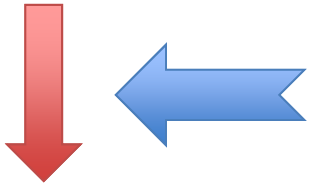
Science Goal and Mission Plan for the Future Lunar Exploration Discussed in Japan

Makiko Ohtake, **Masaki Fujimoto, and Hisashi Otake**
(Institute of Space and Astronautical Science,
Japan Aerospace Exploration Agency)

Procedure of listing up mission targets

1. Progress of recent lunar science for understanding lunar origin and evolution

2. Remaining major scientific issues

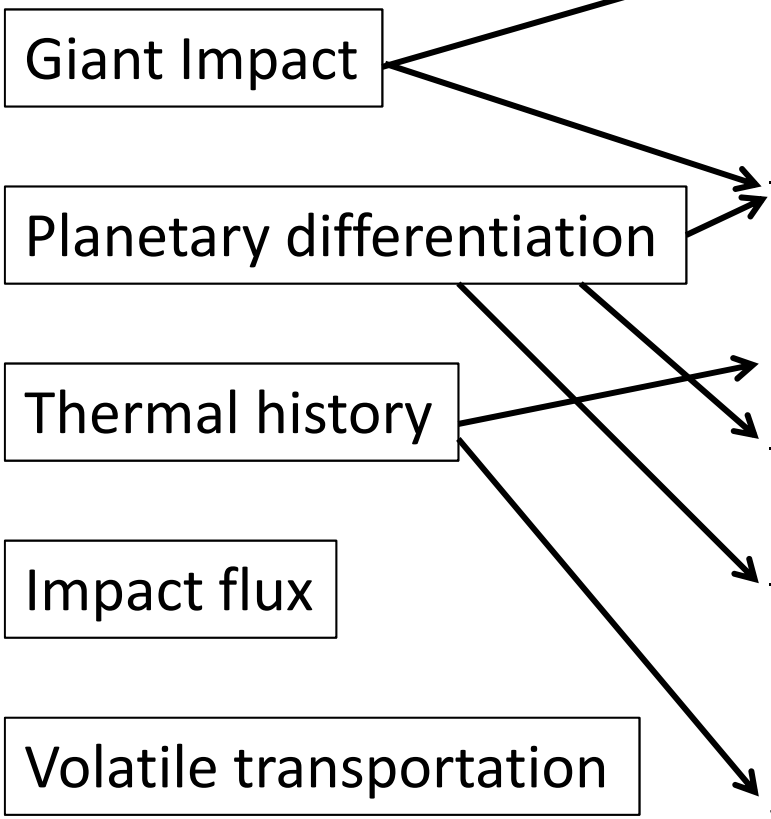


3. Possible mission targets to address each issue

4. Mission schemes for each target for future human and robotic exploration

5. List up of specific investigation sites

1. Progress of lunar science for understanding lunar origin and evolution



Recent progress

Evidence of giant impact (magma ocean)
- -Pure anorthosite crust (Ohtake et al., 2009)
- -Core dynamo, molten deep mantle (Takahashi et al., 2014)

Composition of crust/mantle (Harada et al., 2014)
- -Olivine mantle ejecta (Yamamoto et al., 2010)
- -Pyroxene mantle exposure (Ohtake et al., 2014)
- -Distribution of radioactive element

Solidification of magma ocean (Kobayashi et al., 2013)
- -Asymmetric solidification (from far side) (Ohtake et al., 2012)

Origin of dichotomy
- -Asymmetric solidification
- -Dichotomy of basin structure (Namiki et al., 2009; Kamata et al., 2014)
- -Evidence of a largest Impact (Nakamura et al., 2010)

Volcanic history/diversity
- -Young volcanism (Morota et al., 2011)
- -Silicic dome/ hole/ irregular mare patches

(Jolliff et al., 2011; Haruyama et al., 2009; Braden et al., 2014)

