Advances in Lunar Science and Lunar Development from the Lunar Mission "KAGUYA"

June 2015


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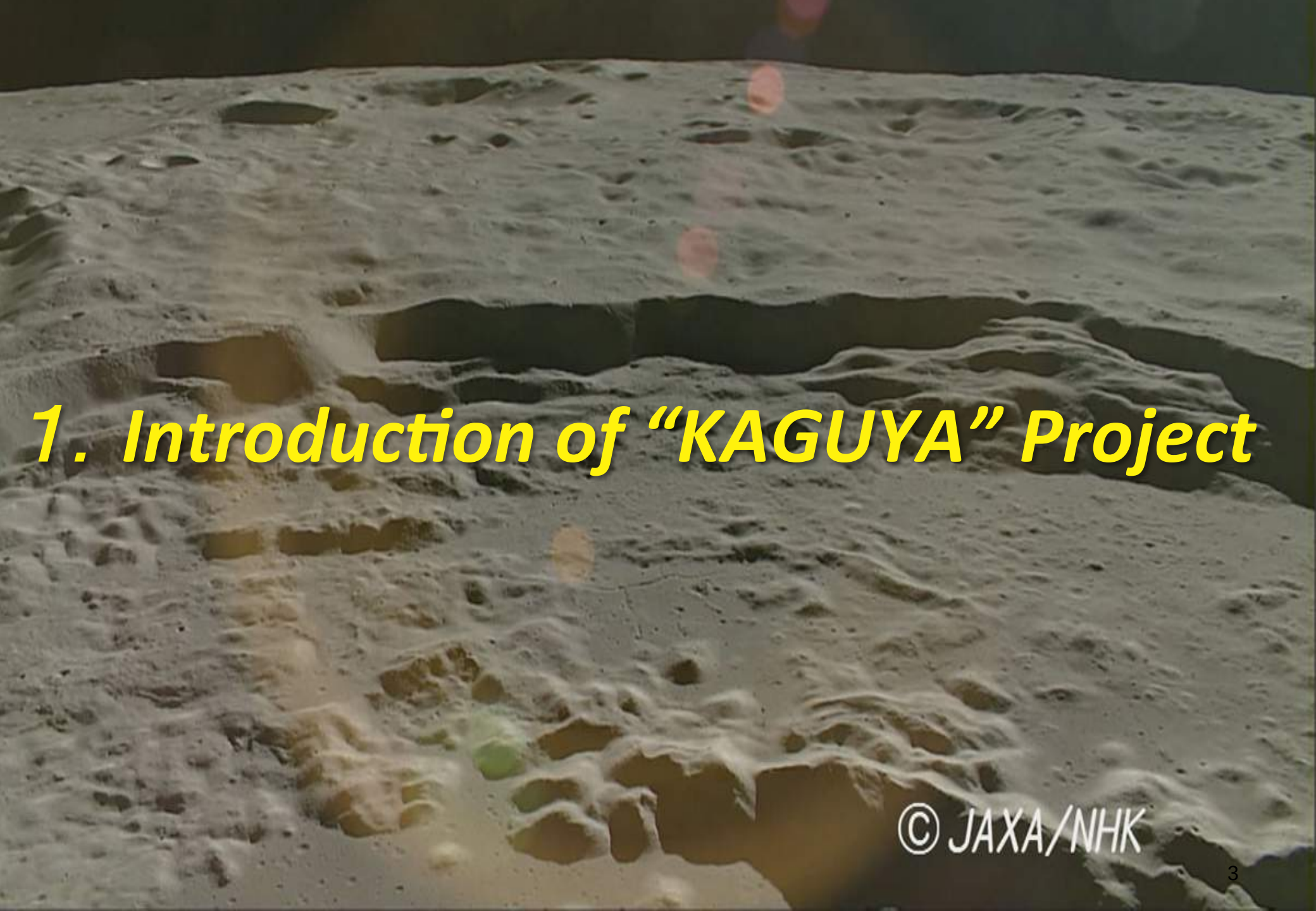
1. Introduction of “KAGUYA” Project
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Position of KAGUYA Project in the History of Lunar Exploration

1960 1970 1980 1990 2000 2010

First Unmanned Exploration
(Orbiter, Hard Landing)

First Unmanned Soft Landing

Manned Exploration

First Sample Return

First manned landing on the Moon attracted global attention.

First lunar exploration boom

A competition between the United States and the Soviet Union.
Lunar science was advanced as a result.

Blank period

Hiten, Hagoromo(Orbiter)

Clementine(Orbiter)

Lunar Prospector(Orbiter)

Smart 1(Orbiter)

The largest mission in the second boom

KAGUYA(Orbiter)

Chang'e1(Orbiter)

Chandrayaan1
(Orbiter)

LRO/LCROSS
(Orbiter, Controlled Crash)

Chang'e2(Orbiter)

GRAIL(Orbiter)

LADEE(Orbiter)
Chang'e3(Lander)

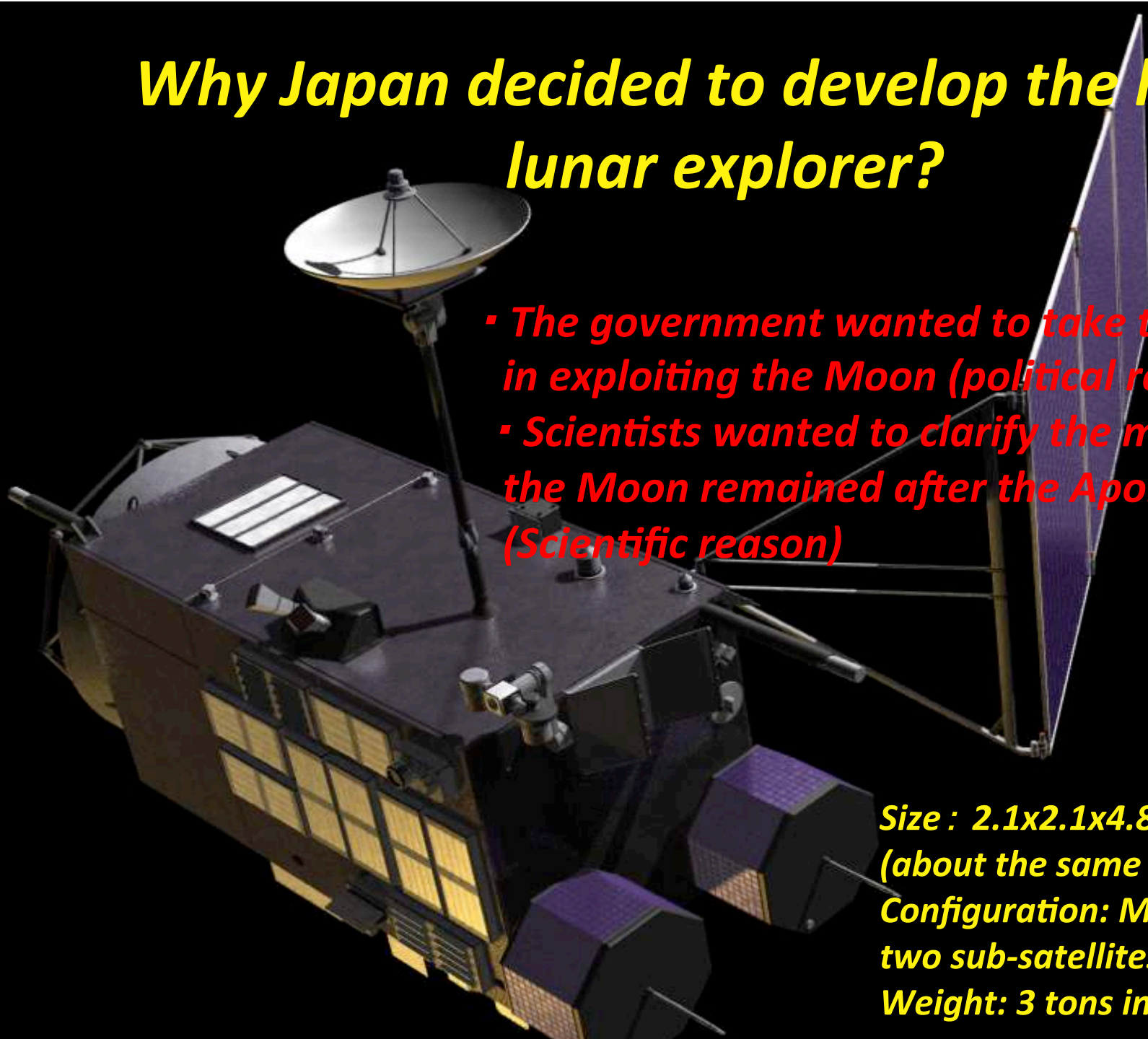
Chang'e5-T1
(Orbiter, Round trip)

Chang'e5
(Sample return)

Second lunar exploration boom

New players, Japan, Europe, China, and India, and USA with the aim of practical use of the Moon and lunar science

Why Japan decided to develop the large lunar explorer?



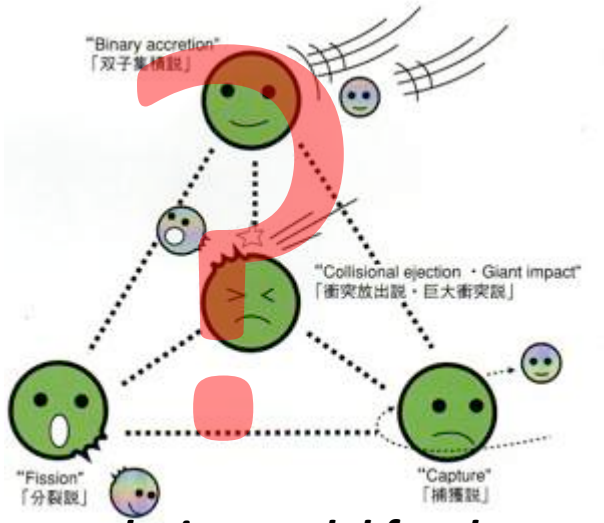
- The government wanted to take the initiative in exploiting the Moon (political reason).
- Scientists wanted to clarify the mysteries of the Moon remained after the Apollo project (Scientific reason)

Size : 2.1x2.1x4.8m
(about the same size of minibus)
Configuration: Main satellite and two sub-satellites
Weight: 3 tons in approx.

"KAGUYA" Mission Objectives

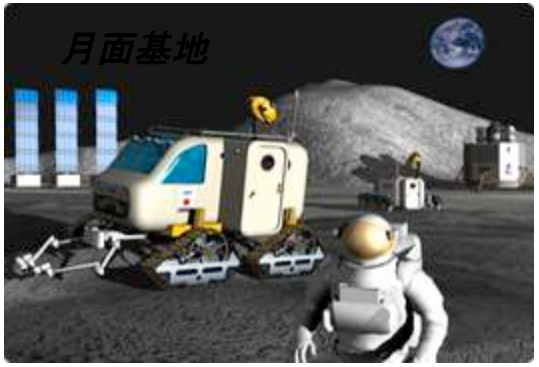
1. *To study the origin and evolution of the Moon.*

2. *To get information for manned lunar activities in the near future.*



No conclusive model for the birth of the Moon

In addition, the mission was aimed at acquiring the technologies (lunar orbit insertion, orbit control, and controlled hard landing) for the next-step lunar exploration.



