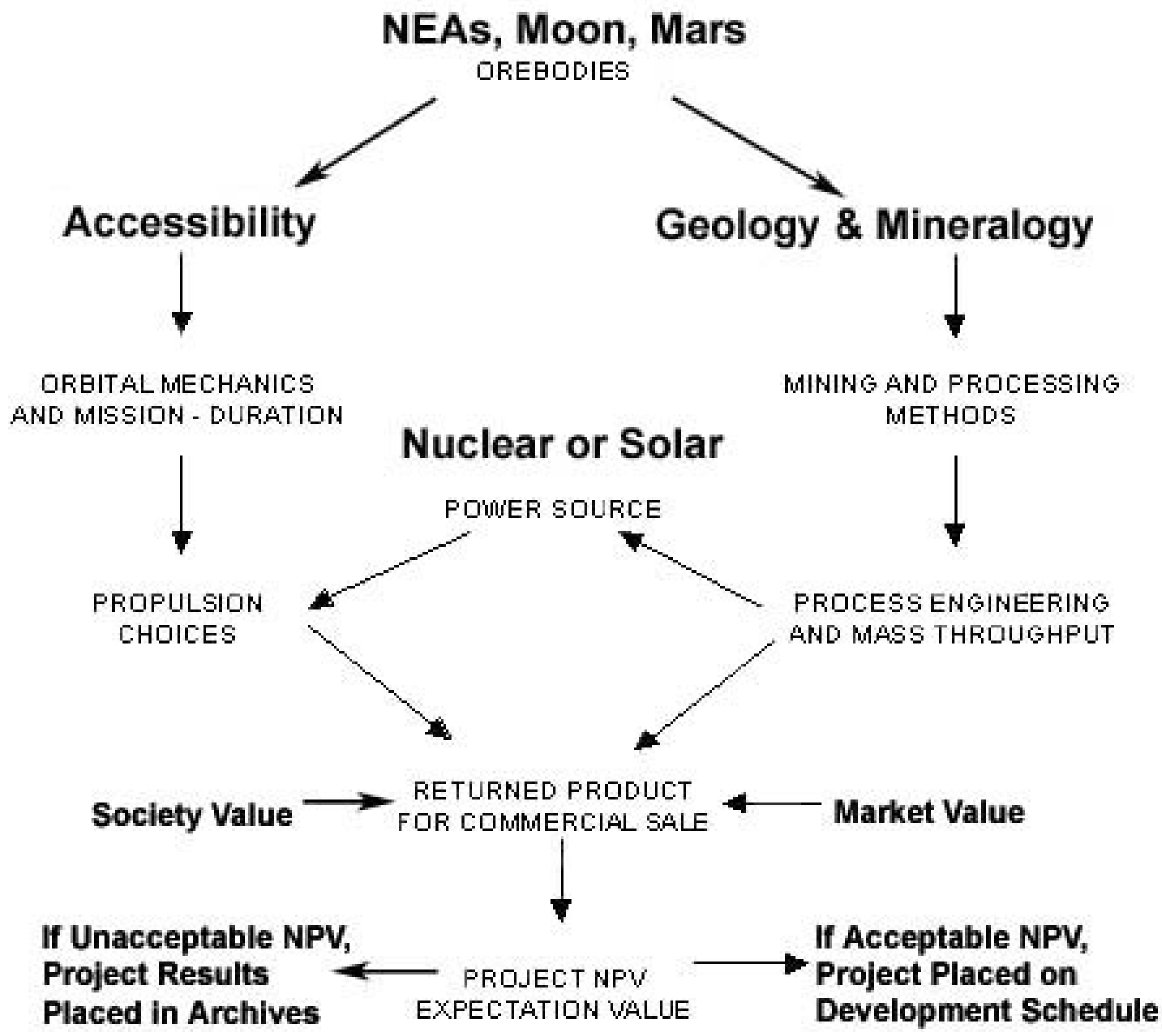
Iron, Nickel, Cobalt, Platinum-Group

What about the Economics of Mining in Space?

The economic and technical requirements are:

1. A market for the products produced and delivered,
2. Adequate spectral data indicating presence of the desired materials,
3. Orbital parameters give reasonable accessibility and mission duration,
4. Feasible concepts for mining & processing,
5. Feasible retrieval concepts, and
6. Positive economic Net Present Value, using appropriate geological and engineering concepts.

What about the Economics of Mining in Space?