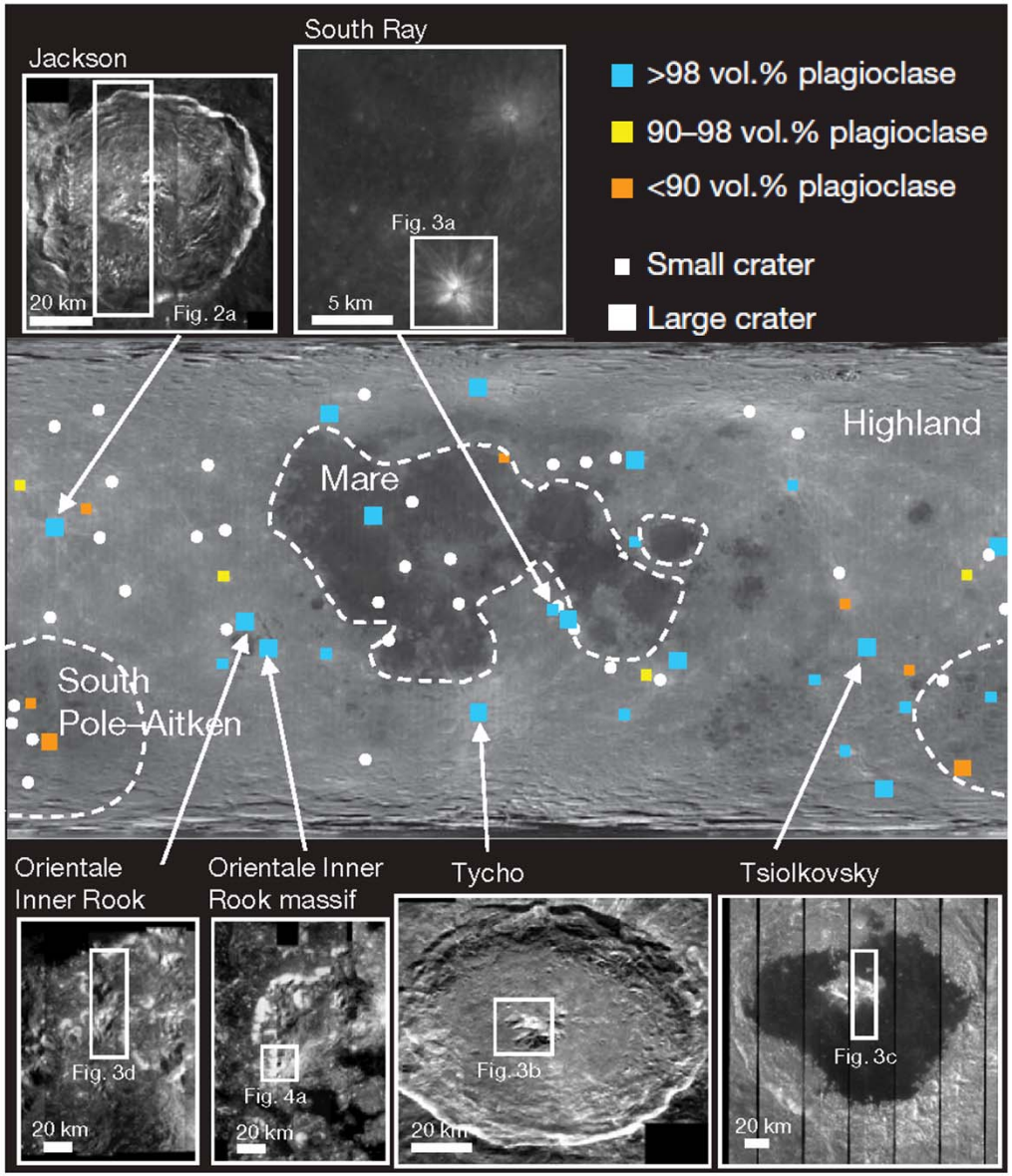
Global presence of Purest anorthosite (PAN)

-Composition of the PAN (>98 vol.% plagioclase) is significantly higher than previous estimates of 82–92 vol.%, providing a valuable constraint on models of lunar magma ocean evolution

-Global (ubiquitous) distribution and wide depth range (4-30 km) of the purest anorthosite suggesting global and huge amount of magma (magma ocean)