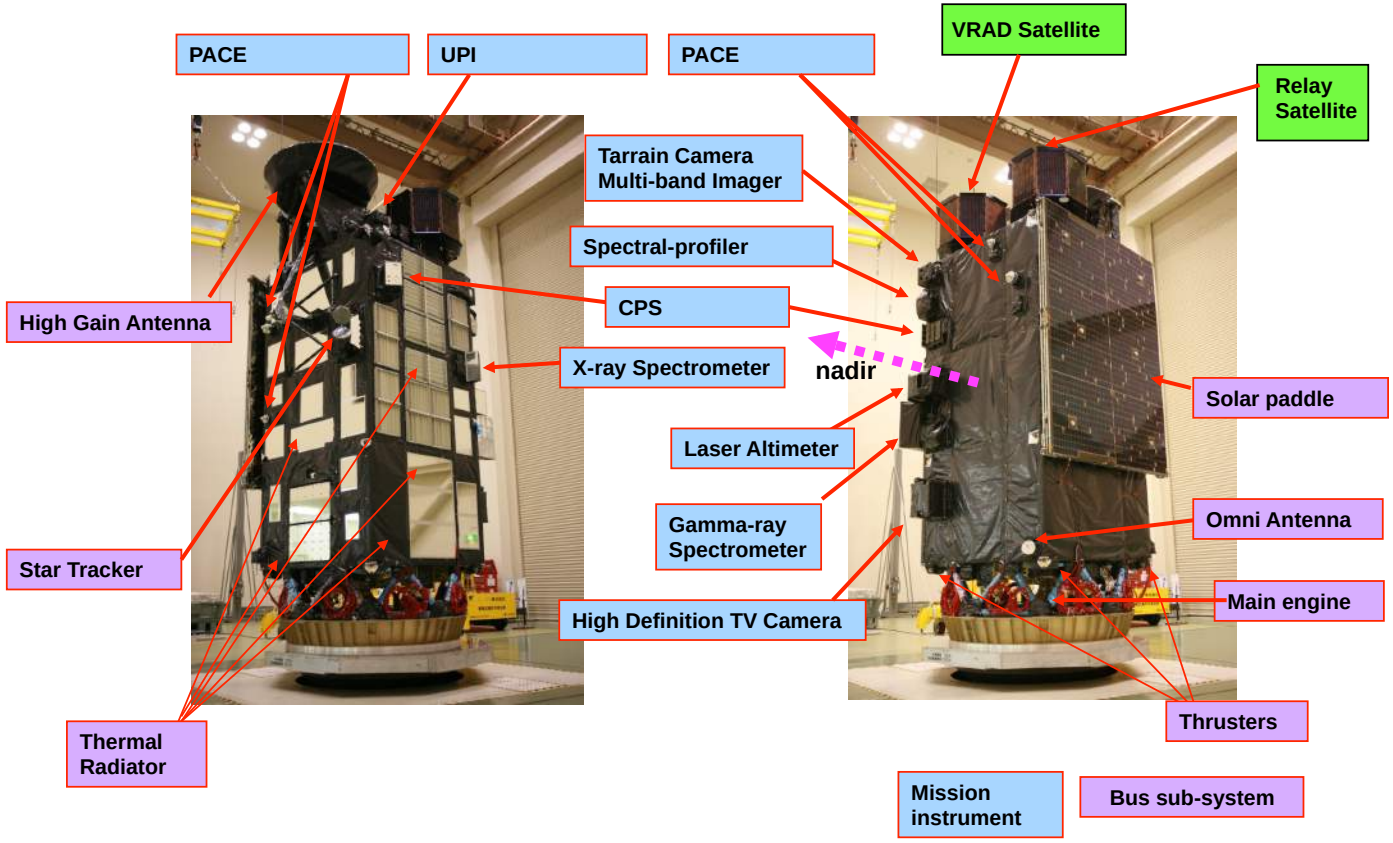
Manned lunar base

Onboard Scientific Instruments

Surface materials and composition・・・4 instruments
Topographical and geological structure ・・・3 instruments
Gravity field・・・2 instruments
Environment (including magnetic field)・・・5 instruments
High-density TV・・・1 instrument

More than 200 researchers participated in development and operation of the scientific instruments.

Called as a "Festival Mission" from both good and bad aspects.



History of "KAGUYA"

1995-1998 — *Preparation/Proposal*

Joint proposal was generated by ISAS and NASDA.

1999-2004 — *Development of Satellite and Scientific Instruments*











2005-2006 — *Assembly /Test*


2007-2009 — *Launch/ Operation*

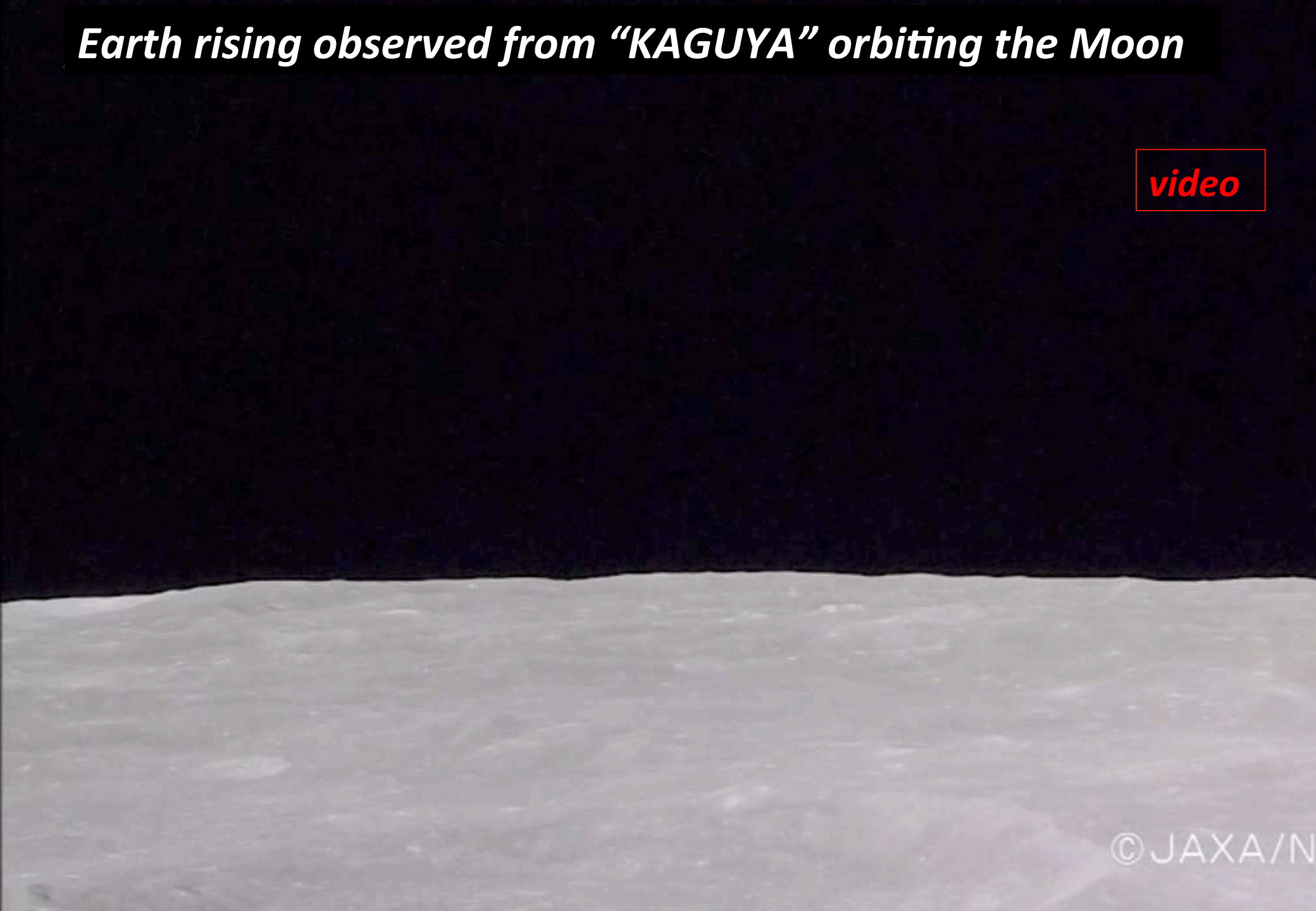


video

Launch

It took 14 years from the proposal to the end of the mission. Many Japanese and foreign scientist are still working for "KAGUYA" data analysis.

Earth rising observed from "KAGUYA" orbiting the Moon




2. Advances in
Lunar Science
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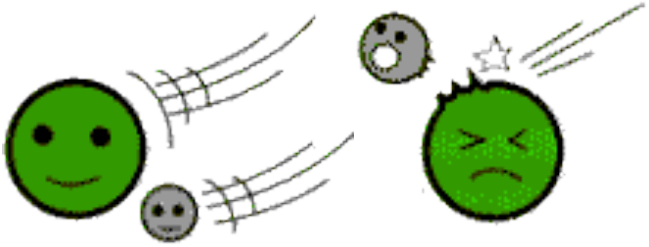
“KAGUYA” Contribution to “Origin of the Moon”



Binary accretion	Fission	Capture	Giant impact
△	○	△	◎

Mechanically feasible?
Global-scale magma ocean?
Material similarity?
Core size?

Studied by “KAGUYA” so far.

Under analysis. A certain conclusion will be obtained.

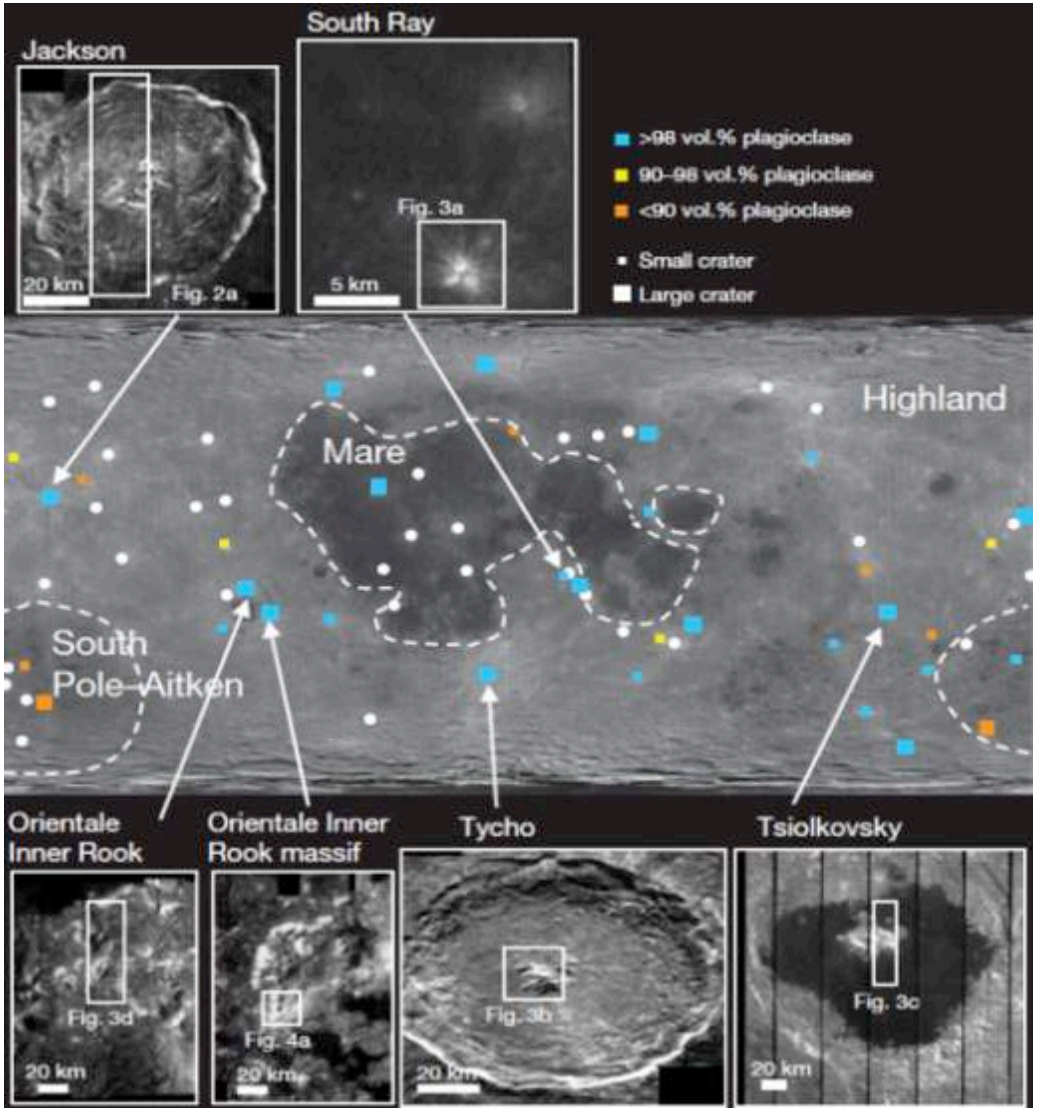
Under analysis. Some conclusion will be obtained. But, will be finally confirmed by another mission to study the internal structure.

