

Instrumentation for the search for habitable ecosystems in the future exploration of Europa and Ganymede

J. Chela-Flores

*The Abdus Salam ICTP, Strada Costiera 11, 34014 Trieste, Italia, and Instituto de Estudios Avanzados, IDEA, Caracas 1015A, República Bolivariana de Venezuela
e-mail: chelaf@ictp.it*

Abstract: The extensive evidence of an ocean over a silicate nucleus makes Europa a candidate for the emergence of a second evolutionary pathway of autochthonous life. We argue that the most urgent question in astrobiology is the origin of habitable ecosystems (a question in geochemistry), rather than the alternative search for the origin of life itself (a question in chemical evolution). Since certain Solar System bodies may share a similar geophysical past with Earth, our more modest approach forces upon us the question: *Can available instrumentation be the ‘pioneer’ in the discovery of habitable ecosystems in geophysical environments similar to the early Earth?* It will be shown that a central piece in this dilemma is the chemical element sulphur (S). The European non-ice surficial elements that distort the water–ice absorption bands were found to be widespread, patchy and, most likely, endogenous. The Galileo Mission discovered these patches, which were subsequently confirmed by the 2007 flyby of New Horizons. We argue that penetrators should be inserted into orbital probes in the future exploration of Jupiter’s System. Penetrators provide what could be a key instrument in the exploration of Europa, given the adverse space weather in its environment due to the Jovian magnetosphere and radiation. Indeed, there are alternative views on the radiation-induced S-cycles produced on the surficial molecules that are present on the icy surface; however, S is common to both interpretations. Hence, mass spectrometry should be an essential part of any future payload. The largest S-fractionations are due to microbial reduction and not to thermochemical processes, allowing a test of the hypothesis for the origin of habitable ecosystems. The microbial fractionation of stable S-isotopes argue in favour of penetrators for the survey of the surfaces of both Europa and Ganymede.

Received 12 November 2009, accepted 7 January 2010

Key words: biogeochemistry, biomarkers, dilational bands, dissimilatory sulphate reduction, Europa Jupiter System Mission, Europa, Ganymede, landing sites, LAPLACE Mission, mass spectrometry, sulphur patches on the European surface.

Introduction

The exploration of the Jovian System is one of the main priorities to be considered in future exploration of the Solar System. Amongst the scientific objectives a major issue is the question: *Is Europa habitable?* From the earliest stages of planning for the post-Galileo era this question has been framed more tightly in two formulations as follows: Does Europa represent a ‘habitable zone’ of the Jupiter System? Does Europa actually harbour life? (Cosmic Vision 2009). The Jovian System indeed displays many facets that are fundamental for astrobiology: It is virtually a small planetary system in its own right, built up out of the mixture of gas and icy material that was present in the external region of the solar nebula. Unique among Jupiter’s satellites, Europa is believed to shelter an ocean between its active icy crust and its silicate mantle (Anderson *et al.* 1997; Kivelson *et al.* 1997;

Spohn & Schubert 2003). In this liquid environment the main conditions for habitability may be fulfilled (Chyba & Phillips 2002). The likelihood of habitability rests on the fulfilment of some conditions: the presence of liquid water, an adequate energy source to sustain the necessary metabolic reactions and a source of the biogenic elements (C, N, H, O, P, S), which can be used as chemical, rather than as photosynthetic means for the synthesis of biomolecules. Appropriate pressure and temperature are also required. Europa is not unique among the three outer Galilean satellites, but according to current models, Europa represents the only case in the Jovian System in which liquid water is in contact with a silicate core (Bland *et al.* 2009). The presence of hydrothermal activity at the interface of the silicate core ocean could provide a variety of chemicals that could play a role in sustaining putative life forms at the ocean floor and, in particular, in its subsurface, since autotrophy at the lowest branches of the phylogenetic

tree does not require sunlight (Jannasch & Mottl 1985). Hence, emerging life in the early Solar System is more likely to have lived in subsurface, rather than surface, environments (Shock 2001).

The question of habitability on Europa by the identification of reliable biomarkers is a major aim in a truly worldwide collaboration for exploring the Jovian System beyond 2020. This project was originally called the LAPLACE Mission (Blanc *et al.* 2008). At present the mission is being planned under the name of the ‘Europa Jupiter System Mission’ (EJSM), in which the main partners are the American space agency National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The mission consists of two flight elements operating in the Jovian System: the NASA-led Jupiter Europa Orbiter (JEO), and the ESA-led Jupiter Ganymede Orbiter (JGO). The JEO and the JGO will explore Europa and Ganymede, respectively. However, significant contributions for the eventual mission are expected to come from the Japan Aerospace Exploration Agency (JAXA), whose main interest is centred on the Jovian magnetosphere. The Russian Federal Space Agency Roskosmos intends to contribute a lander for probing the European surface, but the JAXA and Roskosmos proposals are not yet part of the current baseline of the mission (Grassett *et al.* 2009).

Rather than facing the complex problem of the origin of life on Earth, by means of the time-honoured reductionist methods of chemical evolution, the main thesis of the present work is instead to focus on the origin of habitable ecosystems on Earth and elsewhere. By identifying such ecosystems we would be in a better position to plan rationally the future exploration of the Solar System and beyond. In this context we review the insights that may orient our search for reliable biomarkers. Early during the evolution of the Solar System, terrestrial planets and similar environments may have presented an analogous geophysical context that eventually favoured the emergence of life on Earth in the Early Archean. For instance, there is a large body of discussion regarding an Eden-like era in the evolution on the Martian surface during the Noachian c. 4500–3500 million years (Ma) before the present (BP). Multiple visual evidence of surficial morphological features argues in favour of the emergence of life on Mars in the geological era that was contemporary with the terrestrial Lower Archean (Grady & Wright 2006). The relevant observations include, amongst others, remote sensing from orbit (Mars Global Surveyor, Mars Odyssey and Mars Express) and robotic landers (Pathfinder, Spirit and Opportunity).