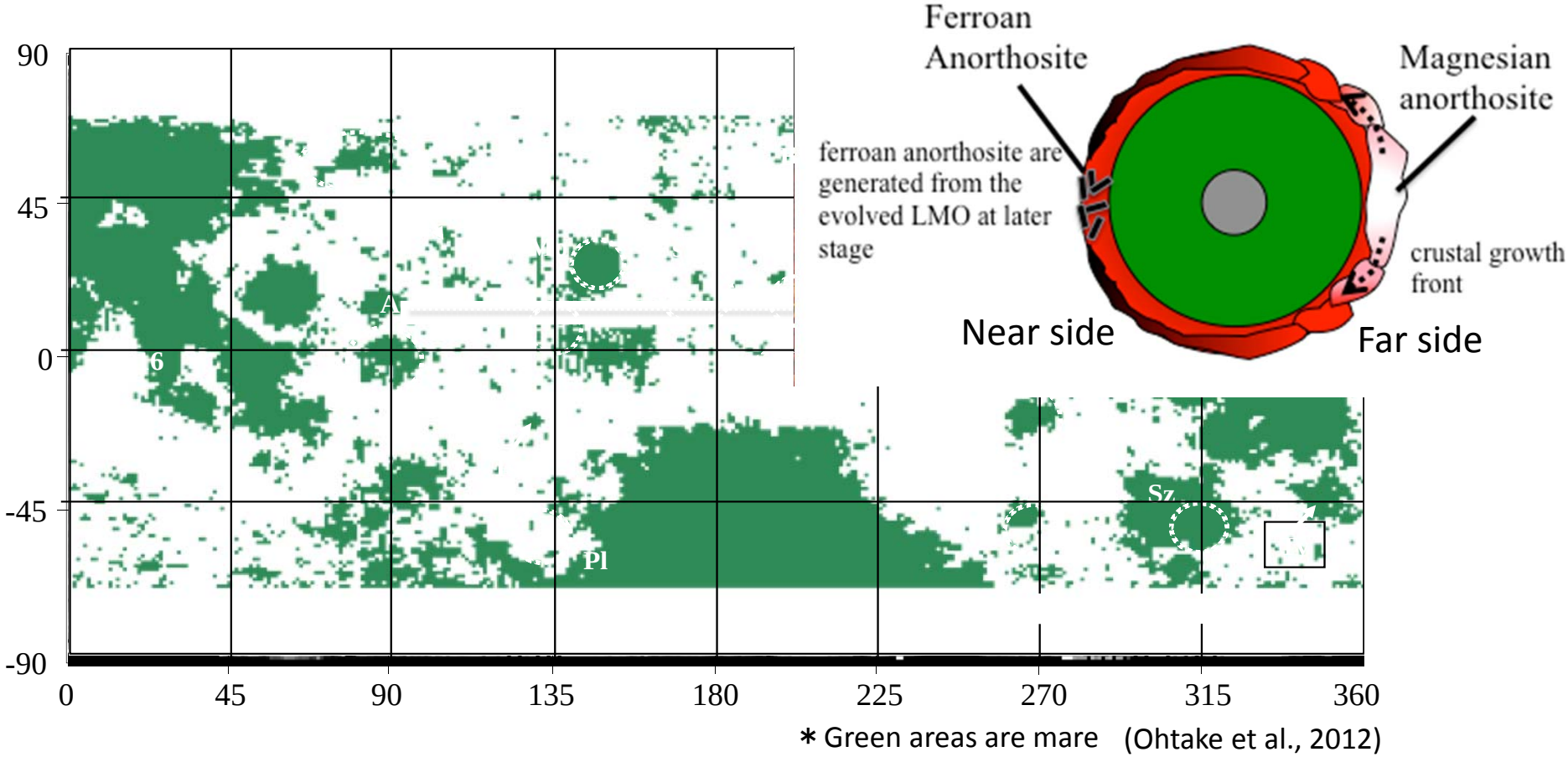
2. Remaining scientific issues

Vertical compositional change with depth of the crust and mantle.



(Ohtake et al., 2009)

Mg/Fe ratio (solidification order) of the lunar crust



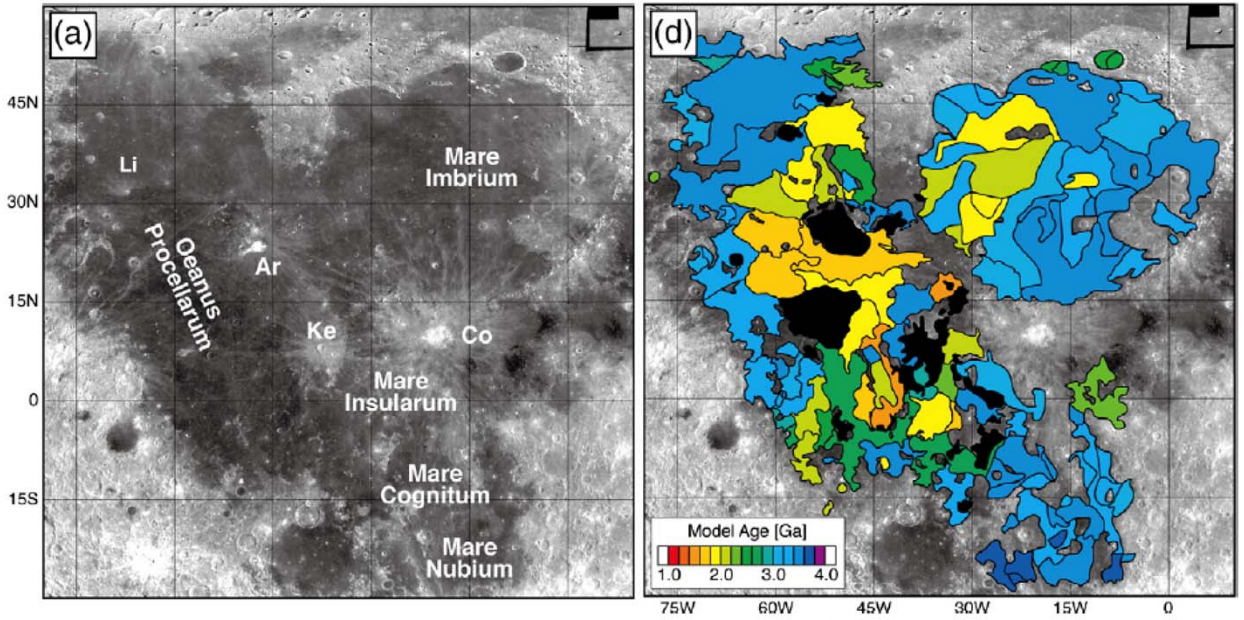
* Green areas are mare (Ohtake et al., 2012)