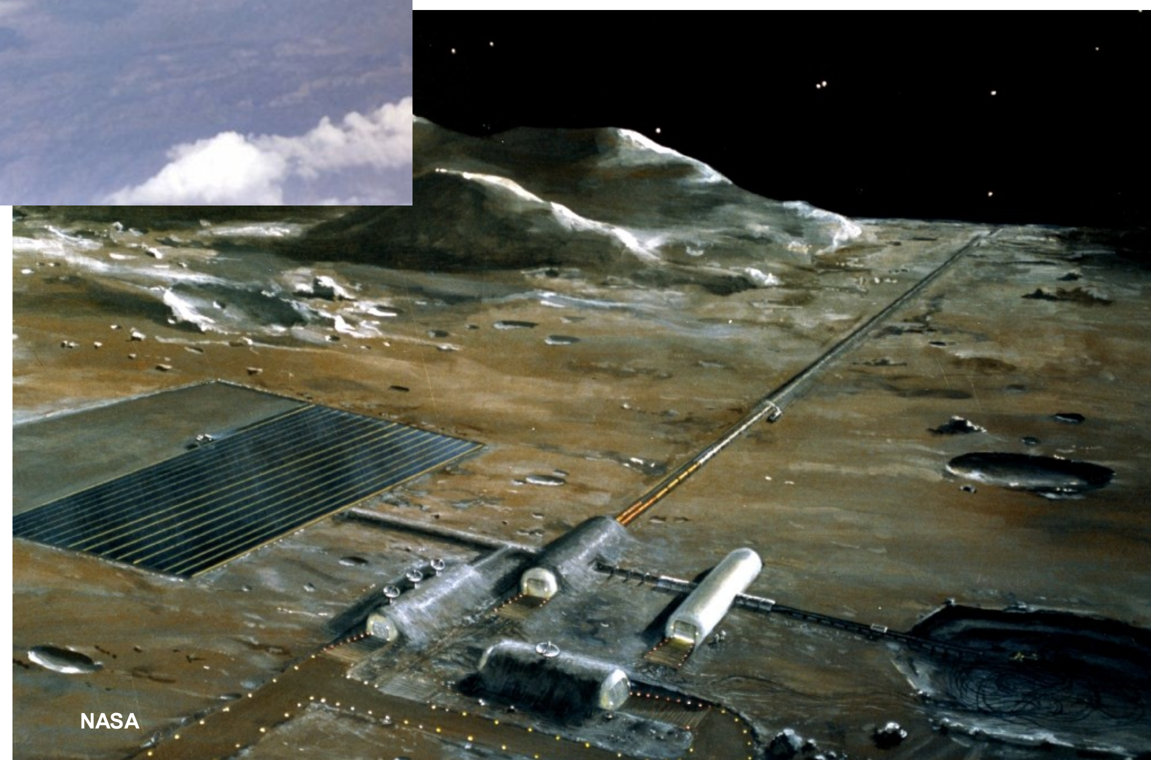
After Sonter, (1998)

New Ways to Achieve a Stable Orbit.

- **Need to Reduce Lifting Costs by Heavy Rockets: Present Cost is about $10,000 per Pound of Payload into Stable Orbit.**
- **Scram-Jet Space Planes, Lunar Catapults, etc. being Evaluated.**
- **Other Approaches Available but Untested.**
- **Favorable Science and Engineering Environments Present in Various Countries Interested in Space…China, India, Russia, etc.**
- **All Efforts Requires Political Will and the Funds to Support Them.**

