Astrobiology of Jupiter's Icy Moons

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ABSTRACT

Jupiter's Icy Moons, Europa, Ganymede and Callisto, may possess energy sources, biogenic molecules, and oceans below their icy crusts, thus indicating a strong possibility that they were abodes for present or past life. Life in Earth's icy areas lives in a wide variety of habitats associated with the ice, in the water column below the ice, and on the floor of the ocean below the ice. Similar habitats may exist on JIM, have been transported to the icy crust, and be exposed in tectonic or impact features. Europa has a young, dynamic surface with many outcrops exposing older ice, fresh ice, possible materials from the subsurface ocean, and a few impact craters. Ganymede has older, darker, tectonized terrains surrounded by light ice. Callisto has a much older, heavily impacted surface devoid of significant tectonic structures. Past and present life habitats may be exposed in these features, making Europa the most favorable target while Ganymede is of interest, and Callisto seems more unlikely to have detectable life. A proper search strategy requires detailed orbital imaging and spectrometry of the likely places, and surface data collection with microscopic, spectrometric, and biochemical instruments.

Keywords: Astrobiology, life, Jupiter's icy moons, Callisto, Europa, Ganymede, ice organisms, remote sensing.

1. INTRODUCTION

Jupiter's Icy Moons (JIM), Callisto, Ganymede and especially Europa, may be abodes for life because liquid water or ice-water slush may exist below their ice crusts. If life exists or existed on JIM, it might be abundant, varied, and widespread as well as preserved in the moons' surface ice. Life is tenacious, and on Earth it is abundant and diverse in habitats in close association with ice, below it[1-4] and in it[4-6]. Life on the icy moons of Jupiter then seems possible, if other conditions are met. For Europa, life has been inferred and modeled to exist in its oceans[7-9], but it may be less likely on Ganymede and Callisto. So far no direct evidence for life on any JIM yet exists, so reasonable assumptions must be made in order to develop models of possible habitats life might occupy on the icy moons and the processes through which those habitats might be preserved at the surface of JIM.

1.1. Four assumptions

No direct evidence exists for the presence of life on any of JIM. Indeed, insufficient evidence exists even for life support systems. We therefore make four reasonable assumptions based on indirect evidence or inferences: 1.) Each JIM has a water layer below its ice crust, 2.) the chemistry of life is present on JIM, 3.) an energy source is available for life, and 4.) life originated or was transported to JIM. If any of these fail, then life, more or less as we know it on Earth, cannot exist or have existed on JIM. Each of these assumptions has greater or lesser possibilities of being confirmed for each JIM. Europa is the most likely, while Ganymede is less likely, and Callisto the least likely to harbor life.

1. Water is essential to carbon-based life. NASA's generalized life search strategy therefore is "Follow the Water". It appears to be present on JIM, especially Europa, so they are primary targets for life in the Solar System. Magnetometer measurements from Galileo indicate a conducting layer of briny water or slush ice on each moon as do certain surface structures on Europa and Ganymede[10, 11]. On Callisto and Ganymede the water may be enclosed between ice layers[10], but on Europa, the ocean seems to lie on the rocky interior. While these inferences are accepted by some scientists[7-10, 12, 13], not all find the evidence compelling. The salinity of the Europan ocean is calculated to range from about 1g/kg to

100g/kg, probably chiefly as $MgSO_4$[14]. Microbes on Earth easily tolerate that range. Ganymede's and Callisto's oceans have not been modeled. For this discussion we accept the possibility that all the JIM have briny subsurface oceans.

2. Even more essential are the right chemicals for life, which fortunately are ubiquitous in the Universe and in meteorites, comets, moons, and planets. Indeed, for Europa models of the cometary input of biogenic elements indicate a substantial amount may have accumulated in its oceans and it is sufficient for life to have evolved or to be supported[15]. If Europa was infused with these chemicals then we also assume that Ganymede and Callisto, which have an even more obvious record of impact, have them as well. Short of direct measurement, no way to know actual amounts is available now. We therefore assume that biologically important elements and molecules were present on each moon, and that life is a possibility no matter how life may have appeared on any of the moons.

3. Each JIM may have a different energy source for life support. Europa is strongly affected by the tidal influence of Jupiter not only providing energy, but stressing the rocky interior may generate volcanic activity on the floor of the oceans. In addition, the rocks likely contain radioactive minerals that contribute heat. Ganymede and Callisto are larger moons than Europa and farther from Jupiter (Table 1); the chief source of heat is radiogenic. If JIM have oceans in contact with their rocky interiors then hydrothermal vents may be important drivers for life on all three moons. However, geophysical measurements by the Galileo spacecraft indicate that Ganymede's and Callisto's oceans may lie between the surface ice and dense ice covering the interior rocks. If the bottom ice sheet completely covers the rocky interior, then hydrothermal vent systems providing energy and nutrients may be sealed from the oceans. If so, life becomes more uncertain on these moons, but the possibility is not eliminated because other mechanisms, such as seepage or breaks through the lower level are possible. The input of radiation-, bolide- or otherwise-derived compounds through the ice crust may also be possible, especially for Europa[16, 17]. No one will know until detailed studies are completed at some future time, so we assume that energy to support life is available on all JIM.

4. Life may have appeared on JIM, if the other three conditions prevailed in the past. Life may evolve in place, as we generally believe occurred on Earth, or it may be introduced from another body where it originated[18]. The processes of life's origination are not well understood on Earth itself, although some mechanism for the concentration of appropriate chemicals seems to be required[19]. These mechanisms include the alternation of evaporation and wetting in, for example, tide pools, lakes, ponds, or riverbeds, the assembly of biotic compounds and even protocells on montmorillonite clay[20], or by the freezing of water thus excluding compounds into pores or channels in the resulting ice or in the water underlying the ice. These kinds of environments might promote the reactions and processes necessary for the formation and development of protocells containing nucleic acids[19, 21]. Self replication would then populate the environment. Life may have originated a number of times on primitive Earth, but only a single dominant life form prevailed that eventually gave rise to the three domains, Bacteria, Archaea and Eukarya. Such processes might also have occurred in oceanic hydrothermal vents where considerable energy and raw chemicals come together, although the heat of that environment is destructive to initial biomolecules[22]. That process could also have operated on JIM with their possible hydrothermal vents. How life might form and continue under such conditions is not known, however. The transfer of microbes from other sources in the Solar System is difficult to evaluate. Life may have been far more difficult to transport from the inner to the outer Solar System, but if it existed at Jupiter or beyond, then it might have been easier to transport to JIM.