Fortunately, two reliable and easily accessible windows on the nature of the early habitable ecosystems on Earth are available: Firstly, the Pilbara Craton is an old and stable part of the continental crust and the uppermost mantle, which constitutes the hard and rigid outer layer of Earth. The Pilbara Craton includes its microfossil-rich reservoir, the Dresser Formation in Western Australia. Secondly, another easily accessible window on early Earth is the South African Kaapvaal Craton with its Barbeton Greenstone Belt

containing some of the oldest exposed rocks on Earth (>3.6 billion years (Ga) BP). We can safely infer relevant lessons from these two windows – real archives of the early steps of biological evolution around the Archean hydrothermal vents. For instance, both cratons have preserved details of ancient hydrothermal vents. In these sites we have learnt about the presence of a complex set of both sulphur-reducing bacteria in ~3.47 Ga barite deposit in the Pilbara Craton, North Pole Dome (Shen & Buick 2004), and methanogens of ~3.46 Ga from close to the same location (Ueno *et al.* 2006). It is remarkable that all of these microorganisms were already in existence a mere 1 Ga after the formation of Earth itself. Extraordinary fractionation of the isotopes of sulphur and methane has been recorded in these ancient sites.

In this respect we recall that significant contemporary sulphur reduction is now known to be possible and to take place in pore waters retrieved by the Ocean Drilling Project (ODP), which is now called the Integrated Ocean Drilling Program (IODP): This activity studies the nature of Earth’s seafloor. In 110 expeditions the IODP has collected about 2000 deep-sea cores from major geological features located in the ocean basins of the world. These searches have revealed natural populations that are able to fractionate efficiently S-isotopes up to $\delta^{34}\text{S}$ of -70% (Wortmann *et al.* 2001; the definitions of the delta parameters are given in the Glossary). These extremely high delta values are present, in spite of the Rees upper bound of -46% that had been suggested earlier (Rees *et al.* 1973).

We have learnt a great deal of relevant information concerning the geologic and evolutionary history of how biogeochemical interactions in hydrothermal vents are able to turn rocks and hot water into habitable ecosystems (Reysenbach & Shock 2002). On the Archean Earth we have gathered sufficient insights to extrapolate these possible ‘cradles of life’ (with the inspired phrase of Schopf 2001) to other environments of the early Solar System, when evolving terrestrial planets, or satellites, may have had an analogous geologic structure. Another aspect that emerges from these ancient settings is that discoveries in the Dresser Formation point towards an active subsurface biosphere (Canfield 2006). A prolific current deep terrestrial biosphere can also be documented today with comparable magnitude to that corresponding to the biota on Earth’s surface (Whitman *et al.* 1998). These remarks raise the question that Europa’s seafloor, including its presumably prolific subsurface (as in the terrestrial case), could be a significant ecosystem. The difficulty raised by the ice-closed environment for the European ocean (Gaidos *et al.* 1999) has been argued convincingly not to be an unavoidable impediment for the emergence of life itself (McCollom 1999; Zolotov & Shock 2001). The instrumentation for reaching such biota is not beyond present technology’s grasp, since there are mechanisms capable of raising the processed (microbially fractionated) nutrients from the seafloor and the subsurface to the icy cover of Europa. One example will be discussed in some detail in the fifth section.

Sulphur patches and space weather in the neighbourhood of Europa

The Galileo Mission discovered the sulphur patches of non-ice elements on Europa's icy surface. These patches have been inferred and confirmed over a 20 year period. They match the distribution of an ultraviolet absorber that was suggested quite some time ago by the Voyager data (McEwen 1986). The New Horizons Mission on its way to Pluto has confirmed the patches of non-ice elements (Grundy *et al.* 2007). Based on combined spectral reflectance data from the Solid State Imaging (SSI) experiment, the Near Infrared Mass Spectrometer (NIMS) and the Ultraviolet Spectrometer (UVS), it has been argued that the non-water ice materials are endogenous in three diverse, but significant, terrains (Fanale *et al.* 1999). Effusive cryovolcanism is clearly one possible endogenous source of the non-water-ice constituents of the surface materials (Fagents 2003). The most striking feature of the non-water surficial elements is certainly their distribution in patches. Implantation would be expected to produce a more uniform surface distribution if the source were ions from the Jovian plasma; it may be argued that if the plasma from the magnetosphere were responsible for the sulphur distribution, some geologic process has to be invoked to allow for a non-uniform distribution (Carlson *et al.* 1999). Alternatively, the sulphurous material on the surface may be endogenous. In other words, the cryovolcanism on Europa would be from the bottom of the global ocean, more like the 'black smokers' that are found on Earth's seafloor. Europa's surface is an extremely hostile environment, as a result of space weather, namely the constant exposure to Jupiter's intense radiation belts. The topmost ice layer is subject to harsh radiation, but changes other than chemical reactions (photolysis, radiolysis) are not to be taken into account since, for instance, there is no high-energy (several gigaelectron volt (GeV)) deep-inelastic scattering that would change the nuclear identity of the atomic components of the surficial molecules participating in the above-mentioned S-cycles. Meteoroid gardening might lead to the contamination of the upper surface 1–2 m with regolith (Cooper *et al.* 2001). This would require penetrating deeper than this depth in order to reach *pristine material*, which would be challenging, even for penetrators. However, since sulphur processing by bacteria may lead to such radical and extreme depletions of ^{34}S compared to exogenous sulphur, even if some of the contaminated surface by the gardening process contains non-biological sulphur, and penetrators do not reach the above-mentioned depths (1–2 m), robotic mass-spectrometry analysis of the non-water ice elements would identify biologically processed sulphur (for example, $\delta^{34}\text{S}$ reaching from -50‰ to -60‰).