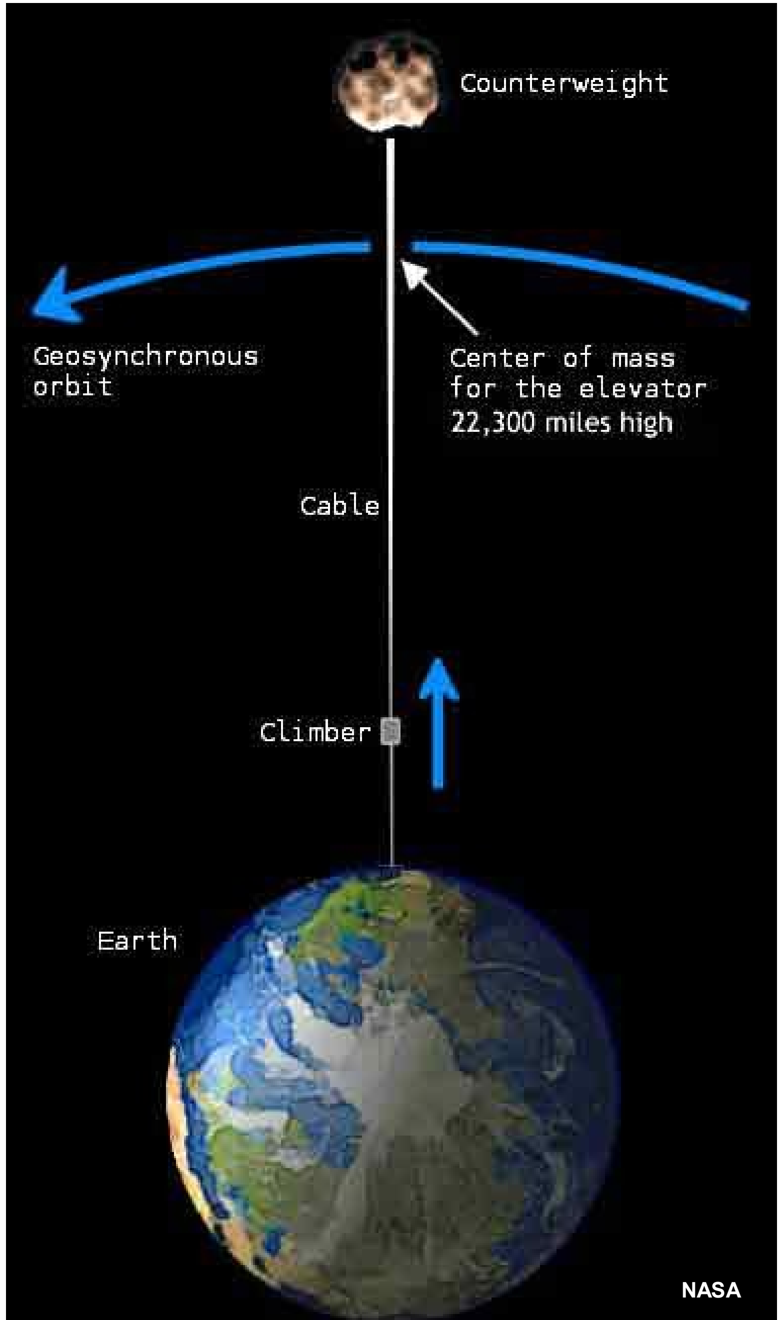
Orbital Achievement with Payloads

Lunar Catapults for Return Flight Carrying Products Back to Earth



Leading the List: The "Space Elevator"

- The "Space Elevator"
  - Conferences, including Boeing, Lockheed, Microsoft, etc.
  - Carbon nanotube technology has lead to stronger materials that are strong and flexible enough for the elevator's requirements.
  - Nuclear power will be utilized to power the electric motors.