1.2. Purpose of this paper

Because JIM meet the assumptions, they are prime targets in the search for life in the Solar System. Of the three icy moons, Europa is the most likely to possess life, while Callisto is the least likely. To assess the possibilities of life and to develop an exploration strategy, we enumerate possible habitats that life might occupy, as well as the possibility that these habitats might be transported to and preserved together with organisms in the very near-surface ice. Future missions to JIM will be very costly, time-consuming, and require planning years in advance, so that reasonable expectations and search strategies may offer alternative ways of developing those missions. They can also guide instrument development as search criteria are defined. Because these missions may take place in the distant future, new and improved technologies may be available or developed to meet the criteria. This paper is a step in those directions. We present the Multiple Instrument Distributed Aperture Sensor (MIDAS), an innovative remote sensing concept to enable high science data acquisition.

2. THE ICY MOONS OF JUPITER

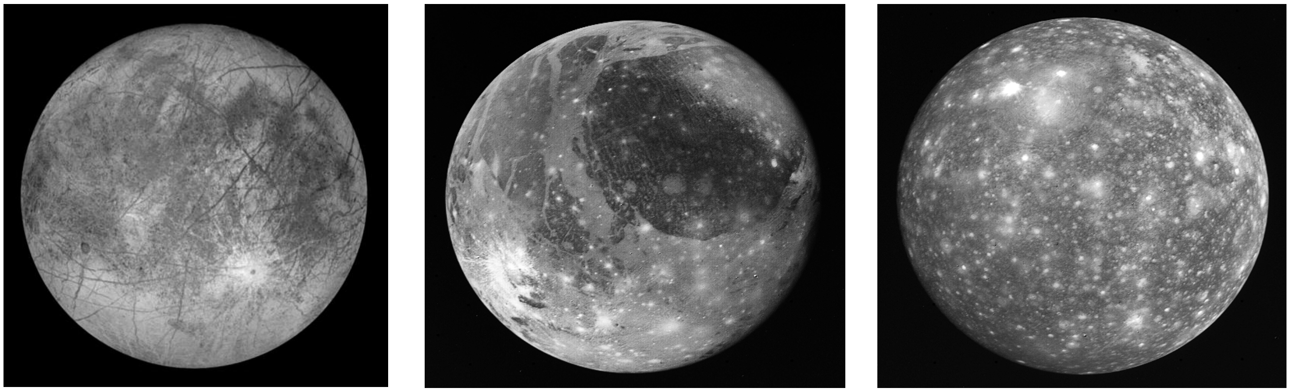


Fig. 1. Left to right: Europa, trailing hemisphere, Ganymede and Callisto. NASA/JPL images.

2.1. General features of JIM

Jupiter's icy moons are among the first objects discovered telescopically by Galileo Galilei in 1610, hence together with Io, are referred to as the Galilean moons of Jupiter (Table 1). Each one of them is quite different from the others (Fig. 1); these differences have been reviewed in detail in eight chapters in Bagenal et al[23]. Io, the closest of these moons to Jupiter, is powerfully affected by the planet's gravity, undergoing sufficient tidal stress every 1.7 days to maintain a permanent state of volcanism; we do not consider it here. Europa, Ganymede and Callisto have water ice crusts with possible water layers (oceans) in the subsurface. The surfaces of the moons differ in a systematic way. Europa, closest to Jupiter, has been tectonically active recently and possibly still is, while Ganymede was active in the remote past, and Callisto appears not to have undergone tectonic alteration of its surface crust at all. Each moon possesses impact craters, but Europa with the youngest surface has fewer than Ganymede and Callisto. Callisto is the most heavily cratered indicating a long geologic history for the present crust.

Table 1. The Galilean moons of Jupiter include the volcanic moon Io and the three icy moons Europa, Ganymede and Callisto. Each has its own characteristics, as indicated, that effect whether or not life may be present and if so is detectable. Determination of the age of the surfaces of the satellites is difficult because of the assumptions that must be made about cometary and asteroidal flux, bolide size, and degradation of impact craters. The ages reported here are from a detailed analysis of previous interpretations[24] and are dates estimated for the oldest surfaces on the moon. Younger aged surface features may also be present.

Moon	*Distance from Jupiter (km)*	*Equatorial radius (km)*	*Mass (kg)*	*Orbital period (Earth days)*	*Orbit eccentricity*	*Orbital inclination to Jupiter*	*Age of surface crust*
Io	422,000	1830 x 1819 x 1815	$8.93 X 10^{22}$	1.77	0.004	0.04°	Recent
Europa	671,000	1565	$4.79 X 10^{22}$	3.55	0.009	0.47°	~60 Myr
Ganymede	1,070,000	2634	$1.48 X 10^{23}$	7.15	0.002	0.21°	4-0.7 Gyr
Callisto	1,883,000	2403	$1.08 X 10^{23}$	16.69	0.007	0.51	~4.3 Gyr

2.2. Europa

Europa's surface (Fig. 1, left) has undergone substantial tectonic activity, driven in part by tidal flexing and in part by other processes[11, 25, 26]. The age of its icy crust is young; the oldest crust is estimated to be about 60 Myr, although other interpretations give ages of billions of years for some parts of it[24]. Nevertheless the crust is marked with impact craters and with numerous and varied tectonic features, including ridges, troughs, bands, folds, pits and domes, and chaos regions. The ways these tectonic features were formed are not clear and many hypotheses exist to account for each feature[11, 27-30], yet each has astrobiological potential. We make no judgment about which may be correct, but instead develop a search strategy for life that will accommodate most hypotheses.