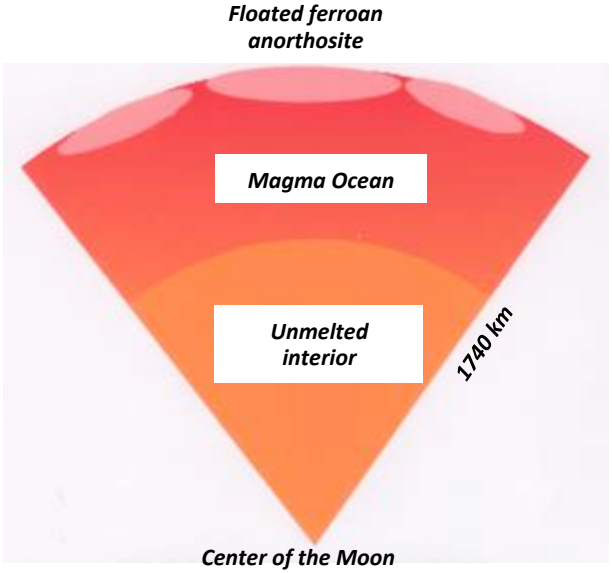
Evidence obtained.

Source Material	Internal Structure	Global-scale Magma Ocean

3 major keys to conclude the origin of the Moon.

Evidence for Global-scale Magma Ocean





Ferroan anorthosite layer floated on the magma ocean

Composition of lunar crust was studied by Multiband Imager. The global distribution of rocks of high plagioclase abundance was confirmed. It is a direct evidence for the global-scale magma ocean, suggesting that the giant impact model is plausible (Ohtake et al., Nature, 2009)

"KAGUYA" Contribution to "Evolution of the Moon"

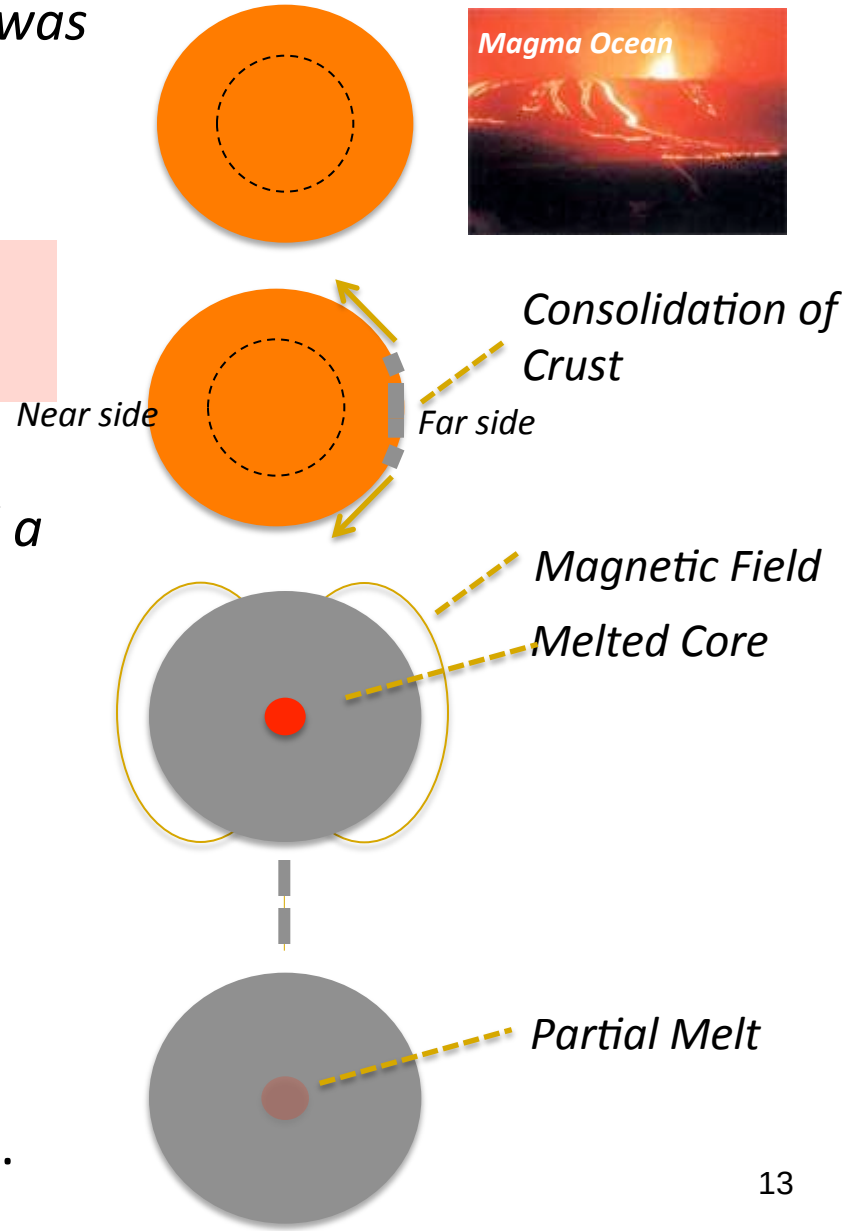
When the Moon was born, the temperature was so high that the surface was globally melted (global-scale magma ocean).

Then, the crust was formed from the far side to the near side.

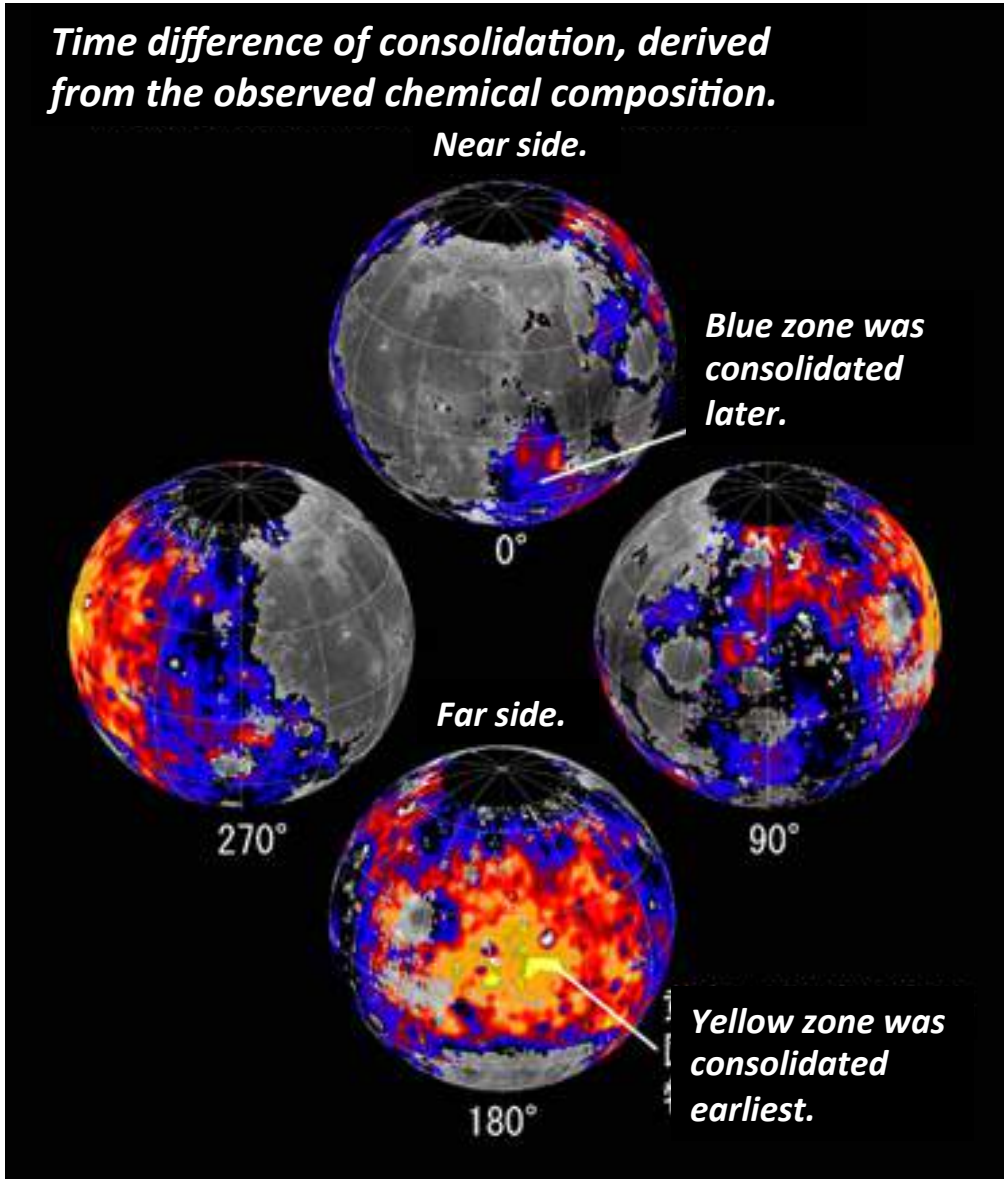
In the initial stage of evolution, there existed a melted metal core which generated a large scale dipole magnetic field.

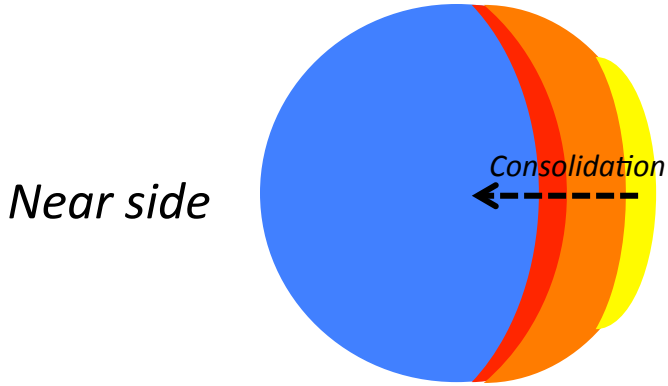
The cooling rate of the Moon's far side was slower than previously considered. Volcanic activities existed until more recently

There is a a low-viscosity layer at the core–mantle boundary, suggesting partial melting.