Indeed, if seafloor microbes were present, they would be able to fractionate substantially all of the endogenous sulphur that would reach the icy surface (for instance, by means of the mechanism, discussed in the fifth section). The biogeochemical signatures would be robust and could in principle be revealed by mass spectrometry. In fact, our original hope to

get underneath the ice with a cryobot and a hydrobot (Horvath *et al.* 1997) has to be seen in the light of the advent of feasible technologies that can probe the European surface searching for biogenicity (cf. the following section). Although in the present discussion we argue in favour of the detection of biomarkers imprinted on the icy surface itself with the help of penetrators, alternative instrumentation with new feasible technology is in the process of being developed for penetrating even deeper into the ice (Ulamec *et al.* 2007; Weiss *et al.* 2008). Such additional instrumentation would give us a better understanding of the icy crusts of Europa and Ganymede, providing additional tests of our hypothesis.

In the post-Galileo era, New Horizons' mapping of Europa not only largely confirmed what we knew about Europa, but it has extended coverage of its surficial icy surface. The new charts have shown that the non-ice material is distributed symmetrically about the apex of the trailing hemisphere (270°W , 0°N). This is somehow in contrast to what was said earlier regarding the endogenous nature of the surficial sulphur. We can rationalize this apparent dilemma as follows: the New Horizons result is consistent with some implantation of sulphur from Io and of bombardment by magnetospheric charged particles. Some deviation from this symmetry is an area of cleaner ice south of the trailing apex associated with ejecta from the Pwyll crater (271°W , 25°S). The Pwyll ejecta contain less 'non-ice' with an external source for that material. However, this does not exclude at least some significant endogenic component in the non-ice elements (Carlson *et al.* 2005), nor does it exclude the possible traffic of fractionated sulphur from the ocean floor to the icy surface.

Earth analogues of the European icy patches and the penetrator technology

Recently a group of microorganisms was discovered in Antarctica underneath Blood Falls (Taylor Dry Valley). This ecosystem had survived under the ice for more than a million years in very harsh conditions (Mikucki *et al.* 2009). In addition, underneath 4 km of ice in that continent there is a subsurface lake that presumably contains living microbes. This hypothesis has been confirmed, since microorganisms have been found from accretion ice retrieved from ice 3590 m below Vostok Station (Priscu *et al.* 1999). Extrapolation of the data to the lake itself, known as Lake Vostok, may support a microbial population, despite more than 10^6 years of isolation from the atmosphere. These examples are just the 'tip of the iceberg', since by means of ice-penetrating radio-echo sounding surveys we have discovered the existence of about 280 subglacial lakes, most of them being located under the East Antarctic ice sheet (Smith *et al.* 2009).

The extremophilic microorganisms (both prokaryotes and eukaryotes) that are known to inhabit some of these lakes, in particular those of the McMurdo region, may serve as models for extraterrestrial life on planets and their satellites. Water oceans are expected to exist on the moons of Jupiter, such as Europa, Ganymede, Callisto (Spohn & Schubert 2003), Titan (Lorenz *et al.* 2008) and even Enceladus (Postberg *et al.*

2009). If indeed under the surface of Europa there is an ocean, it is reasonable to search for biomarkers in forthcoming missions, such as the EJSM.

All of the above facts encourage the search for biogenicity. Our main interest is the search for biosignatures on Europa on the sulphur patches discovered by the Galileo Mission (Singer 2003; Chela-Flores & Kumar 2008; Chela-Flores *et al.* 2009). The most appropriate technology – the penetrator – is currently being further developed by the UK Penetrator Consortium for preliminary trials on our own Moon. These instruments consist of small projectiles that can be delivered at high velocity to reach just beneath the surface of planets or their satellites for probing samples of surficial chemical elements, amongst other investigations.

This type of instrumentation (the penetrators) has a long history of feasible technological development by several space agencies. So far delivering them to Mars has encountered technical difficulties on two occasions.

(a) The preparation of the MARS-96 robotic spacecraft scientific mission to Mars was begun in 1989 by the Russian Academy of Sciences and the Russian Space Agency (Zakharov & Fechtig 1994). It contained penetrators with scientific instruments developed and manufactured in institutes of various countries of the European Union, Bulgaria, Russia, Slovakia, Switzerland, Ukraine and USA. The Mars 96 spacecraft was launched from Baikonur on 16 November 1996. The spacecraft was not inserted into the interplanetary trajectory to Mars due to a malfunction in the third stage of the rocket. During the third revolution around Earth the spacecraft re-entered Earth's atmosphere and fell into the Pacific Ocean (Surkov & Kremnev 1998).

(b) Deep-Space-2, NASA's first penetrator attempt, intended to demonstrate planetary micro-penetrator technologies for Mars. Unfortunately, in December 1999, it failed to land successfully in the north-polar region. The 2 kg probes were expected to enter the Martian atmosphere and passively orient themselves to meet peak heating and impact requirements. The forebody was to reach a depth of 0.5–2 m, while the aftbody would remain on the surface for communications. Each penetrator system included a suite of highly miniaturized components for a science payload package (Gavit & Powell 1996).