-Higher Mg/Fe ratio at the far side indicates asymmetric solidification of the magma ocean from far side to near side

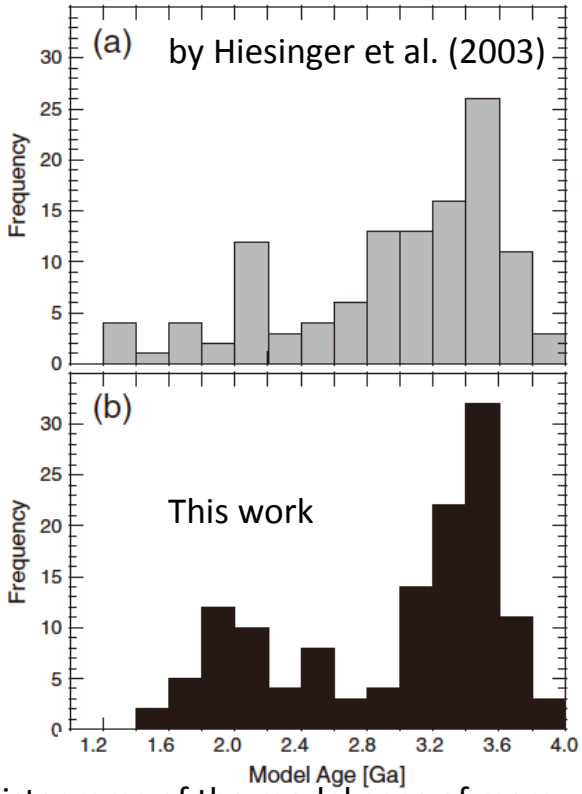
-The lunar dichotomy is directly linked to crystallization of the magma ocean

2. Remaining scientific issues: When and How the MO solidified?

Young mare eruption (until ~1.5 Ga) on the Moon



Blue: old Red: young



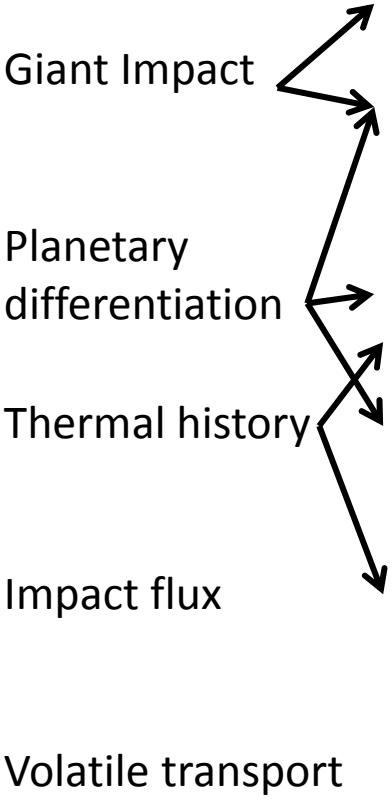
(Morota et al., 2011)

Histograms of the model ages of mare basalts in the Procellarum KREEP Terrane

-<u>Mare volcanism in this region continued until ~1.5 Ga</u>, suggesting that volcanic activity in this region ceased ~1.0 Ga after the magma eruption had globally ceased 2.5–3.0 Ga. <u>Volcanic activity may have peaked 1.8–2.2 Ga ago</u>

2. Remaining scientific issues: Age of the youngest and oldest mare. Variety of volcanic activity.

3. Possible mission targets to address each scientific issue



Recent progress

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Composition of crust/mantle
- -Olivine and Pyroxene mantle
- -Radioactive element