The surface of Europa is bombarded by high-energy radiation (up to 10MeV) trapped in Jupiter's magnetosphere[31]. The radiation is more intense on the trailing than the leading hemisphere. This creates sputtering of the surface ice producing various surface products (Na, $NaSO_4$). Hydrated $MgSO_4$ in various forms is present on the surface, as is H_2O_2, H_2SO_4, and others[32-34]. Thus the surface is a hostile environment. However, it has color as well. In particular the trailing hemisphere and areas adjacent to ridges and troughs, impact craters, and disrupted terrains are reddish-brown. The color halo around and in these structural features might be material flushed from the ocean; this is also debated[35-38].

Ridges and troughs span enormous distances on Europa, and the general background structure is of an older ridged and troughed surface[11, 30, 39, 40]. Ridges and troughs appear to have formed throughout Europa's visible history of ~60 Myr. The fresh looking ones are fairly young. The ridges are doubled with a trough in the center, forming, according to one hypothesis, by tidal pumping of water or slush through the trough as it opens and closes, thus forming a bilateral ridge system[30]. This mechanism implies a thin icy crust, which is debated[11]. At least five other mechanisms for double ridge origination have been proposed[11, 13]. The ridges are marked on their lateral extremities by darker material that appears to overlie and smooth the adjacent terrain, implying perhaps that materials from the putative ocean may have reached the surface and been cast out through the central cracks[30]. These are complex systems without analogs on Earth. Nevertheless, they hold excellent astrobiological potential worthy of further exploration and consideration.

Pits, domes and chaotic terrain occur over most of the surface of Europa no matter what the age[30]. These patches of terrain range in size from a few km to over 1000 km across. The domes and chaos are raised features above the general surface of the moon, while the pits are lower. The domes may be several hundred meters above the surroundings and the tops may be relatively undisturbed surface material. They have sharp linear boundaries, suggesting tectonic emplacement. The edges therefore may expose ice from depth. The pits may have rather steep walls, again exposing deeper ice. Chaotic terrains have broken, tilted, rotated, or otherwise disturbed angular blocks of surface ice set in a matrix of finer material. About 60% of the terrain surface, after reconstruction of the blocks, is matrix. In some scenarios, the matrix material could include frozen water from below the ice[37]. In others, the chaos terrains are suggested to be areas of diaper emplacement from below, probably of warmer ice from near the ocean, causing the disruption of the surface, but not necessarily connected to the ocean. The low-albedo halos around such features may be ice or water erupted (cryomagmatism) from below[41]. Astrobiological targets abound in these terrains and structures.

Darker colored bands of smoother ice appear to have formed as the surface ice pulled apart, sometimes laterally[42-44]. New ice then formed in the area between the surface pieces from warmer material, either ice or water, just below the surface[11]. These are considered to be among the youngest features on Europa's surface, and a target for astrobiological study[45].

Strike-slip faults[11, 46] commonly cut features like troughs and ridges, and are involved in the formation of young bands. These cuts may expose targets of astrobiological interest. Folds, both anticlines and synclines, of long wave length may exist on Europa, although most of Europa's surface is apparently tensional[11, 46]. They are so broad that they never appear to break the surface; they are unlikely to be good astrobiological targets. A relatively small number of craters are present on Europa because of its resurfacing. Yet these craters are essentially probes into the interior ice, and their walls, central peaks, overturned edges, and ejecta are all of possible interest for astrobiological exploration.

2.3. Ganymede

Ganymede (Fig. 1, center), between Europa and Callisto, is somewhat transitional in its surface features as well. Its surface is complex and varied, and is fragmented into older plates with younger bright material between them. The surface is characterized by the dark terrains of much older age than either Europa or the intervening bright-colored regions. The dark colors are due to surficial deposits produced by sublimation, mass wasting, ejecta covers, and tectonic activity[10] below which light-colored ice can be observed. Numerous craters exist in the dark terrains, as well as tectonism, although volcanism is rare or nonexistant[47]. These dark surfaces are the oldest surfaces on Ganymede, based on crater analyses[24]. As such, outcrops in these terrains, should they contain preserved biosignatures including fossils of organisms, would provide data for very ancient life on the JIM, perhaps 2-3 Gyr or older.

The bright terrains are grooved and ridged features sweeping long distances across the moon's surface[10]. They form apparently as grabens that are filled with ice or water as the surface on either side is extended by lateral rifting, and are significantly younger than the dark terrains[24]. The ridges and grooves may well contain outcrops of younger ice that contain traces of life. These, like those of Europa, could then be compared with the older fossils and signatures from the dark terrains and from Callisto.

Impact craters of wide morphological variety occur on Ganymede[24]. They range from very small bolide to very large comet impacts. Like Europa, they penetrate through significant ice thicknesses, exposing interior ice in outcrops within the craters or multi-ringed structures. Their ejecta likely contain interior ice too. All of these may be good astrobiological targets.

2.4. Callisto

Callisto's surface is very old and dark (Fig. 1, right). It is about half water ice and half salts, possibly clays and other materials. It shows little tectonic deformation, but has numerous impact craters[48]. The craters or their concentric ring structures in the case of large impacts, may be the only sites available for astrobiological exploration of the crustal materials. High topography on Callisto tends to be bright, and probably represents frost on those places, while low areas are dark. The most common high standing features on the surface are knobs and pinnacles that may be the remnants of crater rims, central peaks, and ejecta that have undergone considerable degradation[48]. These, then, may also be astrobiological targets since they represent interior ice, however eroded.