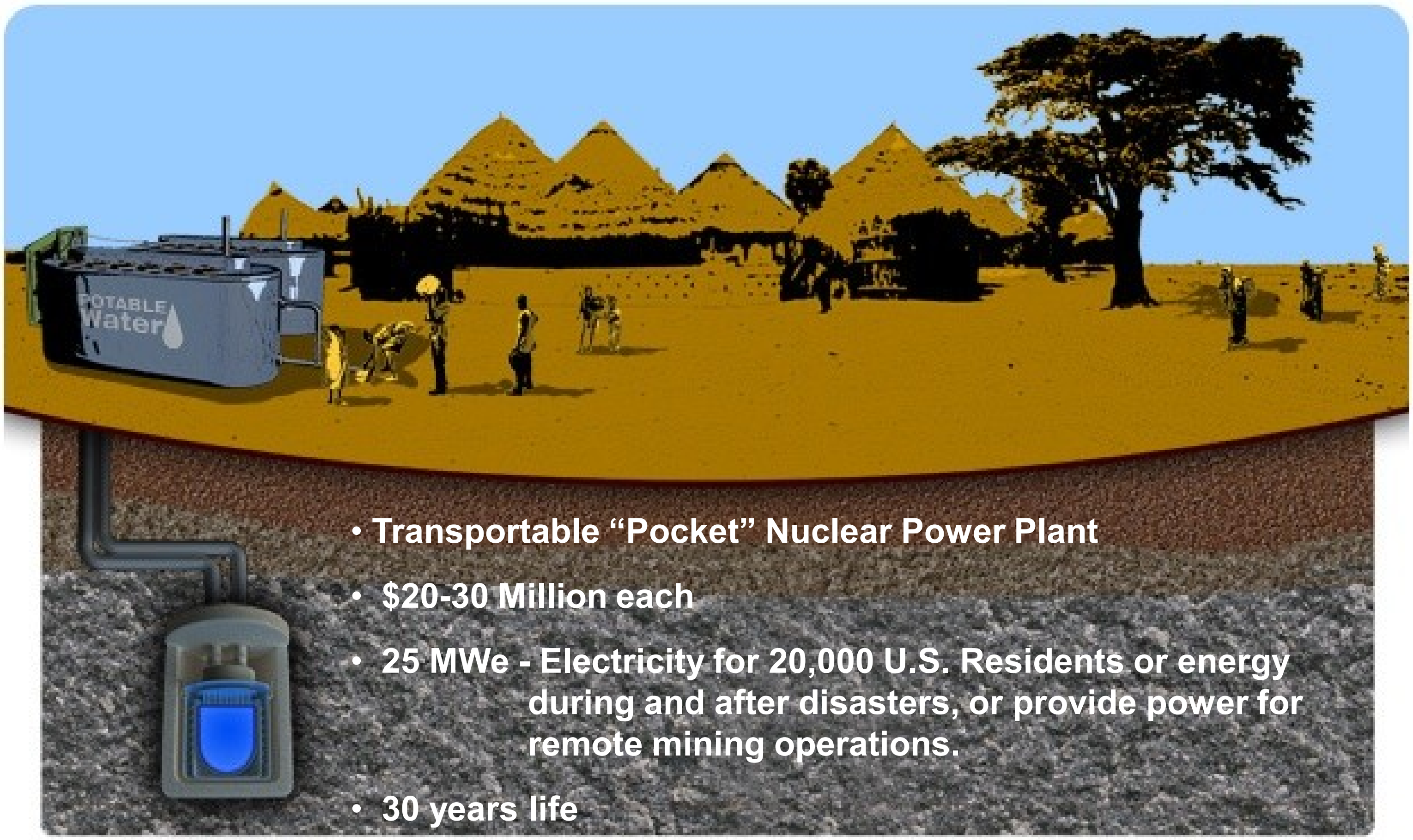

Counterweight
Geosynchronous orbit
Center of mass for the elevator 22,300 miles high
Cable
Climber
Earth
NASA


NASA

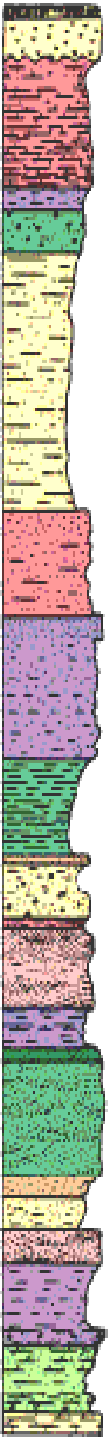
Direct Benefit to Date?

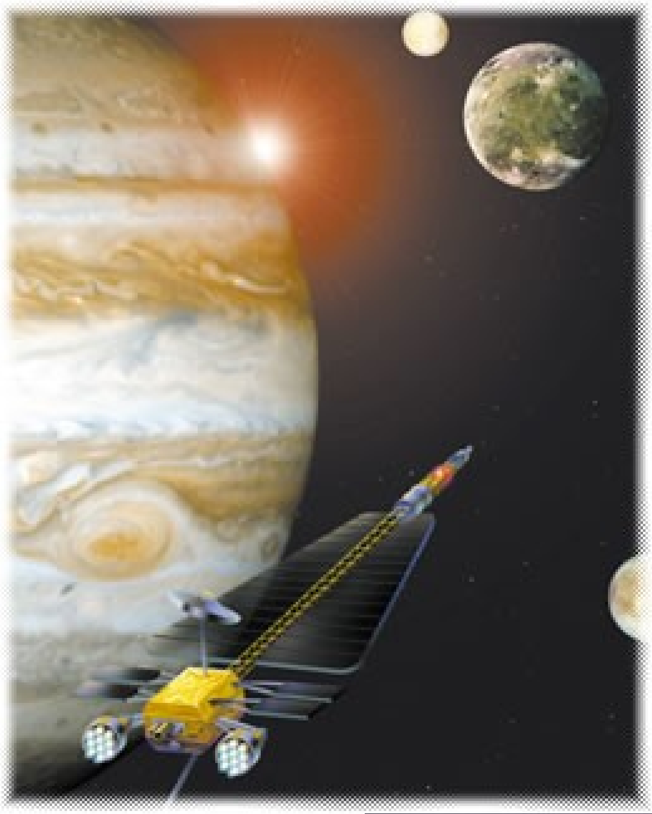
Earth-Based Spin Off from Space Research

- **Best Example: Hyperion Power Generation, Inc.**




NASA





Into Space or ?

or ?

xxx