Solidification of magma ocean
- -Asymmetric solidification

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Volcanic history/diversity
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Advantage of human exploration

Proposed Mission targets

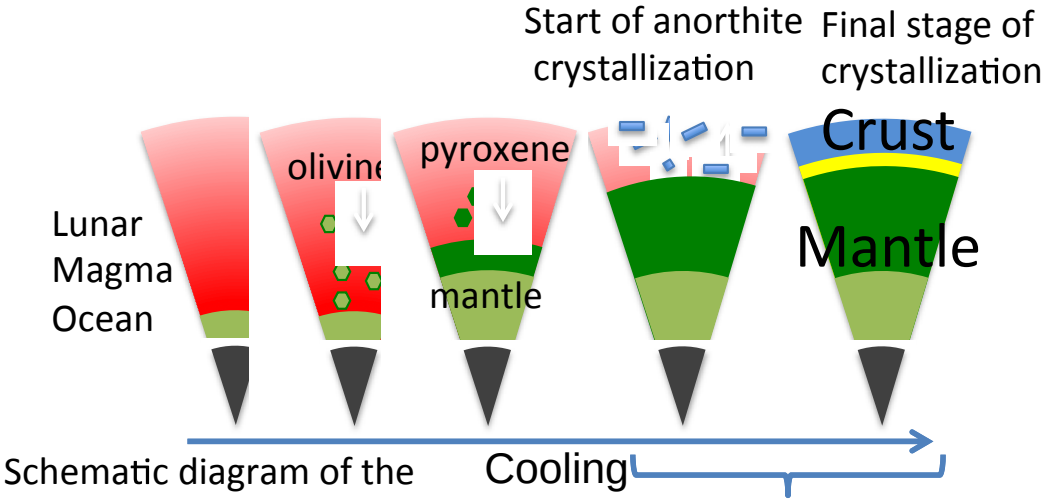
A) Detailed determination of compositional and structural layering of crust and mantle
-Solidification age of magma ocean

B) Age determination of the youngest and the oldest mare material
-Understanding a variety of volcanic activity; composition, age …

C) Age determination of key craters to improve the accuracy of crater chronology and to understand impact flux changes over time

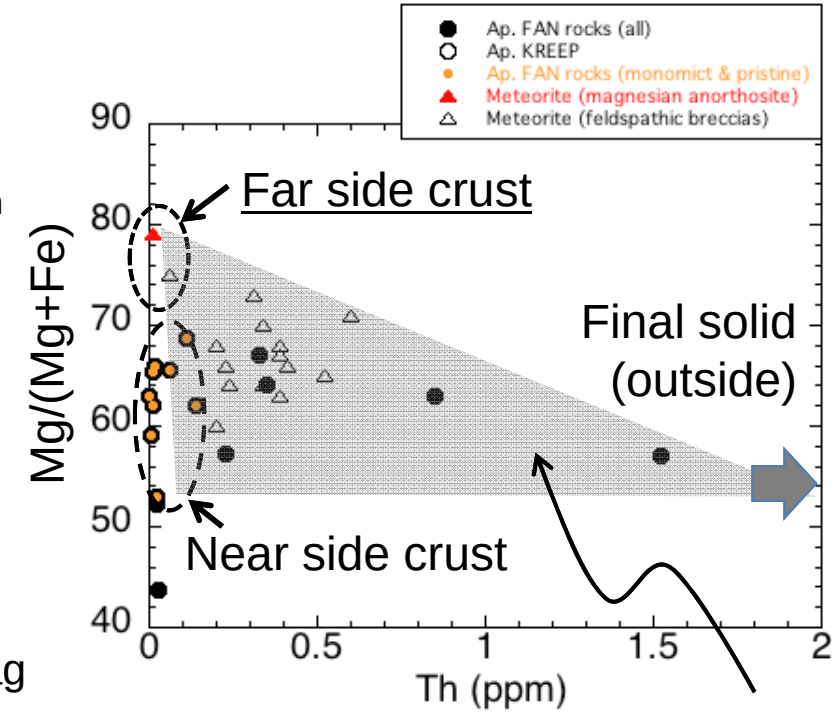
D) Search and sampling of ancient Earth rocks transported to the lunar surface as meteorites to investigate the earliest history of the Earth

A) Detailed determination of compositional and structural layering of the crust and mantle, and solidification age to understand the solidification of the lunar magma ocean and the giant impact process by estimating the bulk composition of the Moon and comparing that to the Earth.