Formation Process of Lunar Crust





Sequence of Consolidation of Magma Ocean (Model)

When the magma is crystallized, the ratio Mg/Fe gets smaller in the latter phase. The spectral Profiler identified the ratio Mg/Fe. It was found that the far side crust was formed earlier than that of the near side. From the oldest, yellow, orange, red, and blue zones are shown in the figure (Ohtake et al., Nature Geoscience, 2012).

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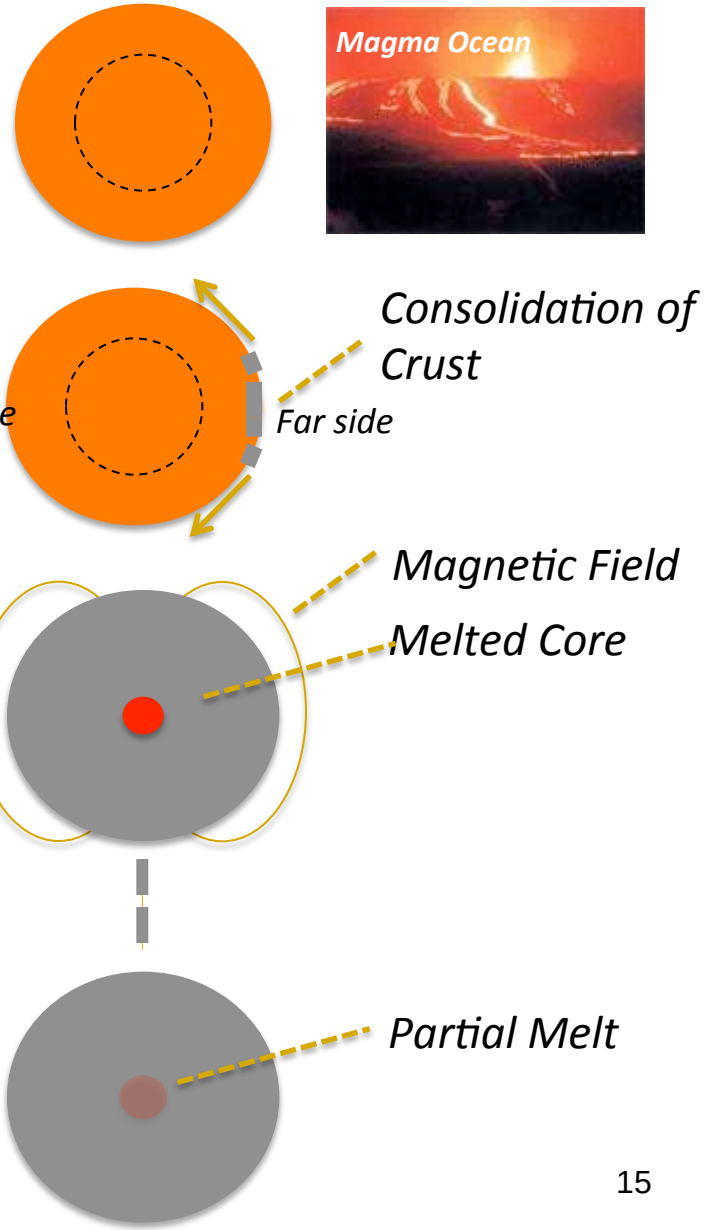
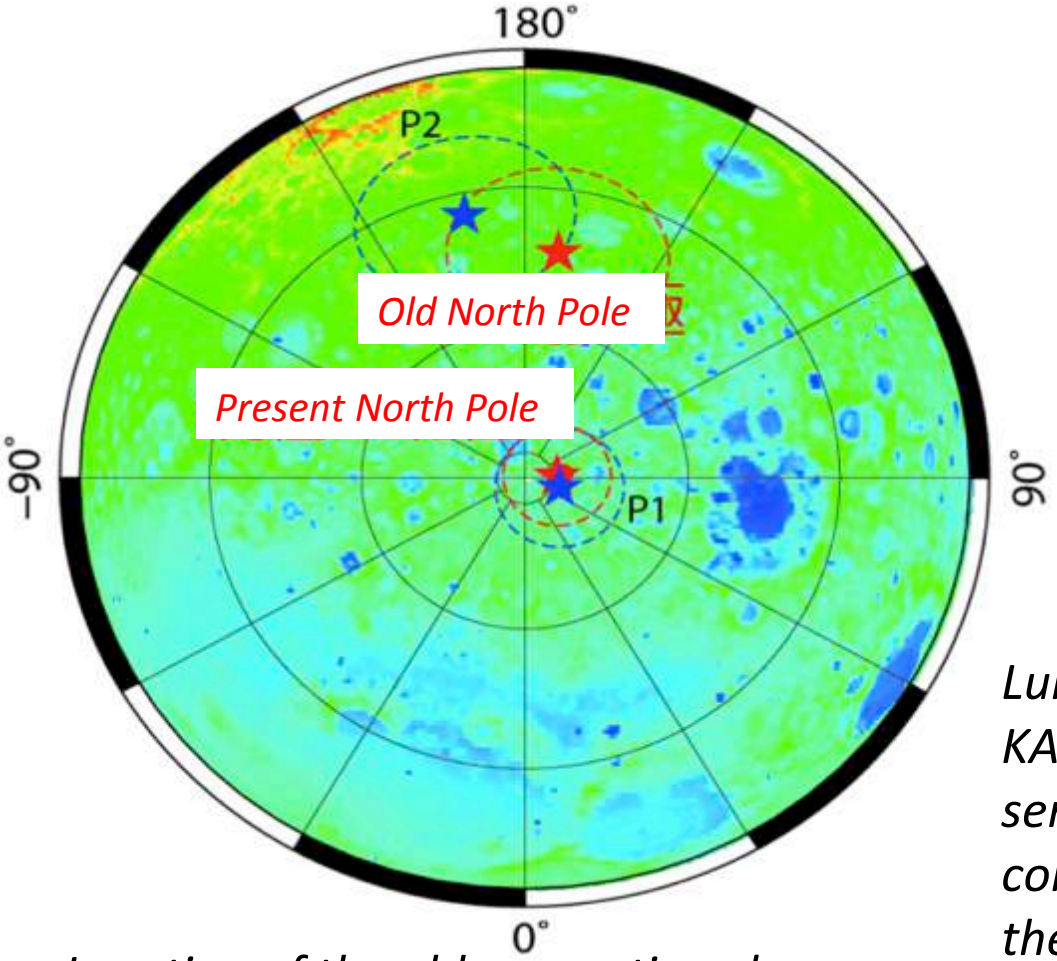


Lunar Magnetic field Structure in Ancient Time



Location of the old magnetic pole. "KAGUYA" magnetometer data suggests that the old north pole was located at the position indicated by blue star.

Earth's Magnetic Filed (The Geospatial Information Authority of Japan)

Lunar magnetic field was measured by KAGUYA Magnetometer with a high-sensitivity. It was suggested that an active core dynamo, just like the Earth, operated on the Moon in ancient time. It was found that the Moon experienced a polar wander event during its ancient history (Takahashi et al., Nature Geoscience, 2014).

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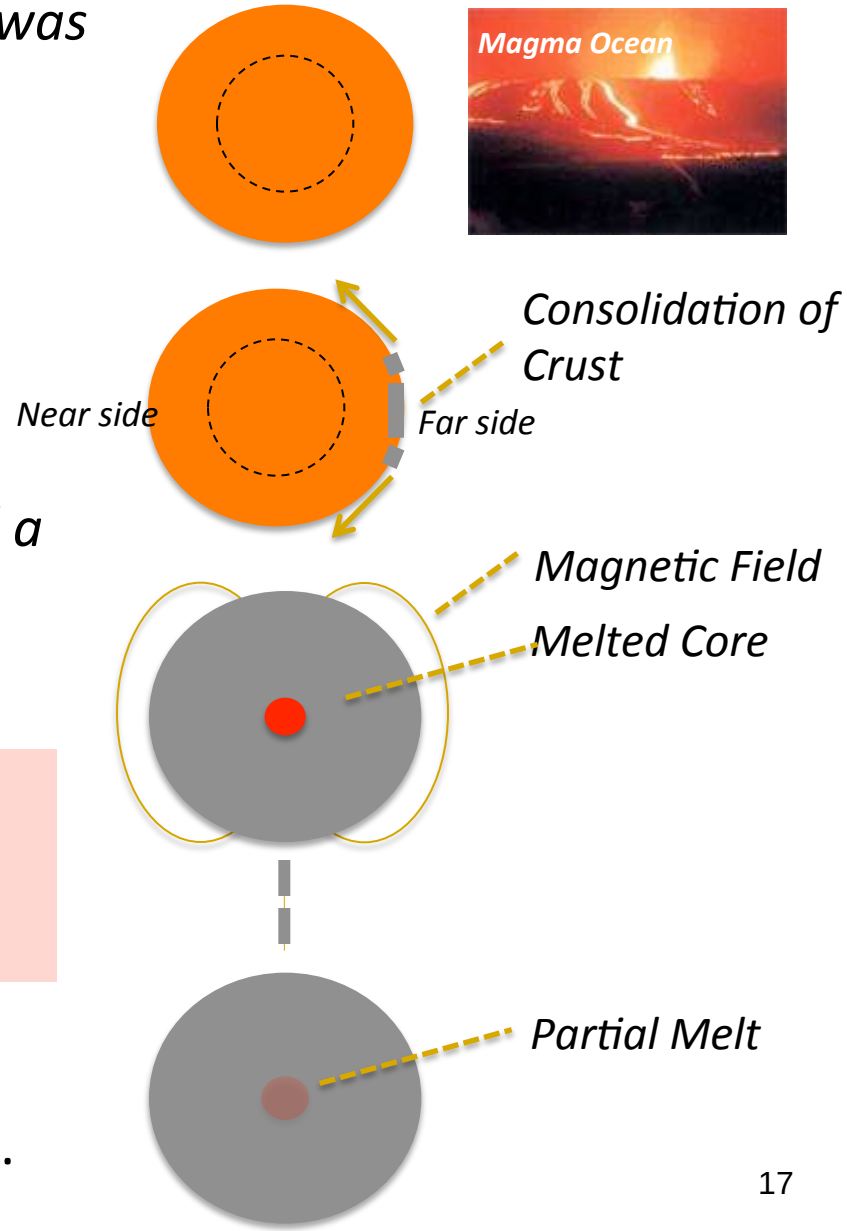
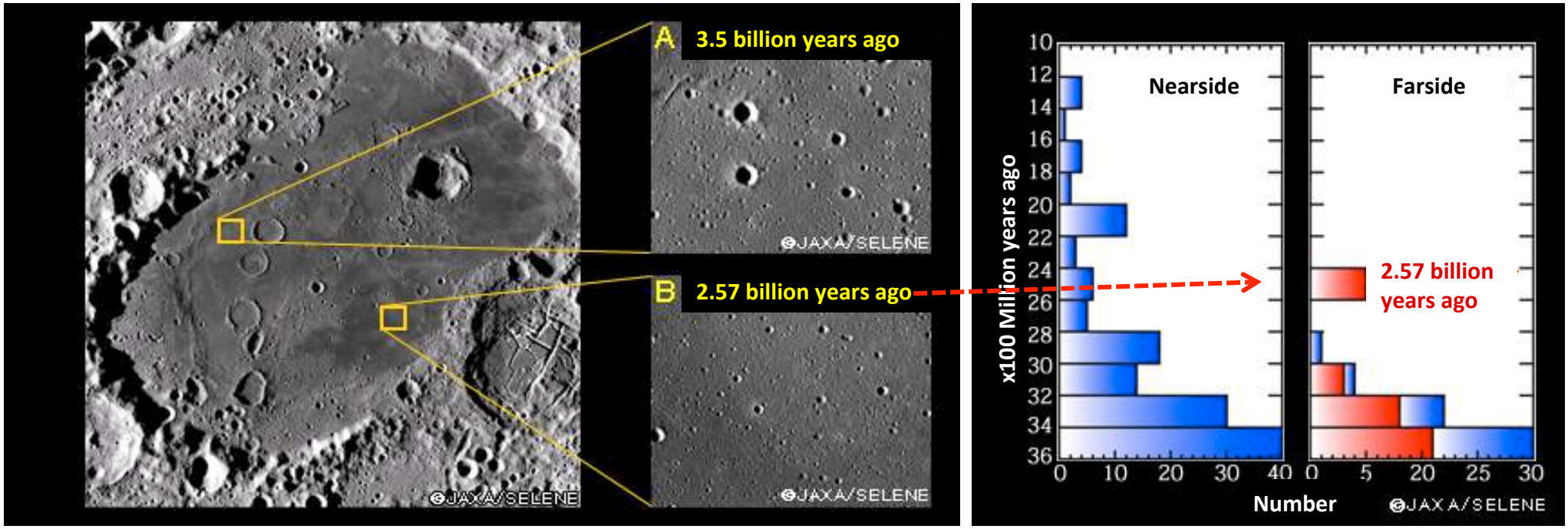