However, in spite of these two failed attempts, in the future a return to the penetrator technology is likely for the exploration of the Solar System, especially due to two current efforts in the UK and Japan.

(c) The recent interest in lunar science in the UK has led to the development of penetrators by the UK Penetrator Consortium (Smith *et al.* 2008; Gowen *et al.* 2009). These instruments are expected to make *in situ* measurements at widely separated locations on the Moon with a payload that would allow a variety of measurements on the lunar surface. In addition, Japan and Russia have indicated their interest in participating in the EJSM (cf. the Introduction). These nations also have extensive experience in the development of penetrators (cf. paragraphs (a) and (d)), strengthening the possible synergy that could eventually lead, with the EJSM,

to a significant penetrator technology for the search of biomarkers on Europa and Ganymede.

(d) A penetrator probe was developed in the course of the former Japanese LUNAR-A project (Mizutani *et al.* 2000), which was cancelled before it could be launched. The penetrator seismometer system (PSS) is now being developed to preserve the sensitivity required to detect small, deep moonquakes, as well as other types of lunar seismic events into the lunar regolith. By taking advantage of the unique qualities of penetrators, multiple seismic stations can be deployed, providing an ideal setup for seismic observations. The seismometer system could be deployed on the Moon to obtain new lunar seismic data. This data will enable a better understanding of the internal structure of the Moon, including its core (Shiraishi *et al.* 2008). To carry out seismic observations after a hard landing (impact acceleration of about 8000 G) the PSS could satisfactorily observe seismic events on the Moon by investigations in a simulated lunar environment after a simulated impact test. The preliminary results indicate that the newly developed seismometer system based on penetrator technology can function properly after impact and is sensitive enough to detect seismic events on the Moon (Yamada *et al.* 2009).

Finally, if budgetary constraints force a choice between penetrators and landers, some advantages of the penetrator approach are evident: the low mass of these instruments, combined with their agility in deployment, make them worthy complements to orbiter missions launched without landers.

How can we tell life from non-life?

Sulphate-reducing bacteria use sulphate as an oxidizing agent, reducing it to sulphide. Most sulphate-reducing bacteria can also use other oxidized sulphur compounds, such as sulphite and thiosulphate, or elemental sulphur. This type of metabolism is called dissimilatory, since sulphur is not assimilated into any organic compounds. Of the possible fractionation mechanisms responsible for sulphur isotope variations that may occur in nature, dissimilatory sulphate reduction produces the largest fractionations in the sulphur stable isotopes (Brunner & Bernasconi 2005). This is a ubiquitous process on Earth, since a large number of species of prokaryotes are known to possess this capability (Detmers *et al.* 2001). These microbes are particularly exciting for their applicability to the nature of a European habitable ecosystem, since they are known to be widely distributed in anoxic environments. Their extremophilicity is characterized by toleration of temperatures in the range from just below freezing point to their highest recorded ambient temperatures, over the boiling point of water. They can also survive in salinities from fresh water to brines.

A great deal (but not all) of what is known about sulphate reducers comes from pure cultures, where the outcome of the depleted sulphide ranges between –4‰ and –46‰ (Harrison & Thode 1958; Kemp & Thode 1968; McCready 1975). In natural environments some significant insights on

the relation between sulphur and life have been retrieved from the Black Sea, called 'Pontus Euxinus' by the Romans (its waters may be referred to as euxinic). The Black Sea derives its name from its dark sulphur-laden waters; unlike the Mediterranean Sea, where visibility extends down to a depth of about 30 m, visibility reaches only as far as about 5 m in the Black Sea. At the Black Sea's oxic/anoxic boundary, anaerobic organisms, such as sulphate reducers, consume the rain of organic material falling from above, producing H_2S , while anaerobic methanotrophs reduce the concentration of methane (Grice *et al.* 2005). More relevant for the main theme of this work is to underline that naturally occurring sulphides in sediments, and in euxinic waters, can be depleted in ^{34}S by as much as -70% (cf. the Introduction).

However, through a repeated cycle of sulphide oxidation to elemental sulphur, followed by a reaction in which a single compound is simultaneously oxidized and reduced (disproportionation), these microbes can generate large fractionations that go beyond the Rees upper bound of -46% (see the Introduction and Canfield & Thamdrup 1994). We must underline that if sulphur fractionation concerns us as a possible trigger for the European patches on its icy surface, then detecting large fractionations would be a fingerprint of life. Measuring this effect is within reach of the penetrator technology coupled with the current capabilities of miniaturized mass spectrometry.

In a micropaleontological context, conventional sulphur isotope studies are inconclusive about the mass balance between the two sources, because the $^{34}\text{S}/^{32}\text{S}$ ratios of vent fluid H_2S and chimney sulphide minerals may reflect not only the mixing ratio, but also isotope exchange between the sulphate and sulphide. Examples may be found in both the Pilbara and Kaapvaal cratons. High-precision analysis of the isotope ^{33}S can provide a unique constraint, because isotope mixing and isotope exchange result in different $\Delta^{33}\text{S}$ values of up to 0.04% , even if $\delta^{34}\text{S}$ values are identical (cf. definitions in the Glossary and Ono *et al.* 2007). However, if we focus our attention on probing Europa's ice to test the hypothesis that substantial processing of seafloor sulphur may have taken place, measuring a large effect (for instance, $> -60\%$) would imply that the biogenic signal would not be ambiguous. In addition, the complementary test on Ganymede should be followed up to test our main hypothesis (cf. the Discussion and conclusions section).