Schematic diagram of the magma ocean solidification

Differentiation during this stag is recorded in highland rocks



Explained by magmatic differentiation and mixing of three component?

4. Mission schemes & 5.List up of specific investigation sites

- Mission scenario: Geologic and geophysical observation and sampling with kilometer-scale spatial intervals of the crust and mantle. Jackson, Orientale, South Pole-Aitken, Tycho, and recently discovered olivine exposure sites are informative.
- The human capability to select the most suitable sampling and seismometer installation site is important for this mission.

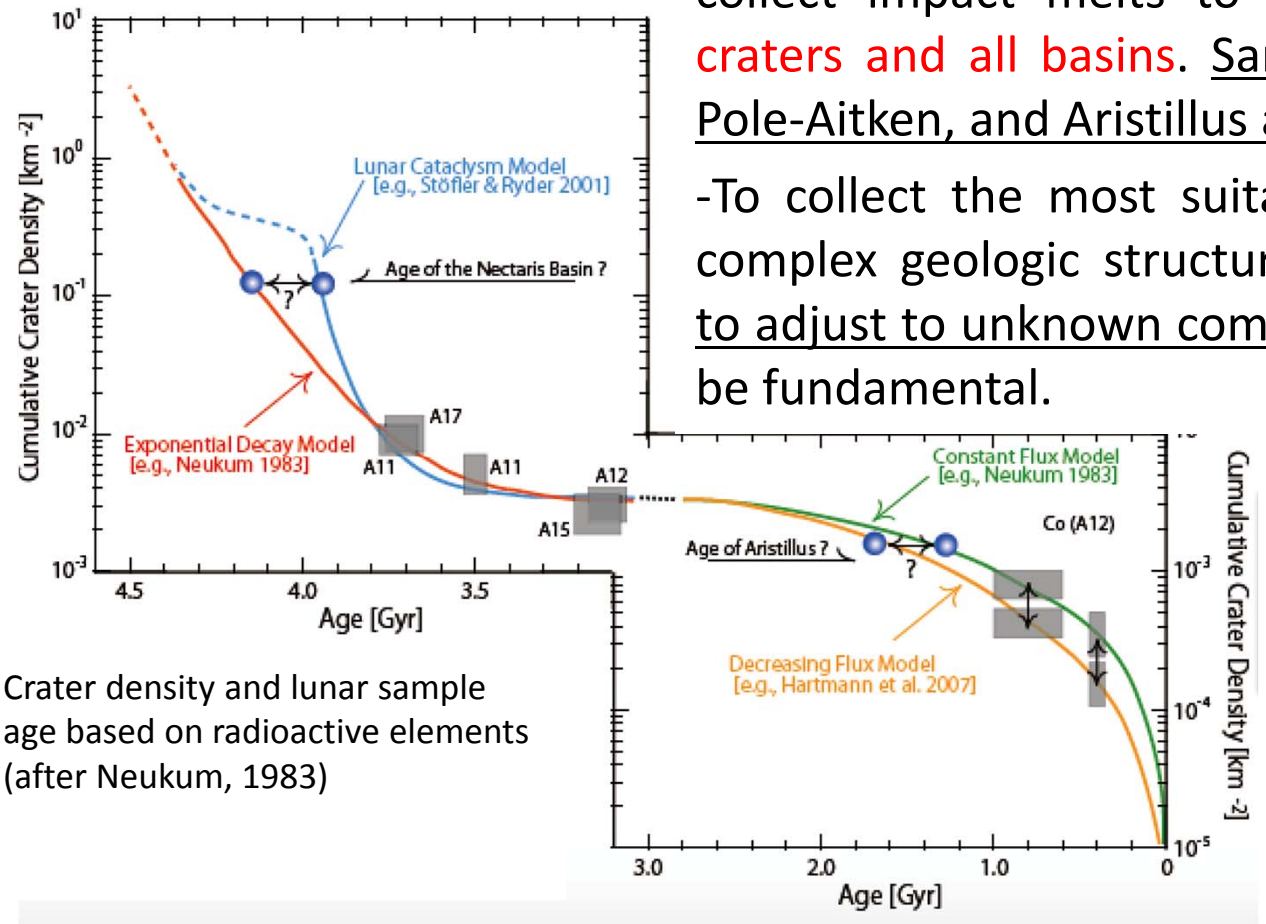
B) Craters on the lunar surface are cumulates of information of impact flux changes since formation of our solar system. However, crater chronology still contains large ambiguity

-Age determination of key craters and basins to improve the accuracy of crater chronology is important to understand impact flux changes

4. Mission schemes & 5.List up specific investigation sites

-Mission scenario: Explore all of the major basins and collect impact melts to determine the age of key craters and all basins. Samples from Nectaris, South Pole-Aitken, and Aristillus are particularly critical.