3. LIFE ON ICY WORLDS

3.1. The nature of life on JIM

We define life here as carbon-based forms capable of regeneration, self-replication, and evolution through a process akin to natural selection as on Earth. We do not consider the numerous suggestions that life may be based on different chemistries, duplicating mechanisms, or that do not evolve. No one knows how to recognize such life forms, other than to say that "we'll know it when we see it". Our paleontological and biological search strategy for biochemicals and body fossils developed for life on Earth should also reveal quite different forms should they exist. Whether or not we could recognize them as life is unknown. Our interpretations are not actually based on the nature of life anyway. Life that requires energy, reproduces, and evolves in any environment will be distributed in habitats because the requirements of different forms would differ, and evolution would select for organisms that can deal with different conditions. We assume with confidence that life would not be distributed homogeneously on any body where it evolved, including JIM. Indeed the presence of life makes the environment heterogeneous[49]. For these reasons, we do not search for life itself, but instead for habitats where many forms may be present. Such a plan provides many more options for exploration than plans aimed at the detection of particular life forms at any place on or in the ice. It also will enhance search strategies that do have specific targets, because a habitat will certainly provide better evidence of life than a general sample from unspecified sites on these moons.

Life on JIM may be extant, extinct, or both. In any case, once it is preserved whether it was a few hours ago or many millions of years ago, we treat the life signals as fossils. Fossils of life then include body fossils (the actual remains of a whole or part of an organism), impressions of whole organisms or parts of organisms, trace fossils (tracks, trails and other markings left by organisms), biotextures (rock or ice structures of biologic origin or influence), and biomarkers (chemicals characterizing life or life processes). These might be detected in a variety of ways from high resolution imaging, hyperspectral analyses, and/or chemical analysis by orbiting or surface instruments. In addition, we expect our search strategy will reveal living organisms if any are present in the near surface ice.

3.2. Habitats for life on icy worlds

Only one example of life in the universe is known—Earth. That life has occupied habitats associated with repeated and varying ice covers for the past 4.55 Gyr. Indeed, ice habitats constitute one of the largest habitats on Earth at present and in the past (Table 2). Earth's glaciations occurred at different times separated by long periods when Earth was not glaciated, yet life adapted to varying degrees of ice cover as the glaciations developed. Bacteria, unicellular eukaryotes, and multicellular eukaryotes lived with ice even when they had to adapt to its appearance rather quickly.

During each of these ice ages starting with a "Snowball Earth" when Earth may have been completely covered in ice some 2400 Myr and again at 750-600 Myr, and at several ice ages in the Phanerozoic, life survived and flourished. Two significant icy regions remain today in the Antarctic and Arctic that team with life. Life has not undergone extinctions during glaciations, other than locally, and in fact has adapted in general to icy environments. The end of the

Neoproterozoic glacial periods may have even triggered the radiation of animals and single-celled eukaryotes[50]. In modern icy seas, many organisms have adapted to spending significant parts of their life cycles in spaces in ice, either for protection or for trophic resources[4-6], and others live well below ice[2, 3]. Ice is no problem for life on Earth, and should not be for carbon-based life, had it evolved, on any icy body with suitable resources.

How might life be structured on JIM? Earth has a complex biota fueled chiefly by solar energy, which is more limited at JIM, so that it's ecosystems may differ significantly for possible ones on JIM. Earth's energy flows through complicated trophic structures based largely on photosynthesis[50]. JIM are unlikely to be that complex although some aspects of the model may apply. For example, a bacterial loop in the pelagic environment (open ocean) might well function on JIM, and microbial-type mats may live on any solid surface in the oceans or on the surface ice where it is protected from radiation and chemicals that degrade organic matter, such as caverns, cracks or overhangs in the ice at the surface.

Table 2. Earth's past and present glaciations. Life was quite common during glaciations 2-6 yet did not suffer significant extinctions, although local extinction and geographic range changes occurred. The Late Cenozoic through Quaternary Ice Ages may well have increased total biodiversity because new cold water environments presented ecologic opportunities for new species to evolve, chiefly from species already in the area or by migration of lower latitude species into the higher latitudes.

1.	**2400+ Myr**	**1st Snowball Earth**	**Archean-Proterozoic**
2.	**750-600 Myr**	**2nd Snowball Earth**	**Neoproterozoic**
3.	**450-440 Myr**	**Glaciation**	**Ordovician**
4.	**265-250 Myr**	**Great southern glaciation**	**Permian**
5.	**~14-0 Myr**	**High latitude glaciations**	**Late Cenozoic**
6.	**2-0 Myr**	**Ice Ages** Includes Glacial-Interglacial periods, including the present interglacial with its Antarctic and Arctic icy worlds	**Quaternary**

Earth analogs suggest several classes of habitats that could occur on JIM (Table 3). These include habitats on the sea floor, in the water column, and associated with ice. Life could exist in benthic soft and rocky substrates below the water-slush, in the water column, and in the icy crusts themselves. All of these situations are known in Earth's icy environments and have the potential for preservation in surface ice.

Benthic habitats are surely available on the floor of JIM's oceans whether the substrate is ice, rock or sediment. Surely the sea floor would have irregularities where sediment and debris would accumulate and that would create ecological opportunities for life. Hard substrates would result from erosion or bypassing of sediment by bottom currents induced by rotation or tides that might expose rock or ice.

Fig 2. Soft benthic habitat below the Ross Ice Shelf, Antarctica, at 620 m depth. The known biota in this habitat consists of foraminifera, mollusks, amphipods, ostracodes, isopods, and fish (shown here), which indicate that a much more complex biota is present at this site, some 500 km from the open ocean. Fish is about 15 cm long. Image of TV monitor picture by J.H. Lipps, 1979.

