Jupiter’s Icy Moons
1. Callisto: Geology of an old icy body

2. How do we ‘know’ there are oceans?

3. Ganymede: Ocean on an icy world?
The Moons of Jupiter

Galileo Galilei, 1610
The Moons of Jupiter

Jupiter has 63 moons, though the 4 largest moons are the most well known. Several dozen of these were only discovered in the past 10 years.

The 4 largest moons are believed to have been first observed by Galileo Galilei in 1610, thus they are often called the ‘Galilean moons’.

Io is a volcanically active moon, whereas the other 3 large moons are dominated by ice and may contain liquid water oceans beneath their icy crust.

Ganymede is the largest moon and is actually larger than Mercury!

These 4 moons are spheroidal and would be considered dwarf planets if they orbited the Sun directly (like Ceres).

The Galilean moons are believed to have formed by accretion of dust and gas in a disk surrounding Jupiter, similar to a protoplanetary disk. They are not consistent with captured objects.
All 4 appear to be differentiated, and several likely have distinct cores.

Three are believed to have significant amounts of water beneath the outer crust...liquid or ice??

This has opened up the possibility that these moons may be good places for life beyond Earth.
The Galilean satellites are each unique with respect to their geologic histories, as evident from even visible images of their surfaces.

Ganymede & Callisto exhibit numerous impact craters (surfaces are ‘older’). Io and Europa lack impact craters (surfaces are ‘younger’).
When we examine the icy satellites at higher resolution, we see that even though they may have experienced roughly similar geologic processes they have very different surface features.

- **Callisto** contains hills, numerous craters, and appears more ‘rugged’.
- **Ganymede** has a complex surface of ridges, grooves, and craters.
- **Europa** has a very complex surface of intersecting ridges/grooves and has clearly been affected by tectonic processes.
While all three moons are believed to be nearly as old as the solar system (4.5 billion years), the age of the surfaces is still subject to debate. Without having surface samples in hand, the only method to roughly determine the geologic surface age is by crater counting. However, assumptions about the impactor fluxes must be made based on theoretical models and possible observations of candidate impactors: asteroids and comets.

Asteroids should have been very common in the early days of the solar system, but this source should have been largely exhausted by ~3.8 billion years ago. For comets, the impactor flux is believed to be rather constant throughout the whole lifetime of the solar system, meaning that the probability of an impact of a large comet is similar today as it was even 4 billion years ago.

If asteroids have been the dominant bodies that impacted the Galilean satellites (which is believed to be the case on the Moon, the Earth, and other inner solar system bodies as well as within the asteroid belt itself), the surfaces of Ganymede and Callisto must be roughly 4 billion years old whereas Europa's surface is only several hundred million years old. Low-level geologic activity on Europa might be possible today, but Ganymede and Callisto should be geologically dead.

In contrast, if we assume that comets have been the main impactors in the Jovian system, Callisto's surface would still be determined to be old (4 billion years), but Ganymede's youngest large craters would have been created only ~1 billion years ago. In this model, Europa's surface should be very young, and it would be quite geologically active even today.

or

?
Callisto is the 2nd largest of the Galilean moons and is almost the same size as Mercury.

As with Ganymede, the low mean density (1.83 g/cm$^3$) implies the presence of water/ice.

It is tidally locked such that the same side always faces Jupiter.

As with Europa & Ganymede, Callisto may have a liquid ocean beneath the crust.

It may have a small solid core, but this is not clear. Callisto accreted relatively slow and it may not have had time to fully differentiate.
The surface of Callisto is covered with dark material (only reflects 20% of light) that is relatively smooth and seems to fill in topographic lows and small craters.

The darker regions likely contain silicates, possibly organics, and other non-ice phases; the brighter regions are dominated by water and other ices.

Unlike Ganymede & Europa, the surface seems to be dominated by impact events and not tectonics; it also appears that Callisto did not experience significant tidal heating.
These images are some of the highest-resolution views ever obtained of Callisto. The bright knobby terrain seen in the top image is unusual for any of Jupiter's moons. The spires are very icy but also contain some darker dust. As the ice erodes, the dark material apparently slides down and collects in low-lying areas. The knobs are about 80-00 m tall and may consist of material thrown outward from a major impact billions of years ago (theses areas lie to the south of the large Asgard impact basin).