Age of the Mare Deposits of the Far side



Using the 10 m resolution images by Terrain Camera, the ages of mare deposits on the far side were determined on the basis of the crater frequency distributions. Several mare deposits at various locations on the lunar far side show a much younger age, clustering at ~2.5 billion years ago. These young ages indicate that mare volcanism on the lunar far side lasted longer than was previously considered（Haruyama et. al., Science, 2008）.

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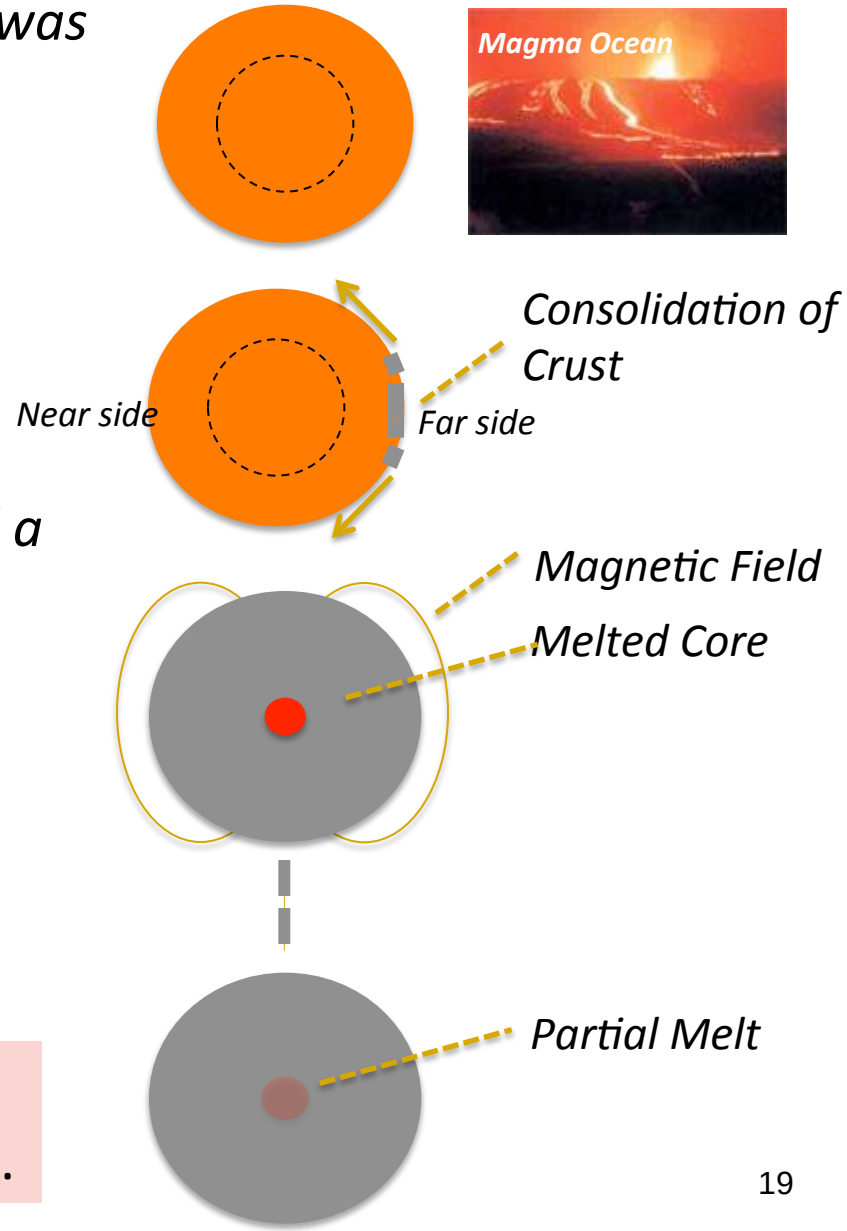
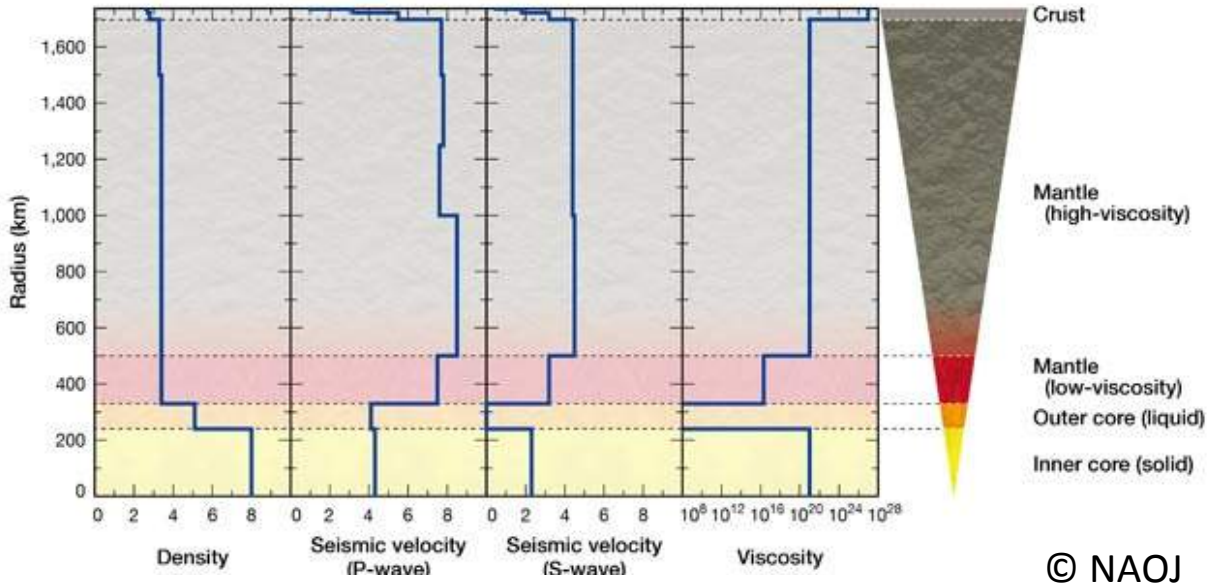


Tidal Heating at the Core–Mantle Boundary of the Moon



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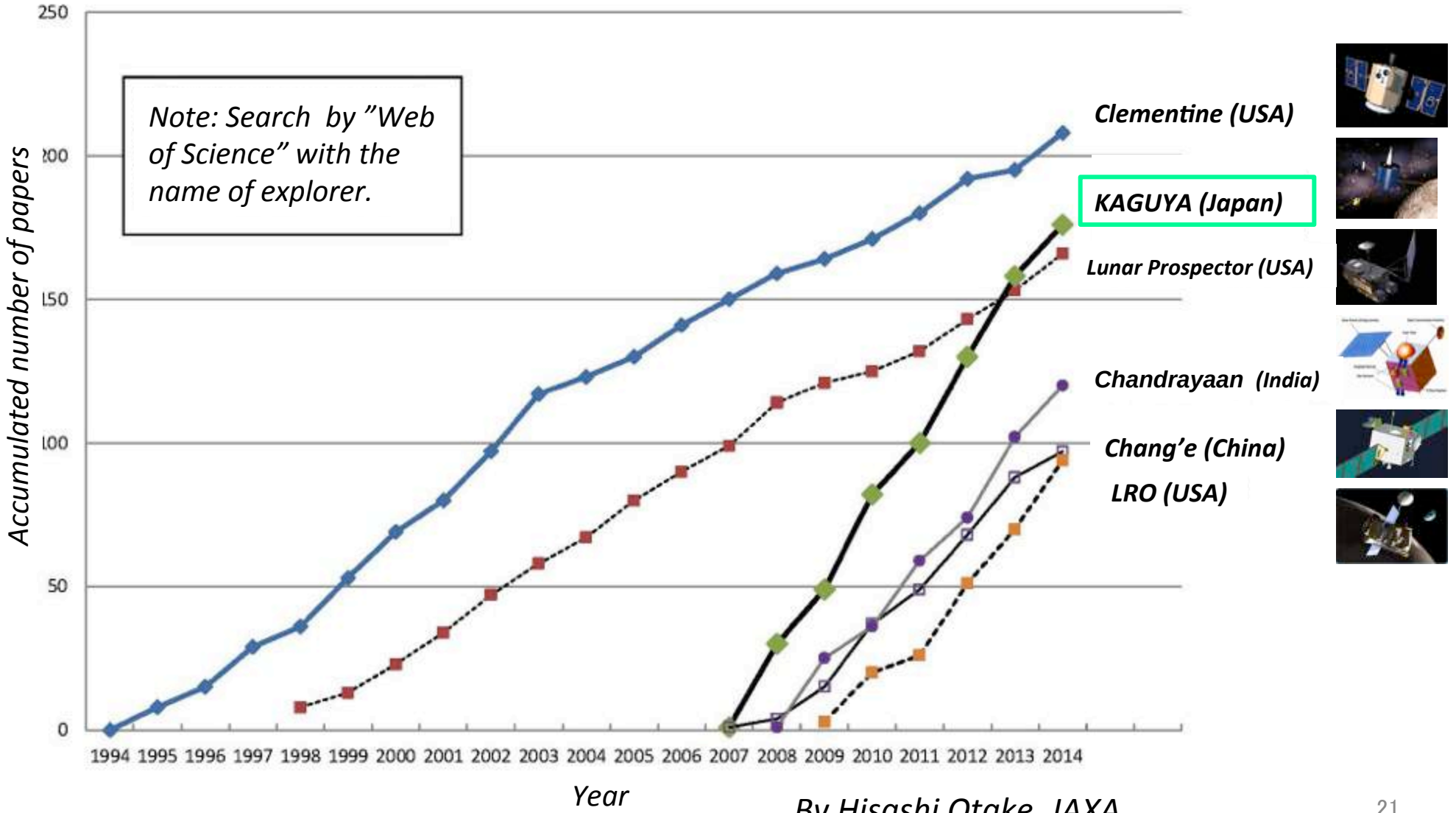
Moon's interior viscosity structure replicating the observation

Gravity measurements by KAGUYA to give information on the shape of the Moon.