These might be expected to sweep some rocky areas where they exist bare of sediment that falls out of the water column or is transported past. Likewise, the ocean floors are unlikely to be smooth; instead basins and ridges or other high spots might be expected, especially if hydrothermal vents or rock ridges inflated by interior heat source. On soft substrata, organisms may burrow, wander on the surface or be attached to it. Firm substrata harbor attached and motile organisms, and a few types may be able to create holes. On both soft and firm substrata, microbial films and mats may develop.

These habitats under Antarctic ice contain a diverse assemblage (Fig. 2) utilizing transported resources[2, 3, 51]. In most respects, these habitats resemble those in the deep sea[52-56].

Table 3. Possible habitats, modes of life, transport mechanisms, and location at surface on the Icy Moons of Jupiter based on inferences from life associated with ice on Earth. Each JIM varies in the possibilities for life targets. The letters E, G and C show which moons may harbor particular preserved habitats.

Possible Habitats		**Organisms' Mode of Life**	**Transport to Surface Ice**	**Where at Surface**
Ice	Overhangs, caves, ledges, cracks, fissures, cavities	Biofilms, attached, motile	Present at surface where shielded by >2 m of ice	Areas protected from radiation & chemicals. E/G/C
	Fissures & cracks below surface level in water or ice	Biofilms, attached or motile on sides, drifting in water.	Accreted to sides by pumping or tidal action	Ridges & troughs, bands, chaos, craters, ejecta. E/G/C
	Pores & channels near surface in ice	Biofilms, attached, motile below surface in water or slush	Migrate to surface. Tectonic tilting or rotating of ice	Blocks & matrix in chaos, troughs & ridges, edges of bands, craters, ejecta. E.
	Pores, channels & cracks on bottom of ice shell	Biofilms, attached, motile, cryptic	Tectonic tilting or rotating of ice	Blocks in chaos, craters, ejecta. E/G/C
Water Column	Water-ice interface	Plankton, nekton	Accreted to ice, erupted, or flowed.	Overturned or tilted blocks, craters, flows or eruptions of water or slush. E/G/C
	Throughout water column	Plankton, nekton	Accreted to ice, trapped in rising anchor or other ice, water eruptions or flows, diapiric action	Flows or eruptions of water or slush. E/C
	In different water layers in stratified ocean	Plankton, nekton	Trapped in rising anchor or other ice, water eruptions or flows, diapiric action	Flows or eruptions of water or slush. E/G
	Near bottom water	Plankton, nekton	Trapped in anchor or other ice	Matrix of chaos, in & near ridges, cryovolcanoes. E.
Benthos	Soft substrata (mud, sand) on bottom of ocean	Epibiotic, motile, burrowing, interstitial, tiered	Trapped in anchor or grounded ice, ice gouging	Blocks & matrix in chaos, in & near ridges. E
	Hard substrata (rock, ice	Epibiotic, motile, attached, tiered	Trapped in anchor or grounded ice, ice gouging	Matrix in chaos, in & near ridges, cryovolcanoes. E.
	Hydrothermal vents	Epibiotic, motile, attached, tiered, symbiosis	Trapped in anchor or grounded ice, ice gouging, or floated in buoyant water	Matrix in chaos, in & near ridges, cryovolcanoes. E/G
	Submarine volcanoes	Epibiotic, motile, attached, tiered, symbiosis, zoned with depth	Trapped in anchor or grounded ice, ice gouging, or floated in warm buoyant or erupted water	Matrix in chaos, in & near ridges, cryovolcanoes. E/G?

Hydrothermal vents and possibly submarine volcanoes may be present on the icy moons, as they are on Earth. Vents support a wide diversity of microbes and metazoans alike[57-59]. These may be good models for life on JIM as well. Organisms associated with hydrothermal vents utilize symbiosis between bacteria and metazoans as a primary means of support. The bacteria provide nutrients required by the multicellular animals. However, such a complex association of organisms on Earth was accumulated over time from shallow-water organisms evolved much earlier that later developed the specialized symbioses that now support them. Bacteria and Archaea have likely occupied vents for much of the geologic history of Earth, but animals are relative newcomers, having appeared close to 580 Myr[60]. Submarine volcanoes would provide not only heat and solution sources but an edifice on the ocean's floor that would create depth differences and additional habitats.

The water column provides a variety of habitats. The water just above the sea floor is a different habitat from mid-water or shallower depths because of the suspension of bottom materials into it and the presence of bottom organisms. The mid-water habitat might be depauperate compared to other water column habitats because production of organic material might not reach it from shallower depths nor suspended material from the bottom may not reach that high. Life might utilize the water near the bottom of the ice because of organic matter liberated from ice-bottom habitats. These water column habitats would differ considerably from Earth's photosynthetically-driven ones. However, they may be powered by leakage of nutrients through the ice cover or from submarine vents. These may be very sparsely inhabited habitats if nutrient supply is low.

Ice on Earth includes a large variety of habitats (Table 3). These are usually inhabited by abundant photosynthetic primary producers[4, 5] (Fig. 3), a condition unlikely on JIM. However, other mechanisms for production might be possible there that would allow life to utilize cyrohabitats. Life seems improbable on the surface of Europa because of the high radiation, energetic chemical environment, and the lack of an atmosphere. Yet microbes on Earth can tolerate extremes of these, and a similar microbial biota might have evolved on Europa in places protected from such environmental hazards. These places could be in crevices, cracks, and channels, overhangs, caverns, and cliffs facing away from the radiation input. While such a biota seems unlikely, an adequate search for it should be undertaken on a future mission. On the other hand, the lower surface, cracks and fissures that penetrate from the bottom of the ice upwards are likely habitats for life[39, 61]. Surfaces commonly provide advantages for organisms in Earth's ice and would likely do so on Europa. The bottom of the ice might also contain abundant brine channels and pores that could be occupied as well.

Figure 3. Photosynthetic biota in basal sea ice habitat cored off Barrow, Alaska. Chief organisms are diatoms and bacteria. While a photosynthetic biota is not expected at JIM currently, the base of the ice with its pores and channels may be an important habitat there. Image by J. H. Lipps, 2003.

