JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. E9, PAGES 22,517–22,518, SEPTEMBER 25, 2000

Introduction to the special section: Galileo Mission results from the icy Galilean satellites

James W. Head III

Department of Geological Sciences, Brown University, Providence

Ronald Greeley

Department of Geology, Arizona State University, Tempe

The four largest satellites of Jupiter, Io, Europa, Ganymede, and Callisto, have fascinated scientists since their discovery by Galileo in 1610. The four bodies, named the Galilean satellites in honor of their discoverer, represent what might be viewed as a miniature solar system, with planet-sized dimension, systematically changing densities, and as diverse a set of surface characteristics, ages, and geologic activity as observed across the realm of solid bodies in the solar system. In the late 1970s, Voyager revealed [*Smith et al.*, 1979a, 1979b] that innermost Io was characterized by multiple active volcanic eruptions and constant resurfacing. Europa had a silicate density, but its surface was dominated by extremely high albedo material composed of water ice, pervasive cracks and mottling, few impact craters, and a possible liquid water ocean underneath. Its youthful surface and global tectonic activity were hypothesized to originate from its tidal interactions with Io and Ganymede, the next outermost satellite. Voyager showed that about half of Ganymede was made up of a very ancient dark and heavily cratered surface which was broken and replaced by global-scale bright stripes of heavily lineated, more sparsely cratered terrain. In contrast, outermost Callisto had a density similar to Ganymede, but its surface was even older than the heavily cratered terrain on Ganymede and apparently uninterrupted by tectonic activity and younger resurfacing. Why were the four Galilean satellites so similar in some ways and so different in others? What were the geological processes that formed the array of surface features on these bodies? What was the nature of surface geological units and their ages? What were the surface composition and mineralogy, and how did they relate to their geological evolution and to the Jovian environment? And how could one determine if there was an ocean beneath the surface of Europa today?

These types of questions formed the basis for one of the main goals of the highly successful Galileo Mission, which has been in orbit around Jupiter since 1995. The complement of experiments on board the Galileo spacecraft has provided unprecedented new data about the nature of Jupiter, its satellites, and its environment. The remote-sensing instruments have provided new perspectives on the geology and mineralogy of the Galilean satellites, addressing many questions raised by Voyager data and, of course, raising additional ones. The nature of the spacecraft orbit, the sequence of encounters, and mission events dictated that results from Io would primarily come late in the mission. Thus most attention in the initial encounters has been focused on the icy Galilean satellites, Europa, Ganymede, and Callisto. These three outermost satellites are particularly important in that they provide a window into geological processes operating on the realm of icy satellites surrounding the other outer planets, Saturn, Uranus, Neptune, and Pluto. The acquisition of comprehensive image data for the icy Galilean satellites by the Solid State Imaging (SSI) System has provided a basis for the recognition of key geological features and processes, the analysis of their distribution, and comparison to other data sets such as the Near-Infrared Mapping Spectrometer (NIMS). In this special section a series of papers outline the emerging character of these icy satellites of Jupiter and begin to address the questions raised by Voyager.

One of the basic mechanisms of deciphering the geologic history of a planetary body is to define and characterize the major geologic units making up the uppermost crust and to employ these definitions to analyze specific areas and, ultimately, the planetary body as a whole. For Europa a major step has been taken in this direction through analysis and synthesis of Galileo data. *Greeley et al.* [this issue] review detailed image data for Europa and document the major structures and surface features on this satellite, defining and establishing the characteristics of several primary geological units and subunits: ridged plains, which occur with a wide range of ages, including some of the oldest terrain; smooth plains, which typically embay other units in a manner reminiscent of fluid emplacement and are some of the youngest units; undifferentiated plains, which can be further subdivided with data at near-infrared wavelengths; chaos material, plains which have been severely disrupted into blocky and hummocky terrain by apparent internal activity; bands, broad curvilinear to cuspate zones formed by faulting, separation, and spreading; and crater material, formed in association with the few impact craters observed on the surface. The detailed definitions and documentation of type areas by *Greeley et al.* [this issue] will provide a basis for the systematic study and analysis of Europa in the years ahead.

Employing these definitions and approaches, *Figueredo and Greeley* [this issue] mapped a large portion of the northern leading hemisphere of Europa and found four major episodes in the geologic history of this region. Background lineated plains formation was followed by a second episode of extensive lineament formation, which was in turn followed by surface disruption to form chaos at low to middle latitudes. The final phase was characterized by relatively recent high-latitude ridges and bands. Establishment of this sequence enabled Figueredo and Greeley to determine that stress directions rotated clockwise with time, consistent with models involving tidal deformation and nonsynchronous rotation of Europa's outer layers.

Paper number 2000JE001318.
0148-0227/00/2000JE001318$09.00

A major issue in the study of Europa is the nature and thickness of its outer compositional and mechanical layers and how they relate to the possible presence of a subsurface ocean [e.g., *Pappalardo et al.*, 1999]. Impact craters penetrate into and perhaps through these layers and thus provide information on their thickness and character. *Kadel et al.* [this issue] map the geology of the Tyre region of Europa and use this information to establish a stratigraphic sequence (oldest to youngest: ridged plains, ridge bands, chaos, and fracture formation) similar to that found in the northern leading hemisphere by *Figueredo and Greeley* [this issue]. Most prominent in this region is Tyre, a 150 km diameter multiringed impact structure interpreted by *Kadel et al.* [this issue] to have formed when an impactor penetrated several kilometers of water ice to a more mobile, low-viscosity (perhaps liquid) layer below. The very low crater density suggests to these workers that this shallow mobile layer has characterized the region in its very recent geological past.