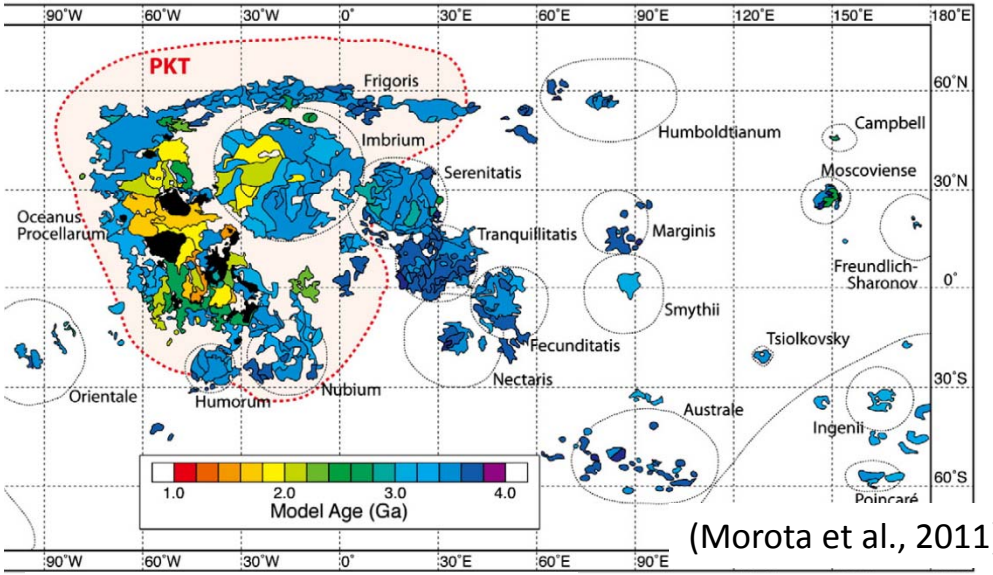
-To collect the most suitable samples from old and complex geologic structure basins, human capability to adjust to unknown complex geologic conditions will be fundamental.



Crater density and lunar sample age based on radioactive elements (after Neukum, 1983)

C) Age determination of the youngest and the oldest mare material are important for understanding the thermal history of the Moon.

-Understanding a variety of volcanic activity, including newly recognized features, such as silicic domes, scoria cones, and holes to obtain eruption information, composition, and age.

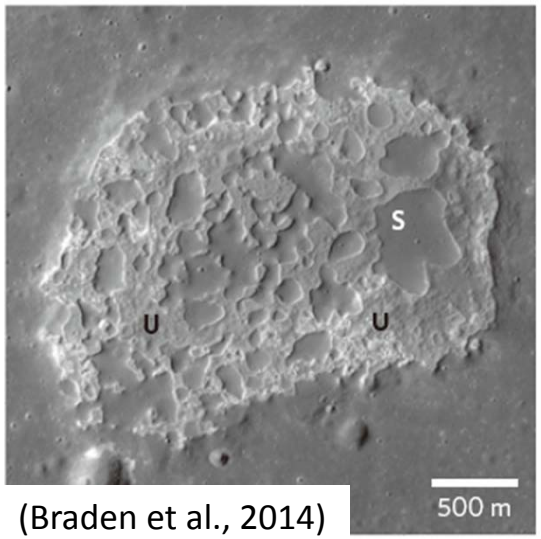


(Morota et al., 2011)

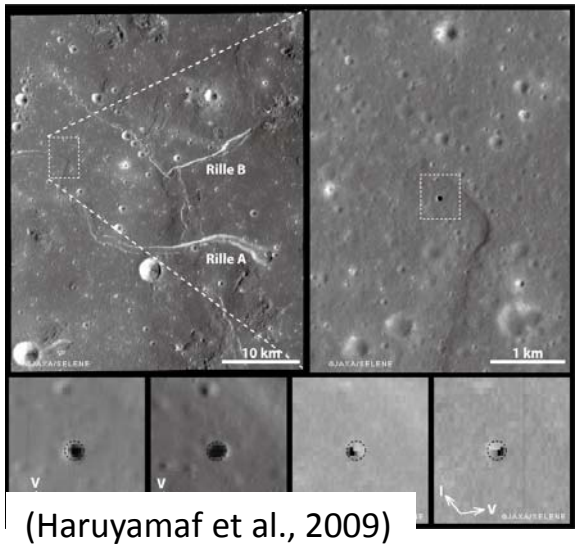
4. Mission schemes & 5.List up specific investigation sites