Three other habitats may be possible on JIM for which Earth analogs are poorly known or non-existent: impact craters, cryovolcanoes and subice lakes. On Earth, bacteria rapidly occupy impact areas[62, 63] and proceed through a process of distinctive succession because of disturbance. Possibly impact craters in the icy crust of Europa, of which there are few, may provide a similar kind of habitat. Europa has suffered impacts for its entire history in spite of the fact that the current surface is young. If life adapted over millennia to impacts or if impacts create a special habitat that becomes occupied by a subset of organisms from other habitats, like the water column, then these craters may constitute a separate habitat. Cryovolcanoes could also create conditions different enough to allow separate habitats to exist. The third possible analog is the 100 or so sub-ice cap lakes in Antarctica[64, 65]. These are unexplored except for their dimensions, depth below the surface and accreted ice with viable bacteria from the lake frozen onto roof of Lake Vostok[1, 66]. If Europa has a single large ocean, then the lake model will be imprecise for a number of reasons, although it may be informative. These reasons are lack of connectivity with other water bodies, long-term isolation, and probable limited biota not representative of the planetary biota as a whole. Plans by others are to study these lakes by probing into them in the future.

4. TAPHONOMIC SETTINGS FOR LIFE ON JIM

4.1 Taphonomy

Taphonomy is the study of the processes affecting an organism, part, biomolecules, marks and traces life makes, or a habitat from the time of an organism lived through the preservation process in rocks or ice, and finally to its discovery and study by a scientist. Thus, this is a critical field of study for astrobiology, or more correctly astropaleontology, since the geologic record contains a long and commonly abundant record of life. On bodies like JIM, it is also critical for another reason: it may well tell us where to target further investigations, even for extant life, in the surficial ice, and help to define conceptual designs for future exploratory instruments.

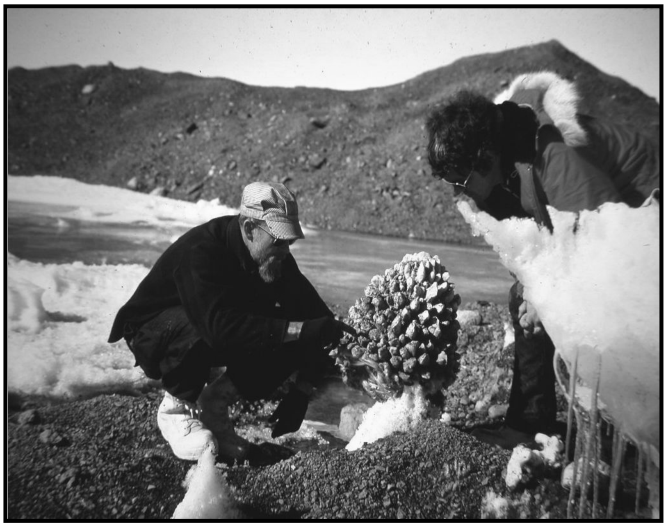
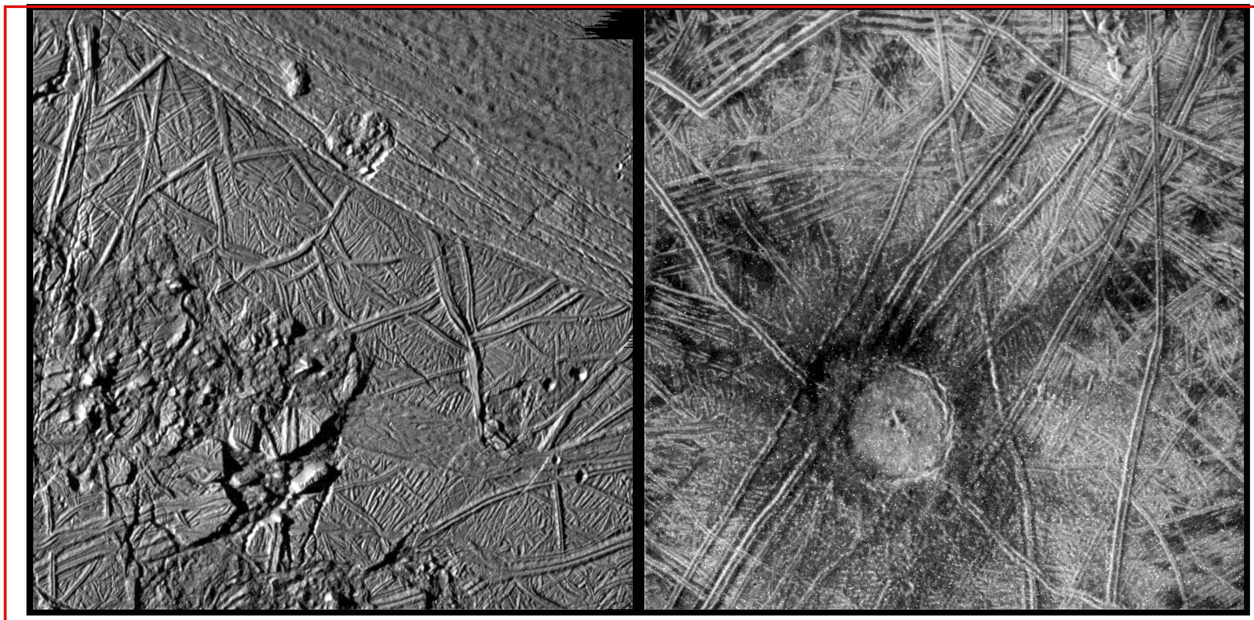


Fig. 4. Sediment and fossils (a sponge is shown here between the people) on the McMurdo Ice Shelf, Antarctica. These were trapped by anchor ice on the seafloor, transported to the bottom of the ice, then carried to the surface by sublimation[67].