However, we must be certain to separate clearly geochemical signals that are linked with life from those signals that are of a non-life nature, since inorganic sulphur fractionation can indeed take place. Fortunately, bacterial and thermochemical sulphate reduction apparently occur in two mutually exclusive thermal regimes. We should recall that diagenesis refers to changes that take place in a sedimentary rock at low temperatures and pressure after its deposition. The first of the two mutually exclusive regimes where sulphate reduction takes place is low-temperature diagenetic environments with $0 < T < 60-80^\circ\text{C}$. The second regime is high-temperature diagenetic environments with $80-100 < T < 150-200^\circ\text{C}$ (cf. Machel *et al.* 1995). Thermochemical

sulphate reduction is an abiotic process, in which sulphate is reduced to sulphide, due to heat, rather than due to biology. However, the above two thermal regimes overlap in some cases (Krouse *et al.* 1988), when aqueous sulphate can be reduced by organic compounds at temperatures close to the water boiling point. A major difficulty for an unambiguous biogenic signal fortunately is once again avoided, since sulphate abiotic reductions are generally not as large as the biogenic ones. For instance, experiments have yielded fractionations in the range $10-20\%$ for temperatures in the range of $100-200^\circ\text{C}$ (Kiyosu & Krouse 1990).

Particularly relevant for the putative European habitable ecosystem is the hydrothermal reduction seawater sulphate, which would take place, according to equilibrium fractionation processes, varying with temperature. The corresponding isotopically heavy sulphates are easy to distinguish from marine sulphate in the geologic record. Isotopic depletions can also take place during the magmatic reduction of gaseous SO_2 to H_2S , but the expected range of $\delta^{34}\text{S}$ depletions lie constrained in the range $15-20\%$ (Rollinson 2007). Thus, abiotic sulphur isotope fractionation tends to be the result of hydrothermal reactions and is quite constrained with respect to the large effects that sulphur bacteria are capable of achieving. Bacterial sulphate reduction is characterized by large $\delta^{34}\text{S}$ (reaching over -70% , as mentioned in the Introduction), whereas thermogenic sulphate reduction generally leads to smaller ^{34}S depletions (Machel 2001; Hoefs 2009).

The imprint of microbial activity on Europa's surface and not on Ganymede

Traces of seafloor microbial activity could be found on the European icy surface for a variety of reasons. Amongst the many mechanisms that have been suggested, we underline the fluid-dynamics analysis of the European ocean (Thomson & Delaney 2001). It invokes the possibility of plumes reaching the bottom of the icy surface from the seafloor, potentially carrying the microbial fractionated sulphur to within reach of the penetrators. Indeed, the sulphurous material on the surface may be endogenous (Carlson *et al.* 1999; Kargel *et al.* 2000). The size of ice domes and movement of ice rafts on the surface of Europa are consistent with what one could expect if hydrothermal vent plumes in an ocean beneath the ice cause melting.

If the plumes arise from magma-heated regions of the seafloor, some of the sulphur non-ice elements observed on the surface of Europa could be remnants of the sulphur particles that were processed on the seafloor and in the oceanic subsurface. They should be absent on Ganymede's surface, since the contact of a silicate core with the ocean would be missing and the longer distance from Jupiter would favour more cryovolcanism on Europa. To sum up, with Thomson & Delaney's (2001) analysis it is possible to interpret the non-water elements on the icy surface as the product of eruptions on the seafloor that were subsequently raised to the icy surface. The rotation of Europa and the weak stratification of its

ocean are in principle capable of inducing hydrothermal vent plumes from dispersment, continuously rising like a cyclone through 100 km of ocean to reach the base of the ice. This assumption is particularly reasonable in the chaos-type features, such as melt-through structures that could be formed by rotationally confined oceanic plumes from heated regions on the seafloor. In other words, Thomson & Delaney (2001) apply plume dynamics to Europa from what we know on Earth, particularly in our oceanic floors that have been fully explored, such as the Juan de Fuca Ridge off the west coast of Canada and the USA.

Where should we land the penetrators to probe for reliable biomarkers?

In ice dynamics dilation is a term associated with an opening process, where crusts on either side are moved apart and new surface is created between them. Dilational areas, where cracks open wide – making them more attractive for the search of landing areas – are called dilational ‘bands’. These features are a common occurrence on the icy surface of Europa. These bands slope at about five degrees, or less. These broad tracks, tens of kilometres wide and hundreds of kilometres long, form when cracks in the ice shell open in response to the gravitational pull of Jupiter and the other Galilean moons. For landing, the penetrator should aim at a site that is not near levels that have been raised beyond an inclination of 30°. There is a large concentration of dilation features south of the equator from 180° for roughly 60°. For example, there is the ‘Sickle’ dilation area at longitude 240° W, just below the equator, within a large area discovered by the Galileo NIMS team. It extends north of the equatorial region, between 0° and 30° N, and between the longitudes 240° and 270°. In other words, one of the major discoveries of the Galileo Mission was what we call in the text the ‘*large NIMS area*’ (Plate 1, p. 11,843 in McCord *et al.* 1999). On this wide location there is an appreciable abundance of non-ice material.

The interior of the Sickle band in this region is smooth and flat (Greenberg 2005). Dilational areas could be smoother than the surrounding ice, because they formed gradually, unlike impact craters. Selecting these areas for future landings seems appropriate, keeping in mind that our paramount objective is to search for biomarkers with penetrators that should be deployed in the most favourable locations.