Over time, as the surface continues to erode, the icy knobs will likely disappear, producing a scene similar to the bottom image.

The numerous impact craters in the bottom image indicates that erosion has essentially ceased in the dark plains in that location.
This large multi-ring basin on Callisto was imaged by the Voyager spacecraft in 1979. The complicated circular structure seen at left center is similar to the large circular impact basins that dominate the surface of our Moon and Mercury. The inner parts of such large basins are generally surrounded by radial ejecta and several concentric mountainous ring structures formed during the impact event.

This multi-ring basin consists of light-toned on the floor of the central basin (~300 km in diameter), surrounded by at least eight to ten discontinuous rhythmically spaced ridges.

No radially lineated ejecta can be seen. The great number of rings observed around this basin on Callisto is consistent with its low planetary density and probable low internal strength (lots of ice, not just rock!).
Callisto also exhibits ‘domed’ craters (left image), which may represent impacts into a slushy material. Other craters exhibit bright rays from ejecta, similar to typical craters seen on other planetary surfaces.

Of all the icy satellites of Jupiter, Callisto exhibits the most craters and is likely the oldest surface.
Here, Callisto is in approximate natural color (left) and in false color to enhance subtle color variations (right). The ancient, multi-ring impact structure Valhalla is just above the center of the image. Valhalla, possibly created by a large asteroid or comet which impacted Callisto, is the largest surface feature on this moon. Valhalla consists of a bright inner region, about 600 kilometers in diameter surrounded by concentric rings 3000 to 4000 kilometers in diameter. The bright central plains were possibly created by the excavation and ejection of "cleaner" ice from beneath the surface, with a fluid-like mass (impact melt) filling the crater bowl after impact.

The false color image on the right highlights ejecta from relatively recent craters, which are often not apparent in the natural color image. The colors also reveal a gradual variation across the moon's hemisphere, perhaps due to implantation of materials onto the surface from space. The 'color' data were obtained with the 1 um (infrared), green, and violet filters of the Solid State Imaging (SSI) system on the Galileo spacecraft.
Liquid Oceans?

How do you test for a liquid ocean?

http://www.youtube.com/watch?v=30oPZO_z7-4
Ganymede

The surface of Ganymede consists of bright & dark terrain. The bright terrain is dominated by water ice and the dark terrain is silicate-rich (though the exact composition is unknown).

Ganymede also contains sulfate salts, possibly originating from a salty ‘ocean’ beneath the surface.

Ganymede is the largest satellite in the solar system & is larger than Mercury.

However, it only has a mean density of 1.9 g/cm³, implying a significant component of ice.

It appears to have an Fe or Fe-S core, a silicate mantle, and an outer ice mantle.
Color-enhanced images reveal frosty polar caps in addition to the two predominant terrains on Ganymede (bright, grooved terrain and older, dark furrowed areas).

Many craters with diameters up to several dozen kilometers are visible.

Ganymede's intrinsic magnetic field was detected by the magnetometer on the Galileo spacecraft in 1996, and it may be partly responsible for the appearance of the polar terrain. It is the only moon to have an intrinsic magnetic field and its origin is unclear.
Unlike Europa, the surface of Ganymede (and Callisto) exhibits numerous impact craters. In these Voyager images, bright material appears as rays that can be traced back to an impact crater. The infrared data (right) show this icy ejecta in blue tones, providing a different view of the ejecta pattern and information on its composition.
Ganymede: Surface Features

The images below were acquired by the New Horizons spacecraft during a flyby of Ganymede in 2007 on its way to Pluto; it is from a distance of 2.2 million miles away.

The left image was acquired by an infrared spectrometer that measures infrared light at 200 wavelengths, whereas the center image was acquired at a wavelength in the visible region.