The shape of the Moon responses to the tidal forces. Using the KAGUYA data, the shape was determined accurately. The lunar interior structure was calculated based on the observation. It was found that there is a a low-viscosity layer at the core–mantle boundary, suggesting partial melting. (Harada et al., Nature Geoscience,2014)

Number of Scientific Papers

Counted after launch



By Hisashi Otake, JAXA


3. Advances of Lunar Development in the Context of Expansion of Humanosphere into Space
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Dr.Gerard O'Neill

Expansion into Space

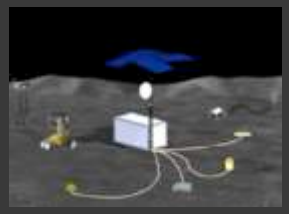
Prof.Tatsu Obayashi

Prof.Obayashi (Enthusiasm for Space, 1985)

Population Explosion: Recent population increases 2 % every year (last 100 years), that means the population will reach 150 trillion in 500 years, one man every 1m distance. Human-beings are destined to expand to any possible space, as is written in DNA. As a matter of fact, modern humans evolved in Africa and then migrated through Europe and Asia to reach the Pacific and Americas, without stagnation or shrinking.

Moon base as the first step, then orbital colonies, and other planets such as Mars.

Logical Steps for Lunar Settlements



Unmanned exploration station

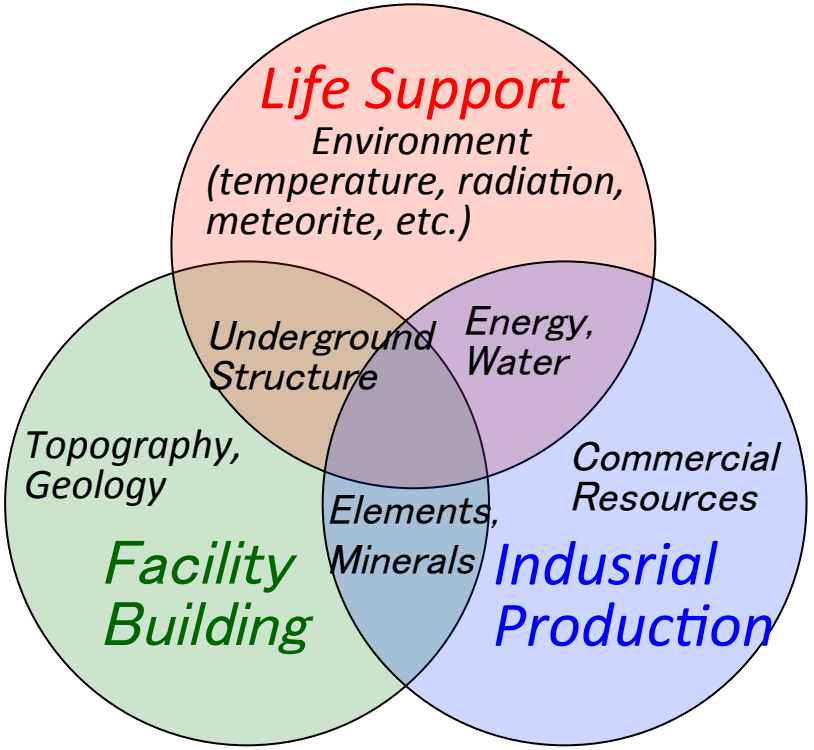
Temporary manned base

Permanent manned base

Lunar city

– – → Exploration → Development → Settlement

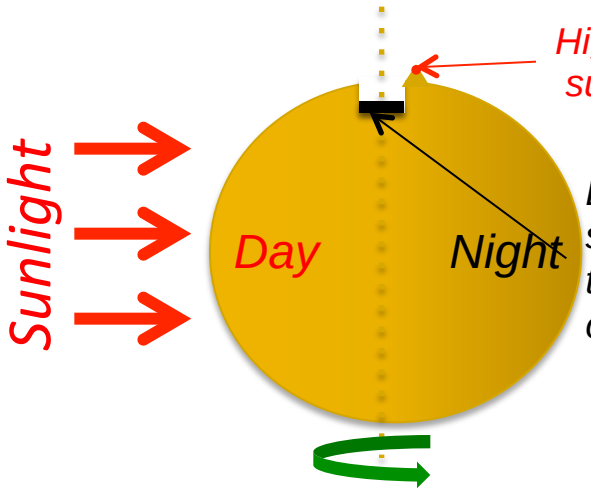
Information Required for Human Settlement

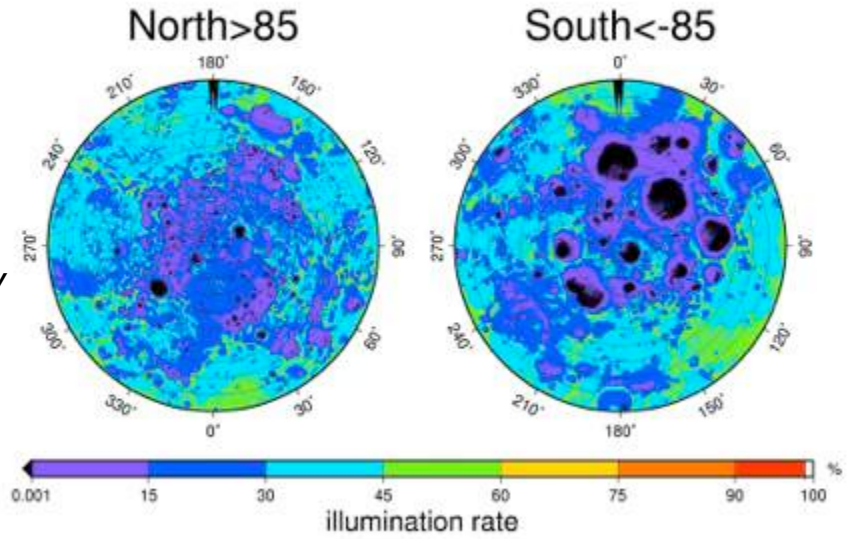


3 Pillars for Human Settlement

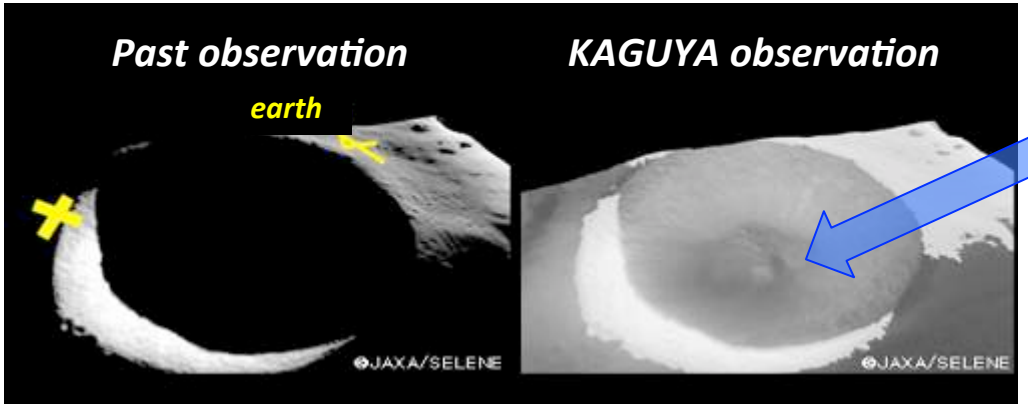
Information	Life Support	Facility Building	Industrial Production	"KAGUYA" Achievements
Environment (temperature, radiation, meteorite, etc.)	√			No study (Basic information already obtained)
Energy, Water	√		√	Sunshine rate Permanent shadow
Underground Structure	√	√		Vertical hole and a possible lava tube
Topography, Geology		√		Global 3-d mapping data (10m resolution), Sub-surface structure at specific areas
Elements, Minerals		√	√	Global Maps of mineral resources and abundance of U and Th
Commercially Valuable Resources			√	No study (He_3, for example)

High Rate Sunshine Area and Permanent Shadow Area





"KAGUYA" observation. "Black" shows "permanent shadow" area. The maximum sunshine rate is 89 % in the north polar region and 86 % in the south polar region. (Noda et al., GRL, 2008) .

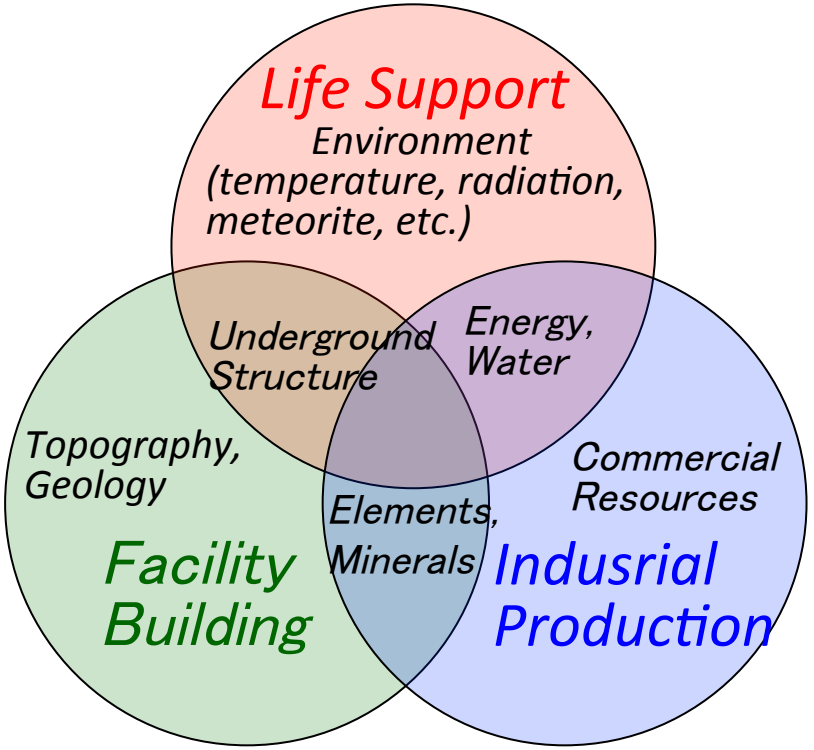


Shackleton crater near the south pole, one of the candidates of the lunar base.