The power of the combined remote sensing instrument complement on Galileo is shown by *Fanale et al.* [this issue], who use information from the Solid State Imaging System, the Near-Infrared Mapping Spectrometer, and the ultraviolet spectrometer (UVS) instruments to characterize the materials in and around the multiringed impact structure Tyre and Pwyll, another young impact feature. The impacts have penetrated the uppermost crust and revealed material that is not the same as the pure H_2O ice seen at the surface. These results, combined with laboratory and theoretical analyses, suggest that the crust of Europa is characterized by an aqueous phase dominated by the $SO_4^=$ anion, lying beneath a thin patina of sputtered H_20 molecules.

The distribution of chaotic terrain on Europa was mapped by *Riley et al.* [this issue] using image data covering 9% of the surface. Almost 30% of the mapped surface is composed of chaotic terrain with the largest area being ~1300 km across, but no dominant size distribution of chaos occurrence was detected. Variations in morphological freshness are reported, and these are interpreted by *Riley et al.* [this issue] to mean that chaos formed at different times in the history of Europa.

What is the nature of Europa's surface tectonic features, and how are they related to tidal deformation? A major result of Galileo analyses is the conclusive documentation of strike-slip fault offset on Europa. *Hoppa et al.* [this issue] map 117 strike-slip faults in four different regions of Europa. They found that left-lateral offset occurs preferentially in the northern hemisphere and right-lateral offset dominates in the southern hemisphere. They interpret these data to support a model in which diurnal tides (due to orbital eccentricity) drive strike-slip motion through a process in which faults open and close out of phase with alternating right- and left-lateral shear. The vast majority of strike-slip faults are associated with double ridges or bands, but few were detected along cracks without ridges. Hoppa et al. interpret this to mean that cracks without ridges have not penetrated to a low-viscosity decoupling layer required for diurnal displacement. Cracks with ridges apparently extend down to such a level, supporting models for ridge formation that require cracks to penetrate down to a decoupling layer.

The very small number of impact craters seen on the surface of Europa suggests to most workers that the surface is geologically very young and that change might be observed during the time span since Voyager observations or during the Galileo mission. *Phillips et al.* [this issue] report on the search for changes since Voyager and current geologic activity on Europa in the form of active plumes venting material above the surface. No evidence was found for plume activity or changes since Voyager, and Phillips et al. use their observations to estimate a maximum steady state surface alteration rate of 1 km^3/yr in the regions analyzed. A minimum average surface age of 30 million years is implied and predictions are made about the scale and type of features to search for during post-Galileo missions such as the Europa Orbiter.

The dark terrain on Ganymede makes up a significant portion of the satellite's surface and represents a terrain that contrasts greatly with the younger high-albedo groove lanes. The sharp contrast between the two terrains and the processes by which the older dark terrain is destroyed and the newer bright terrain is formed are basic enigmas in the evolution of this satellite. Using basic mapping techniques, *Prockter et al.* [this issue] have analyzed the nature of the dark terrain in three areas imaged by Galileo (Galileo, Marius, and Nicholson Regiones) and have focused on the tectonics in the regions between dark cratered terrain and bright grooved terrain. They find and document regions in which dark terrain is fractured as a precursor to bright grooved terrain formation. Such tectonic deformation is seen to be focused along preexisting zones of weakness caused by impact craters and furrows and to involve shear offset and extension. These data have cast new light on the close relation of one terrain type to the other and the role of tectonics in the transition.

Both endogenic and exogenic processes are responsible for the formation and evolution of materials on the surfaces of the icy Galilean satellites. *Hibbits et al.* [this issue] have mapped the distribution of CO_2 and SO_2 on the surface of Callisto using data from the NIMS experiment. They document a sinusoidal pattern of CO_2 on the trailing side of Callisto and interpret this to be due to exogenic effects related to the corotating magnetic field of Jupiter. Enhanced CO_2 concentrations are also observed at bright-ice-rich impact crater sites, and spectral characteristics imply that the physical state of CO_2 is similar over the whole satellite. SO_2 distribution displays a mottled pattern, with some high concentrations associated with ice-rich impact craters. SO_2 appears to be depleted in the polar regions, and the band-center position for Callisto as a whole is more indicative of gas than solid SO_2.

These results are typical of the exciting and emerging new Galileo perspectives on the icy satellites of Jupiter. They form an important part of the foundation for the understanding of previous observations of icy satellites (Voyager results for the Galilean and other outer planet satellites), for the interpretation of data from the Cassini mission to Saturn's satellites, and for the future missions to the outer planets.

References

Pappalardo, R. P., et al., Does Europa have a subsurface ocean?: Evaluation of the geological evidence, *J. Geophys. Res.*, *104*, 24,015-24,055, 1999.

Smith, B. A., et al., The Jupiter system through the eyes of Voyager 1, *Science*, *204*, 951-971, 1979a.

Smith, B. A., et al., The Galilean satellites and Jupiter: Voyager 2 imaging science results, *Science*, *206*, 927-950, 1979b.

R. Greeley, Department of Geology, Arizona State University, Tempe, AZ 85287. (greeley@asu.edu)

J. W Head III, Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912. (James_Head_III@brown.edu)

(Received July 7, 2000; revised July 10, 2000; accepted July 11, 2000.)