With respect to the case of Ganymede (and particularly for testing the hypothesis for the origin of habitable ecosystems), some suggestions are possible at this stage for the best landing site for eventual JGO penetrators: From a detailed examination of the small-scale characteristics of Ganymede’s high latitude terrain, a sequence of high-resolution SSI images was obtained in a transect from 56° N, 174° W to 65° N, 165° W during Galileo’s G2 encounter (Khurana *et al.* 2007). These images imply that few (if any) shadows are visible, since small-scale slopes on Ganymede are generally less than 20° (Oberst *et al.* 1999). These small-scale slopes are compatible with the needs for a good landing site for the proposed JGO

penetrators. However, possibly the technology of penetrators could also be developed in time to a degree that an impacting system will not require smooth terrain.

Can a penetrator be a ‘pioneer’ in the discovery of habitable ecosystems?

This possibility should be given serious consideration (Gowen *et al.* 2009). Most attention on the non-ice components of the icy patches has been given to sulphate salts and sulphuric acid (McCord *et al.* 1998, 1999; Carlson *et al.* 2002; Dalton *et al.* 2005). These interpretations of the sulphur-containing components of the icy patches have a most significant coincidence: the element sulphur continues to be present in both interpretations of the Galileo data. This remark helps to emphasize the main point: knowledge of the source of sulphur fractionation (thermochemical sulphate reduction, bacterial sulphate reduction or sulphur disproportionation) is of vital importance for defining a feasible and reliable biomarker.

From the arguments discussed in this paper a microbial ecosystem at the European seafloor and in its subsurface could indeed fractionate sulphur to a degree that is feasible to be detected by the instruments that are integrated in a penetrator or lander. The penetrator’s agility makes this instrument a leading candidate for the eventual payloads of both the JEOs and JGOs of the EJSM. In addition, the UK supports current penetrator development for the exploration of Solar System bodies, including the Moon, Ganymede, Europa and Mars.

Our main hypothesis that the origin of habitable ecosystems is linked to the seafloor activity of hydrothermal vents requires direct contact between the silicate core and a liquid water ocean, as occurred in early Earth, according to the geochemical evidence that we have retrieved from both the Pilbara Craton and the Kaapvaal craton (cf. the Introduction). There is also evidence for an ocean on Ganymede (McCord *et al.* 2001), but it would not be in contact with its silicate core (cf. the Introduction). In the two Galilean satellites that the EJSM intends to explore, penetrators (supplied with mass spectrometry) should yield different results for fractionated sulphur according to our hypothesis for the origin of habitable ecosystems: *The biogenically processed icy patches of Europa should give substantial depletions of ^{34}S , while Ganymede measurements should give significantly lower values for the depletion of ^{34}S .* In other words, diverging results – large minus $\delta^{34}\text{S}$ for Europa and small minus $\delta^{34}\text{S}$ for Ganymede – would test the above hypothesis for the origin of habitable ecosystems.

Discussion and conclusions

Regarding the significant issue of selecting the most promising landing site, in the present work we have discussed some preliminary ideas implying that there are significant advantages from the point of view of the penetrator technology to prefer Sickle in the case of Europa (and possibly other similar flat dilational bands). Dilational bands would be

steeped with sulphur if they were appropriately chosen (within the large ‘NIMS’ area, cf. the sixth section). If the search for biosignatures is focused on the NIMS area, non-ice chemical elements of the icy patches may bear fingerprints of life (biogeochemical ones). Non-ice elements, particularly sulphur, should be abundant on dilational bands chosen within this large area. Indeed, the disagreement of the two above-mentioned Galileo Mission groups does not question whether sulphur is present in the NIMS area (McCord *et al.* 1998; Carlson *et al.* 2002; Dalton *et al.* 2005). Granted, there is some disagreement on the precise compounds that distort the absorption bands, since most likely they can be either sulphate salts or alternatively sulphuric acid hydrates, but there is general consensus that sulphur is present in the molecular compounds that are present the icy surface. However, in any case, a landing site, such as Sickie, is appropriate for penetrators, due to the lack of significant elevations. The scientific return of taking advantage of the penetrator technology would be justified. Even if the sulphur patches turn out to have a small $\delta^{34}\text{S}$ parameter (with a modulus much smaller than -70% , hence not necessarily biological), the nature of the chemically rich icy surface would be better understood at the geochemical level. For the (essential) simultaneous exploration of the EJSM with Ganymede’s JGO, we have pointed out a suitable landing site.

Further arguments discussed in favour of penetrator technology included the ability to provide measurements at globally spaced sites on planetary bodies, for example, a seismic network (Lunar-A), and in an astrobiological context they are ideal instruments to carry out an unambiguous biogeochemical search for biomarkers.

We conclude that the implementation of penetrators in the future exploration of the Jupiter System is worthy of all the support that will be needed, both at the national and the international level. With the help of such appropriate instrumentation, we can face one of the most transcendental questions in astrobiology, namely the discovery of a habitable ecosystem elsewhere in our Solar System.

Glossary: the delta parameters

The redistribution of isotopic mixtures can be followed up in terms of the parameter:

$$\delta^{34}\text{S} = \left[\frac{(^{34}\text{S}/^{32}\text{S})_{\text{sa}}}{(^{34}\text{S}/^{32}\text{S})_{\text{st}}} - 1 \right] \times 10^3 [\text{‰}, \text{CDM}].$$