Taphonomy involves several processes: how organisms died, how they are preserved, how they are transported and entombed in geologic materials (another subject called biostratinomy), and how they are exposed for scientific study. On JIM, presumably life frozen in ice is relatively immune to degradation, except by tectonic processes and radiation in the uppermost meter or so of the surfaces. Once frozen in ice, then it must be exposed at the surface or near surface by geologic processes. Because the ice on Europa and Ganymede, at least, is clearly of different ages and much of it has undergone tectonic activity of various sorts from rotated, tilted and disrupted blocks, to lateral and vertical displacements, to upwelled water or slush in lineaments and cracks, many possibilities suitable for further study exist among the many outcrops. A paleontological strategy might prove especially fruitful for exploration for life on the icy moons.

All of the habitats noted above have a potential for emplacement in the ice by various modes of transportation. For example, anchor ice, which forms on the sea floor in Antarctica, is also possible on JIM, depending on the temperature of the ocean. Anchor ice attaches to organisms and substrata on the sea floor and buoyantly transports them to the bottom of the icy shell[67] (Fig. 4). Ploughing of habitats by grounded or snagged ice, cryovolcanism ejecting subsurface water onto the surface, tidal pumping through cracks, emplacement of organisms by currents or tides in the ice, and perhaps other mechanisms are all possible on JIM, especially Europa.

Once habitats and organisms are transported to the ice, tectonic and impact activity may expose them at or near the surface. On Europa and Ganymede, the many varied tectonic features may contain material from any of habitats described above. The double ridges may results from water and ice pumped to the surface (Fig. 5), and these would likely contain organisms. The chaotic terrains contain blocks of surface ice that have been tilted, rotated or overturned, so that extensive outcrops of older and lower ice is exposed (Fig. 6). These are important sites to sample for astrobiology. The new smooth ice may be provide excellent targets too, for they may offer less complicated landing opportunities than other topographically high sites and a high probability of finding biological materials[45]. Impact craters, as probes into the interior, offer many complex outcrops in their walls, central peaks, and concentric rings, as well as in overturned crater edges and ejecta nearby. These may be important targets, just as the craters on Mars revealed outcrops of bedded sedimentary rock and hematite nodules discovered by the Opportunity rover earlier this year.

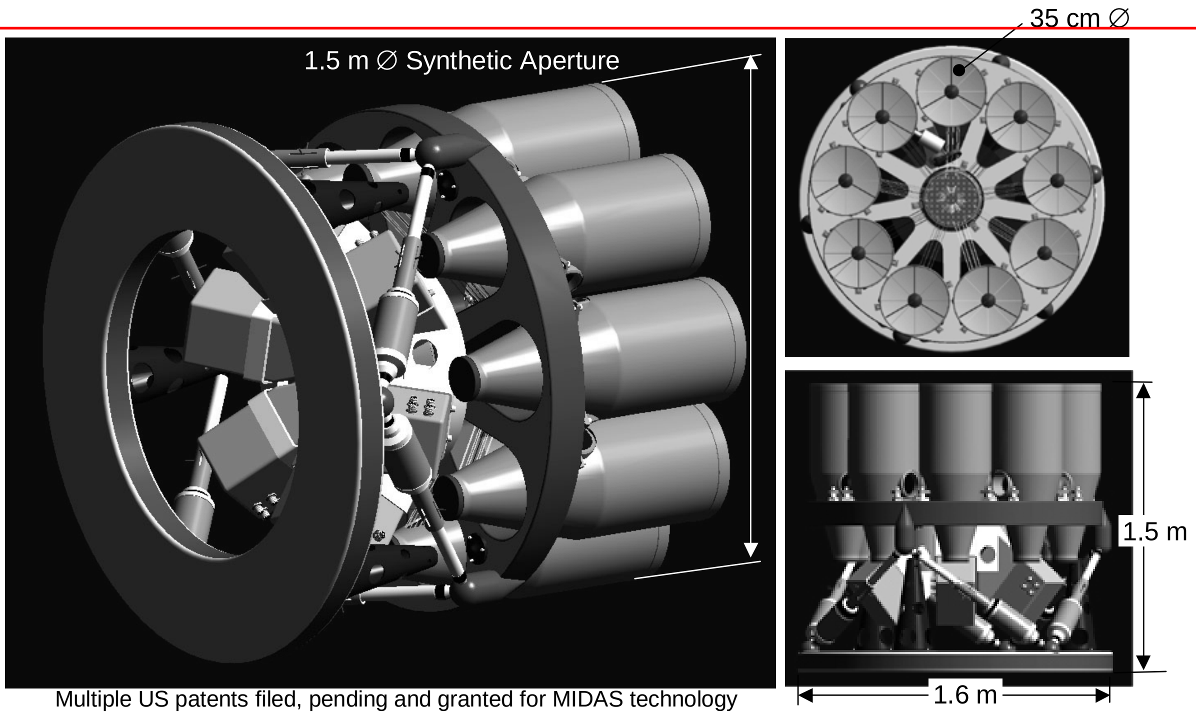


Figures 5 and 6. Astrobiological targets on Europa--ridged and chaotic surface (left) and an impact crater, ejecta and ridges (right). The double ridges (~1-2 km wide and 100-200 m high) may be composed of material pumped to the surface from the water below or merely crushed ice, caused by tidal flexing. Chaos consists of rotated and tilted ice blocks (up to 15 km across) that expose slopes of older ice and possibly bottom ice, and the intervening matrix may expose old broken ice. The crater (~20 km diameter) is surrounded by an ejecta blanket, probable overturned ice, and exposures in the walls and central peak of deeper ice. All of these exposures of older ice or material excavated from the surface or pumped to it are excellent candidate sites for the exploration for life habitats. NASA/JPL images.