By combining the infrared image (left) on top of the higher resolution visible image (center), we can see how different compositions relate to surface features (right).

In this color composite, blue regions contain water ice and red/brown regions contain silicates.
Ganymede: Surface Features

The dark regions retain more craters than the bright regions and the bright regions clearly crosscut the dark regions; thus the dark regions are the older terrain.

The exact origin for the ridges and grooves that cover the surface of Ganymede is not clearly known, but they seem to result from tectonic forces, not cryovulcanism.

Large fracture/crack systems developed at one point and new, fresh surface material was formed, possibly sourced from the potential ocean beneath the frozen surface.
Ganymede: Surface Features

The ancient, dark terrain of Nicholson Regio (left) shows many large impact craters, and zones of fractures oriented generally parallel to the boundary between the dark and bright regions. In contrast, there are fewer craters in the bright terrain of Harpagia Sulcus (right) and it is smoother.

The bright and dark regions are the two principle terrain types on Ganymede, and the nature of the boundary between ancient, dark terrain and younger, bright terrain, was explored in detail by the Galileo spacecraft. Subtle parallel ridges and grooves show that Harpagia Sulcus's land has been smoothed out over the years by tectonic processes.
The ridges/grooves on Ganymede are similar to what is observed during extensional faulting on Earth (and other terrestrial planets).

As the crust is pulled apart, large sections can drop down to form grabens.

In some cases a series of blocks drop down and rotate, sometimes referred to as half-grabens (image below).

This is a possible process that forms ridges on Ganymede (image to the left).
Imaging the surface several times from different viewing angles can allow us to create models of the surface topography. This ‘stereo imaging’ can then be used to determine relative differences in elevation between different types of terrains, as in the image below.
In these images, the bright region cuts across the dark region, thus the bright region is younger.

The bright region that runs north-south is younger than the dark terrain, but it is then cut by the bright band that runs east-west near the bottom. Therefore, the east-west band is even younger than the north-south band of bright material.

The bottom image shows the topography (blue tones are lower elevation) draped on top of the visible image. It then becomes clear that the bottom, east-west bright band is lower in elevation than the surrounding terrain to the north.

Be examining cross-cutting relationships and topography, we can try to piece together the relative ages of different geologic units.
Ganymede: Surface Features

Similar to the previous figure, these data also exhibit cross-cutting relationships and topography. In addition, this image covers several major types of terrain on Ganymede: grooved, smooth, & reticulate terrain. The simple geologic map inset in (b) shows the location of each type of terrain.
These are some of the highest resolution images of Ganymede ever acquired.

They show several important features:

- even ‘smooth’ terrain is rough at small scales
- there are numerous craters that have retained their shape
Ganymede: Internal Structure Like a “Club Sandwich”?

Like a “Club Sandwich”?

Ice I
Ice III snow
Ice V
Ice VI
Liquid ocean layers, more saline with depth

Moon
Mercury

image credit: www.nasa.gov
work by Steve Vance, JPL
https://www.nasa.gov/jpl/news/ganymede20140501/
European (ESA) JUICE Mission

JUpiter ICy moons Explorer (JUICE) to launch in 2022, arrive in 2030.

Focus on Ganymede, Callisto and Europa.

http://sci.esa.int/juice/

| Cosmic Vision Themes | What are the conditions for planet formation and emergence of life?  
How does the Solar System work? |
|----------------------|---------------------------------------------------------------------|
| Primary Mission Themes | Emergence of habitable worlds around gas giants  
Jupiter system as an archetype for gas giants |
<p>| Lifetime | 7.6 years cruise &amp; 3.5 years in the Jovian system |
| Type | L-class candidate mission |</p>
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<thead>
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<th>Callisto</th>
<th>Ganymede</th>
<th>Europa</th>
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<tr>
<td>intrinsic magnetic field</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
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<tr>
<td>induced magnetic field</td>
<td>✓</td>
<td>?</td>
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<tr>
<td>(probably, but hard to separate from intrinsic)</td>
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<td>tectonic activity</td>
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<tr>
<td>liquid ocean</td>
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