-Mission scenario: Geologic observation and sampling of youngest/oldest mare, and sampling of as many volcanic features as possible

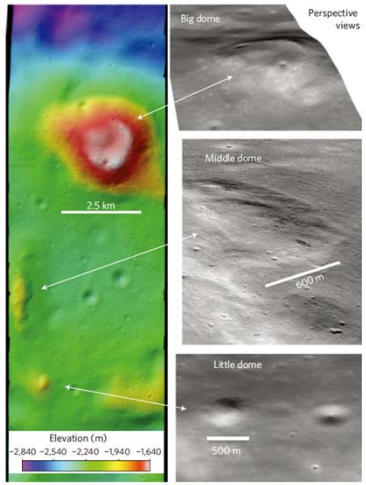
-The human ability to detect possible unknown volcanic structures will be fundamental.



(Braden et al., 2014)

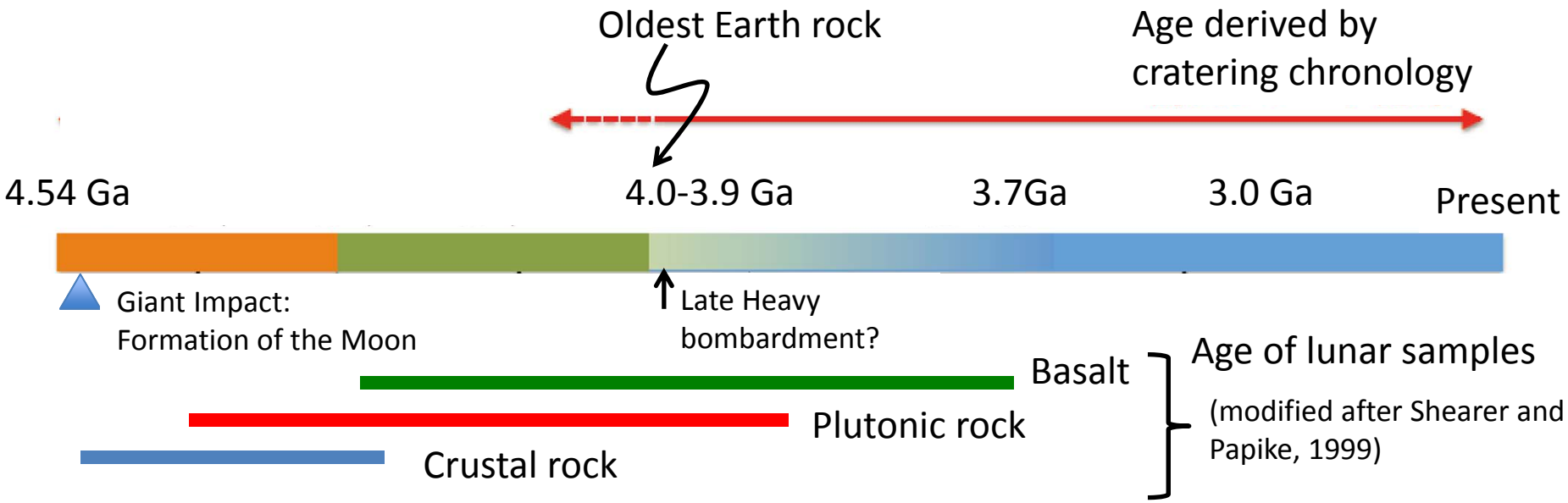


(Haruyamaf et al., 2009)



(Jolliff et al., 2011)

D) Search and sampling of ancient Earth rocks transported to the lunar surface as meteorites from the Earth to investigate the earliest history of the Earth are extremely important for understanding the early evolution of the Earth because rocks of that age were recycled and not found on the Earth



4. Mission schemes & 5.List up specific investigation sites

-Mission scenario: This mission requires continuously surveying the Earth-like rocks on the lunar surface and within the drilled core.

-This mission requires the man's ability to perform complex operations such as drilling of the lunar surface under unknown conditions.

Summary of the proposed investigation sites

Near side

Far side

Marius hills

Aristillus

Ina

Hole

Tycho

Nectaris

Silicic dome

Jackson

Orientale

South Pole-Aitken

Pyroclastic deposit

*Only example target sites are presented

Geophysical observation of the lunar interior
Global search of Earth meteorite

-Search and sampling of ancient Earth rocks transported to the lunar surface as meteorites from the Earth to investigate the earliest history of the Earth. Such samples are extremely important for understanding the early evolution of the Earth because rocks of that age were recycled and not found on the Earth.