4. SAMPLING FOR LIFE ON JIM

In order to understand these possible life sites, the myriad of geologic structures, units, colors, and other features currently observed on JIM must be studied informatively by image analyses and topographic mapping at scales from kms to cms. Images at any one resolution would have value, but together they significantly increase the total science output, significance and understanding. Most of the geologic features of JIM identified in Galileo's low-resolution images are not well understood and need study at the higher resolutions, including global mapping at resolutions of <1m/pixel and for many sites at much better resolution, with <1m vertical resolution of topography. Images with resolution like these will allow the testing of models of formation of major and minor features, and determination of structures within the features. High spatial and spectral resolution imaging will greatly enhance understanding of the surface compositions, chemistry, and thermal properties of the JIM, particularly if those spectra are obtained broadband, from UV to mid-infrared, in order to obtain complementary spectral signatures information to help remove ambiguities in interpretation. Other information on current tectonic and seismic activity can be obtained though use of active laser altimetry, and active imaging modes, such as vibrometry.

Thus, a sampling strategy for life and its history on JIM should include geologic, geochemical, seismic, tectonic and astrobiological analyses of possible sites where life might be preserved. This might be done by using an advanced remote sensing instrument, such as the Multiple Instrument Distributed Aperture Sensor (MIDAS)[68]. This science payload approach is currently funded under NASA's High Capability Instruments Concept and Technology (HCICT) program that focuses on science instrument technology development for the Prometheus class of Nuclear Electric Propulsion (NEP) missions to the outer planets. MIDAS (Fig. 7) provides the means to do these advanced studies by achieving fine spatial resolution of 2cm GSD from the Europa science orbit, and resolution <1m from the months of time spent in the Europa approach and exit spiral orbits. It will provide detailed imaging (Fig. 8) and spectroscopy of sites that might contain life either as biochemicals, biotraces or organisms themselves preserved in the ice. With this kind of information available, various kinds of landers might be more precisely positioned. In addition, the places most likely to



Multiple US patents filed, pending and granted for MIDAS technology

Figure 7. MIDAS Overall Design Concept.

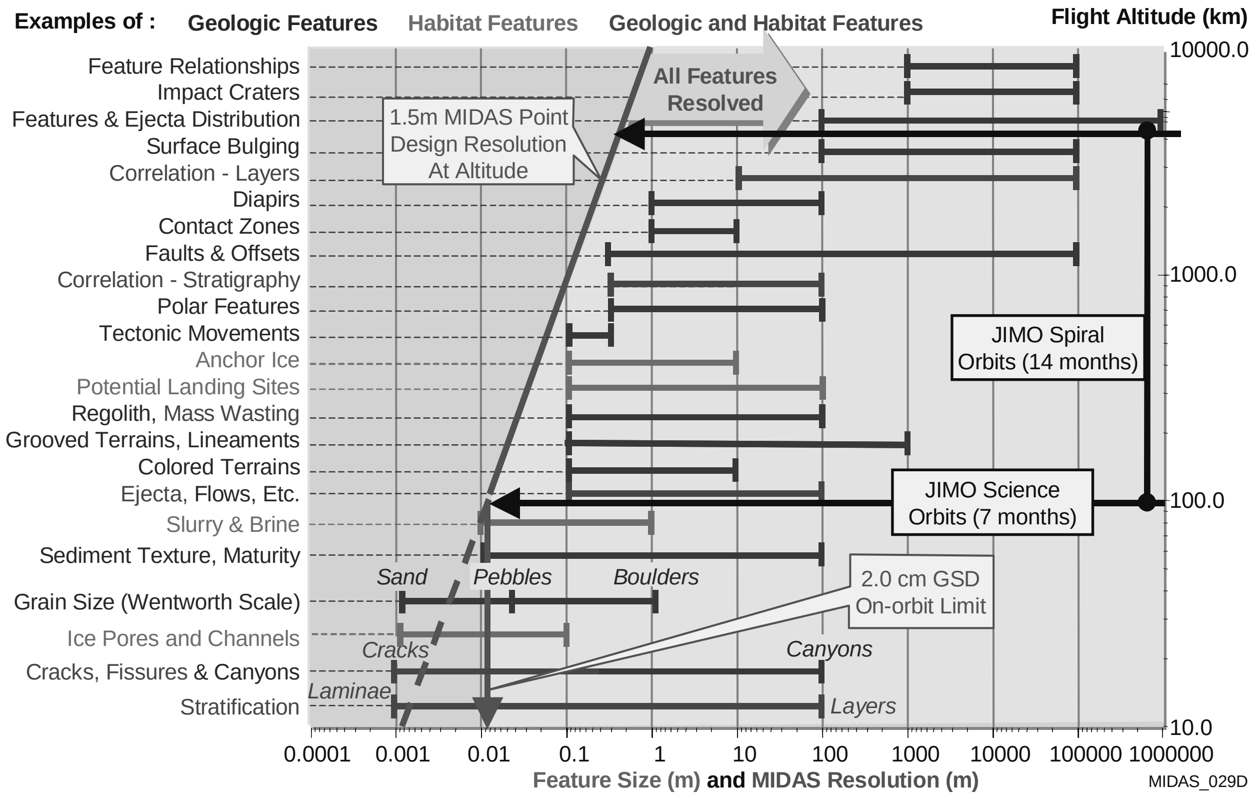


Figure 8. Resolution of geological and astrobiological features anticipated with MIDAS, as a function of orbit altitude.

reveal the presence of life are likely to be rough and topographically high areas that present difficulty in landing. A new vision for landers on the icy moons could be developed in order to take maximum advantage of the detailed data that MIDAS and complementary instruments, such as a high bandwidth topographic mapper, might return. Since orbiters and landers will unlikely launch before the 2015 JIMO (Jupiter Icy Moons Orbiter) mission timeframe, some time is available for detailed preparation. A fully developed landing mission to Europa, for example, may not take place for 40 or 50 years. In the intervening time, a whole new class and style of landing vehicles or robots based on new concepts yet to be devised might be developed. But it requires vision!

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