Its value is close to zero when the sample coincides with the corresponding value of the Canyon Diablo meteorite (CDM), a triolite (FeS) that was found in a crater north of Phoenix, Arizona. This parameter allows a comparison of a sample (sa) with the standard (st) CDM. The relevant terms are the dominant sulphur isotope (^{32}S) and the next in abundance (^{34}S). There are corresponding formulae for the other isotopes of sulphur (i.e., 33 and 36). In terms of them, we can define the capital delta notation Δ^{33} used in the fourth section, as

$$\Delta^{33}\text{S} = \delta^{33}\text{S} - 0.515 \delta^{34}\text{S}.$$

References

- Anderson, J.D., Lau, E.L., Sjogren, W.L., Schubert, G. & Moore, W.B. (1997). *Science* **276**, 1236–1239.
- Blanc, M. *et al.* (2009). *Exp. Astron.* **23**, 849–892.
- Bland, M.T., Showman, A.P. & Tobie, G. (2009). *Icarus* **200**, 207–221.
- Brunner, B. & Bernasconi, S.M. (2005). *Geochim. Cosmochim. Acta* **69**, 4759–4771.
- Canfield, D.E. (2006). *Nature* **440**, 426–427.
- Canfield, D. & Thamdrup, B. (1994). *Science* **266**, 1973–1975.
- Carlson, R.W., Anderson, M.S., Johnson, R.E., Schulman, M.B. & Yavrouian, A.H. (2002). *Icarus* **157**, 456–463.
- Carlson, R.W., Anderson, M.S., Mehlman, R. & Johnson, R.E. (2005). *Icarus* **177**, 461–471.
- Carlson, R.W., Johnson, R.E. & Anderson, M.S. (1999). *Science* **286**, 97–99.
- Chela-Flores, J., Bhattacharjee, A.B., Dudeja, S., Kumar, N. & Seckbach, J. (2009). Can the biogenicity of Europa’s surficial sulfur be tested simultaneously with penetrators and ion traps? *Geophys. Res. Abstr.* **11**, EGU2009-0, 2009, EGU General Assembly 2009, Vienna, 22 April, <http://www.ictp.it/~chelaf/EGU2009JCTetal.pdf>.
- Chela-Flores, J. & Kumar, N. (2008). *Int. J. Astrobiol.* **7**, 263–269, <http://www.ictp.it/~chelaf/JCFKumar.pdf>.
- Chyba, C.F. & Phillips, C.B. (2002). *Orig. Life Evol. Biosph.* **32**, 47–68.
- Cooper, J.F., Johnson, R.E., Mauk, B.H., Garrett, H.B. & Gehrels, N. (2001). *Icarus* **149**, 133–159.
- Cosmic Vision (2009). http://www.esa.int/esaSC/SEMA7J2IU7E_index_0.html, Theme 1.
- Dalton, J.B., Prieto-Ballesteros, O., Kargel, J.S., Jamieson, C.S., Jolivet, J. & Quinn, R. (2005). *Icarus* **177**, 472–490.
- Detmers, J., Brüchert, V., Habich, K.S. & Kuever, J. (2001). *Appl. Environ. Microbiol.* **67**, 888–894.
- Fagents, S.A. (2003). *J. Geophys. Res.* **108**(E12), 5139.
- Fanale, F.P. *et al.* (1999). *Icarus* **139**, 179–188.
- Gaidos, E.J., Neelson, K.H. & Kirschvink, J.L. (1999). *Science* **284**, 1631–1633.
- Gavit, S.A. & Powell, G. (1996). *Acta Astronaut.* **39**, 273–280.
- Gowen, R. *et al.* (2009). Looking for astrobiological signatures with penetrators on Europa. In *Physical and Engineering Sciences Exploratory Workshops*, W08-115: Biosignatures on Exoplanets; The Identity of Life, 22–26 June 2009, Mulhouse, France, <http://www.ictp.it/~chelaf/ESFsummary.pdf>.
- Grady, M. & Wright, I. (2006). *Philos. Trans. R. Soc. London, Ser. B* **361**, 1703–1713.
- Grasset, O., Lebreton, J.-P., Blanc, M., Dougherty, M., Erd, C., Greeley, R., Pappalardo, B. & the Joint Science Definition Team (2009). The Jupiter Ganymede Orbiter as part of the ESA/NASA Europa Jupiter System Mission (EJSM). *EPSC Abstracts* **4**, EPSC2009-784, European Planetary Science Congress.
- Greenberg, R. (2005). *Europa, the Ocean Moon*, p. 136. Springer, Berlin.
- Grice, K. *et al.* (2005). *Science* **307**, 706–709.
- Grundy, W.M. *et al.* (2007). *Science* **318**, 234–236.
- Harrison, A.G. & Thode, H.G. (1958). *Trans. Faraday Soc.* **54**, 84–92.
- Hoefs, J. (2009). *Stable Isotope Geochemistry*. 6th edn, pp. 76–77. Springer, Berlin, Heidelberg.
- Horvath, J. *et al.* (1997). Searching for ice and ocean biogenic activity on Europa and Earth. In *Instruments, Methods and Missions for Investigation of Extraterrestrial Microorganisms (Proc. SPIE, vol. 3111)*, ed. Hoover, R.B., pp. 490–500, http://www.ictp.it/~chelaf/searching_for_ice.html.
- Jannasch, H.W. & Mottl, M.J. (1985). *Science* **229**, 717–725.
- Kargel, J.S., Kaye, J.Z., Head, J.W., III, Marion, G.M., Sassen, R., Crowley, J.K., Ballesteros, O.P., Grant, S.A. & Hogenboom, D.L. (2000). *Icarus* **148**, 226–265.
- Kemp, A.L.W. & Thode, H.G. (1968). *Geochim. Cosmochim. Acta* **32**, 71–91.
- Khurana, K.K., Pappalardo, R.T., Murphy, N. & Denk, T. (2007). *Icarus* **191**, 193–202.