The Inside of the Shackleton crater observed by Terrain Camera. There was no block of water ice exposed inside the crater, rather different from the case of Mars. The amount of water ice is assumed to be several % maximum if any. (Haruyama et al., Science, 2008)。

Water ice observed by Mars Express (2005)

Information Required for Human Settlement



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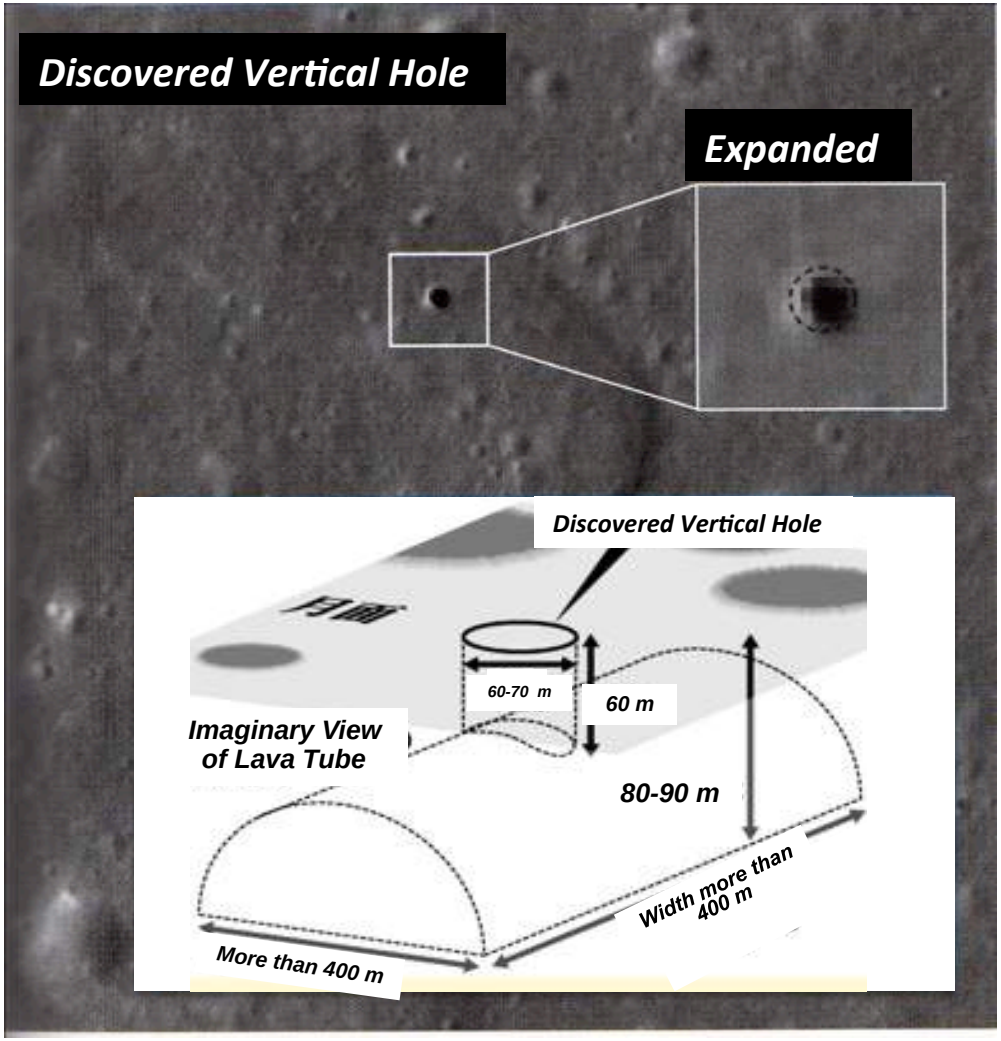
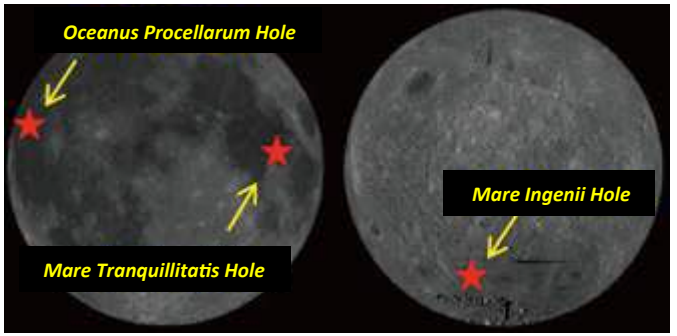
Vertical Hole and a Possible Lava Tube



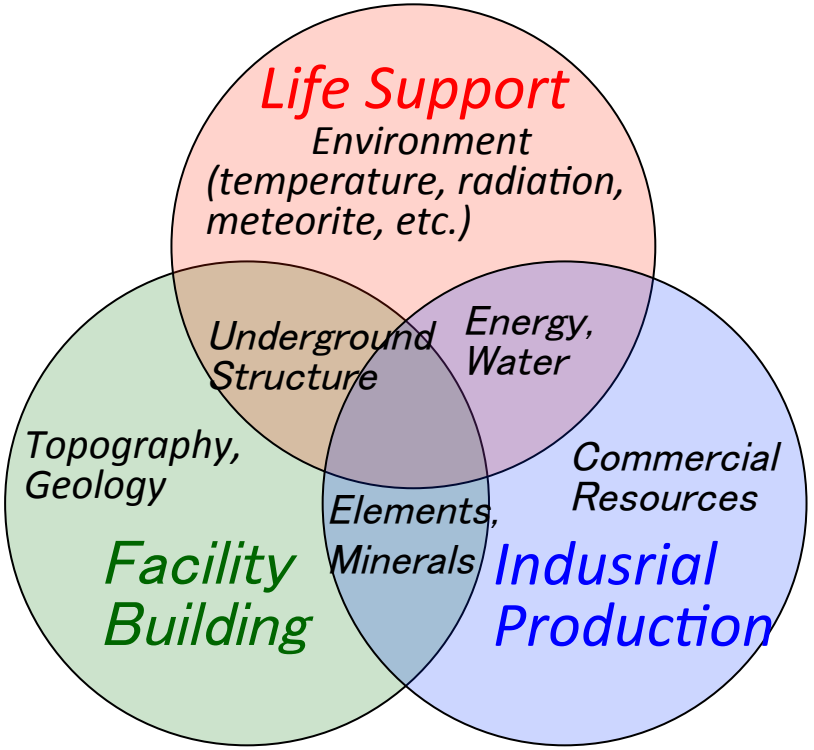
Vertical hole (approx. 70m diameter) and Lava Tube (approx. 370m size) (Haruyama et al., GRL, 2009)



3 Vertical holes discovered by "KAGUYA"

Temperature :-20℃ Constant (Surface: -170～+110℃)
Radiation :same level as the earth surface, aprox. 1 mSv/year (at 5 m below the surface), 100-500 mSv/year at the surface.
Protected from meteorite impacts.

Information Required for Human Settlement



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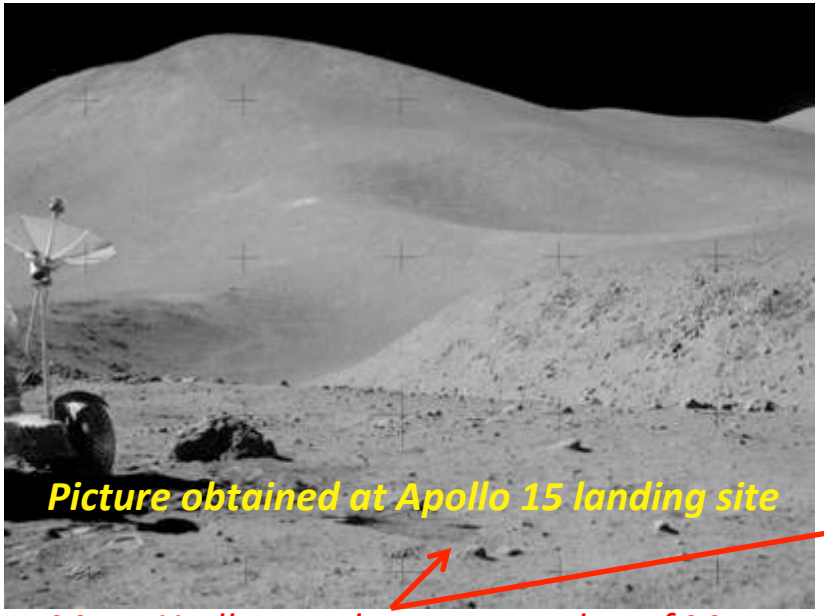
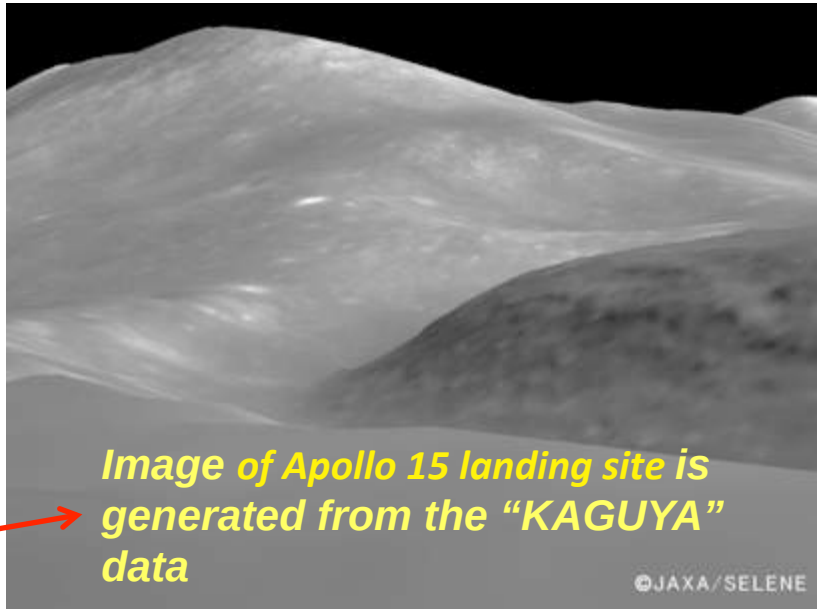
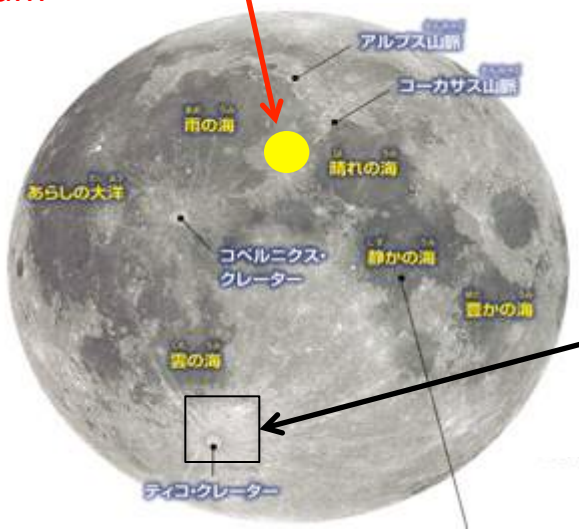
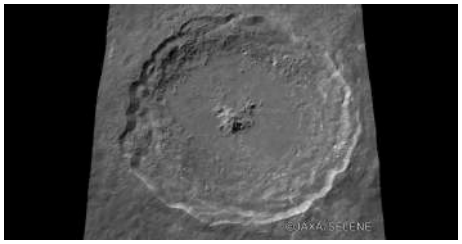
Three-dimensional Topographical Map





Mons Hadley on the eastern edge of Mare Imbrium

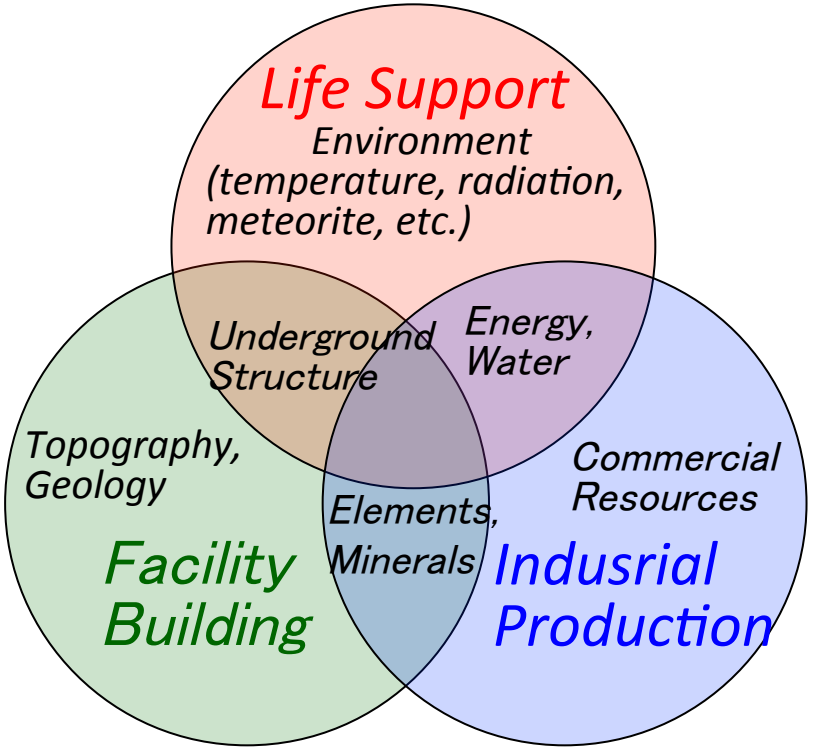




Video

Tycho crater, 85km in diameter with central peaks up to 1.6 km above the floor, relatively young crater formed about 110 million years ago. Since it is one of the places of interest on the Moon, sightseeing flights will be planned in future. You can enjoy the simulated experience well in advance using the three-dimensional KAGUYA data (JAXA/ISAS KAGUYA Gallery).