- Kivelson, M.G., Khurana, K.K., Joy, S., Russell, C.T., Southwood, D.J., Walker, R.J. & Polansky, C. (1997). *Science* **276**, 1239–1241.
- Kiyosu, Y. & Krouse, H.R. (1990). *Geochem. J.* **24**, 21–27.
- Krouse, H.R., Viau, C.A., Eliuk, L.S., Ueda, A. & Halas, S. (1988). *Nature* **333**, 415–419.
- Lorenz, R.D., Stiles, B.W., Kirk, R.L., Allison, M.D., Persi del Marmo, P., Iess, L., Lunine, J.I., Ostro, S.J. & Hensley, S. (2008). *Science* **319**, 1649–1651.
- Machel, H.G. (2001). *Sediment. Geol.* **140**, 143–175.
- Machel, H.G., Krouse, H.R. & Sassen, R. (1995). *Appl. Geochem.* **10**, 373–389.
- McCollom, T.M. (1999). *J. Geochem. Res.* **104**, 30729–30742.
- McCord, T.B. *et al.* (1998). *J. Geophys. Res.* **103**, 8603–8626.
- McCord, T.B. *et al.* (1999). *J. Geophys. Res.* **104**, 11827–11851.
- McCord, T.B., Hansen, G.B. & Hibbitts, C.A. (2001). *Science* **292**, 1523–1525.
- McCready, R.G.L. (1975). *Geochim. Cosmochim. Acta* **39**, 1395–1401.
- McEwen, A.S. (1986). *J. Geophys. Res.* **91**, 8077–8097.
- Mikucki, J.A., Pearson, A., Johnston, D.T., Turchyn, A.V., Farquhar, J., Schrag, D.P., Anbar, A.D., Priscu, J.C. & Lee, P.A. (2009). *Science* **324**, 397–400.
- Mizutani, H., Fujimura, A., Hayakawa, M., Tanaka, S., Shiraishi, H. & Yoshida, S. (2000). LUNAR-A MISSION: science objectives and instruments. In *ICEUM-4 Proc. of Fourth International Conf. on the Exploration and Utilization of the Moon*, pp. 107–114.
- Oberst, J., Schreiner, B., Giese, B., Neukum, G., Head, J.W., Pappalardo, R.T. & Helfenstein, P. (1999). *Icarus* **140**, 283–293.
- Ono, S., Shanks, W.C., Rouxel, O. & Rumble, D. (2007). *Geochim. Cosmochim. Acta* **71**, 1170–1182.
- Priscu, J.C. *et al.* (1999). *Science* **286**, 2141–2144.
- Postberg, F., Kempf, S., Schmidt, J., Brilliantov, N., Beinsen, A., Abel, B., Buck, U. & Srama, R. (2009). *Nature* **459**, 1098–1101.
- Rees, C.E. (1973). *Geochim. Cosmochim. Acta* **37**, 1141–1162.
- Reysenbach, A.L. & Shock, E. (2002). *Science* **296**, 1077–1082.
- Rollinson, H. (2007). *Early Earth Systems*, p. 225. Blackwell, London.
- Schopf, J.W. (2001). *Cradle of Life: The Discovery of Earth's Earliest Fossils*, p. 336. Princeton University Press, Chichester, West Sussex.
- Shen, Y. & Buick, R. (2004). *Earth Sci. Rev.* **64**, 243–272.
- Shiraishi, H., Tanaka, S., Fujimura, A. & Hayakawa, H. (2008). *Adv. Space Res.* **42**, 386–393.
- Shock, E.L. (2001). Geochemical habitats in hydrothermal systems. In *The First Steps of Life in the Universe*, eds Chela-Flores, J., Owen, T. & Raulin, F., pp. 179–185. Kluwer Academic Publishers, Dordrecht.
- Singer, E. (2003). Vital clues from Europa. In *New Scientist magazine*, Issue N. 2414, pp. 22–23. <http://www.ictp.it/~chelaf/VitalClues.pdf>.
- Smith, A. *et al.* (2008). *Exp. Astron.* 10.1007/s10686-008-9109-6 (August 21, 2008), <http://www.ictp.it/~chelaf/Penetrator.pdf>.
- Smith, B.E., Fricker, H.A., Joughin, I.R. & Tulaczyk, S. (2009). *J. Glaciol.* **55**, 573–595.
- Spohn, T. & Schubert, G. (2003). *Icarus* **161**, 456–467.
- Surkov, Y.A. & Kremnev, R.S. (1998). *Planet. Space Sci.* **46**, 1689–1696.
- Thomson, R.E. & Delaney, J.R. (2001). *J. Geophys. Res.* **106**, 12355–12365.
- Ueno, Y., Yamada, K., Yoshida, N., Maruyamaand, S. & Isozaki, Y. (2006). *Nature* **440**, 516–519.
- Ulamec, S., Biele, J., Funke, O. & Engelhardt, M. (2007). *Rev. Environ. Sci. Biotech.* **6**, 71–94.
- Weiss, P., Yung, K.L., Ng, T.C., Komle, N., Kargl, G. & Kaufmann, E. (2008). *Planet. Space Sci.* **56**, 1280–1292.
- Whitman, W.B., Coleman, D.C. & Wiebe, W.J. (1998). *PNAS* **95**, 6598–6583.
- Wortmann, U.G., Bernasconi, S.M. & Bottcher, M.E. (2001). *Geology* **29**, 647–650.
- Yamada, R. *et al.* (2009) *Planet. Space Sci.* **57**, 751–763.
- Zakharov, A.V. & Fechtig, H. (1994). *Phil. Trans. Phys. Sci. Eng.* **349**, 295–307.
- Zolotov, M., Yu. & Shock, E.L. (2001). *J. Geophys. Res.* **106**, 32815–32828.