Information Required for Human Settlement



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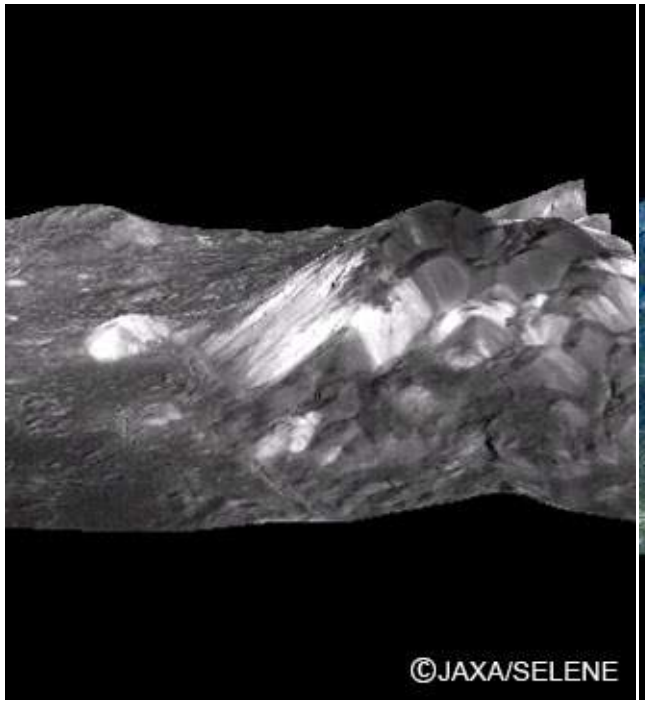
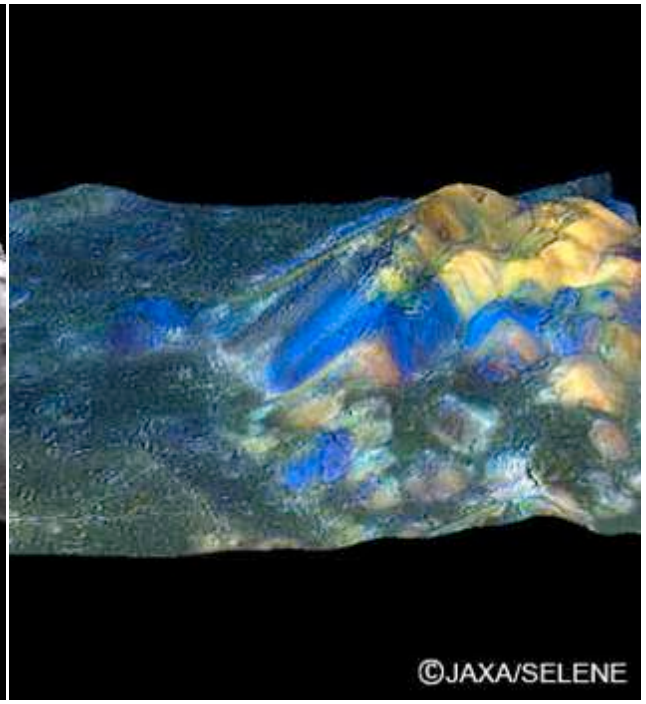
Global Mapping of Mineral Resources

Example of Jackson Crater

Location of Jackson Crater (22.4N/163.1W, 71Km diameter)



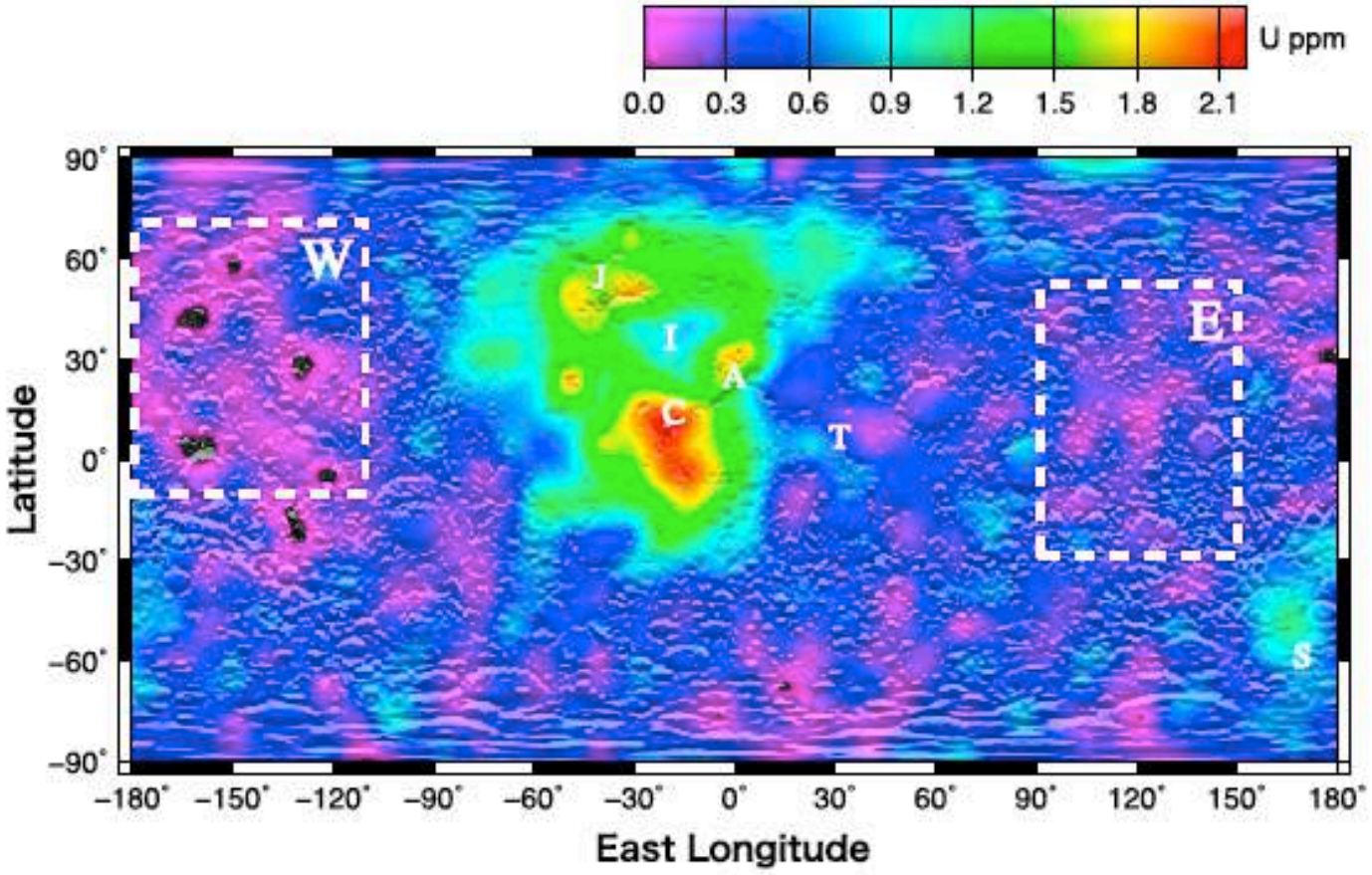
Central Peaks of Jackson Crater



Color shows rock types (Red: pyroxene, Green : olivine, Blue: plagioclase) (Ohtake et al., Nature, 2009)

Distribution of Uranium Concentration

Absolute abundances of Uranium were first observed by KAGUYA gamma-ray spectrometer (Hasebe et al., GRL, 2010).

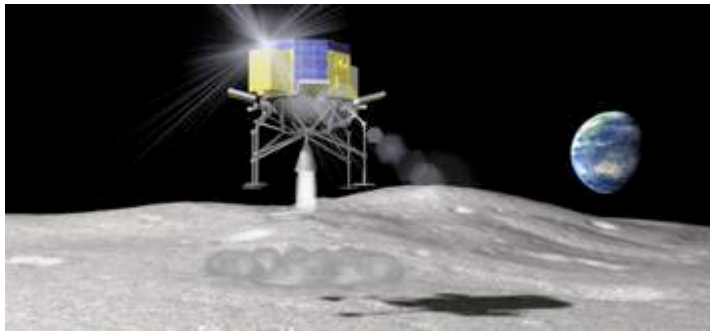


Apollo 11 Landing site

Uranium is most concentrated near the Copernicus Crater (C). The maximum concentration is 2 ppm, which is much lower than the concentration of the earth Uranium ore typically 0.1 %. The information on Uranium abundance is also very important in the study of the evolution of the Moon.

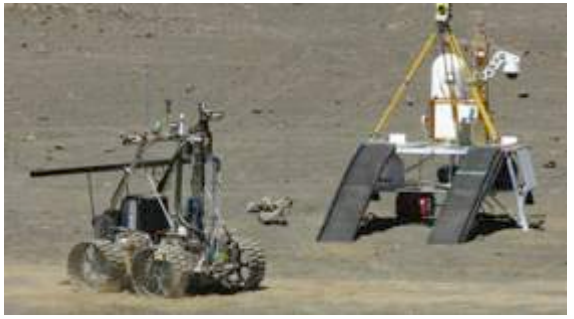
Prospects for Near Future Lunar Exploration

SLIM (Smart Lander for Investigating Moon) was selected in 2015 as a candidate project for the third scientific mission by Epsilon Rocket. SLIM is expected to enter the phase of Pre-Project of JAXA soon.
On the other hand, the successor of "KAGUYA" , which has been in Pre-Project phase, is now considering its landing site near the polar region with more focus on the practical use of the Moon. International collaborated mission is considered as a possibility.
USA, Russia, ESA, China, and India are proposing and studying the lunar exploration mission of the near future.



SLIM (Smart Lander for Investigating Moon). The advanced landing technology will be verified（referring to SLIM home page）.

Landing mission proposed as a successor of KAGUYA.



Resource Prospector Mission (RPM) studied by NASA

（material from MEXT、2014）

Summary

1. During the 1.5 years mission, KAGUYA collected scientific data on elemental abundance, surface and sub-surface structure, gravity fields, and magnetic field. It has significantly contributed to advances of lunar science..
2. The data on the topography, geology, underground structure, permanent shadow, and sunshine rate at the polar region have been obtained, that contributes to planning of the lunar utilization in the near future.
3. The international trends of the lunar exploration are quite fluid. It is most important to take a new step aiming at the sustainable development of the society, thinking about “what we should” rather than “what we can”.