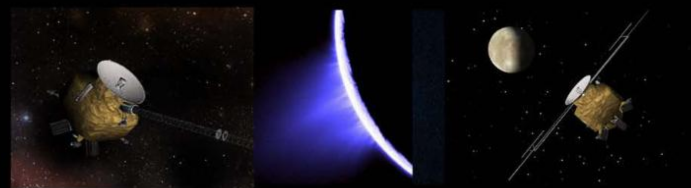
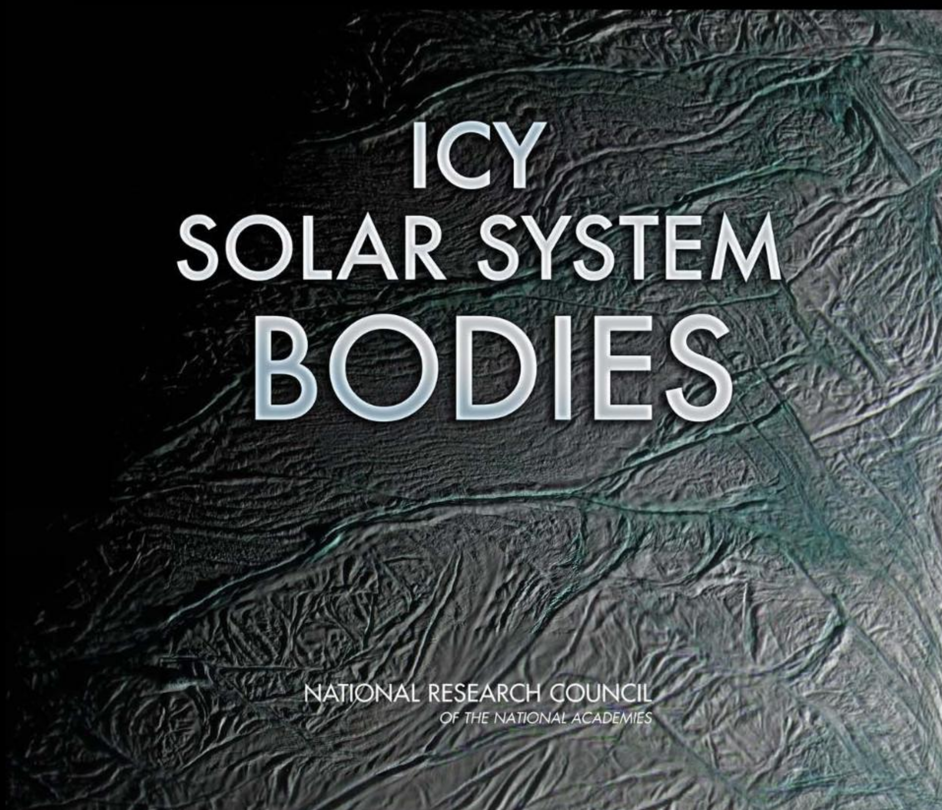
Planetary Protection Subcommittee

May 2, 2012
Washington, DC



Assessment of Planetary Protection Requirement for spacecraft Missions to



Committee on Planetary Protection Standards for Icy Bodies in the Outer Solar System

MITCHELL L. SOGIN, Marine Biological Laboratory, *Chair*
GEOFFREY COLLINS, Wheaton College, *Vice Chair*
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AMY BARR, Brown University
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Biological Sciences
Planetary and Geo Sciences
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Charge to the Committee

• *The possible factors that usefully could be included in a*
Coleman-Sagan formulation
describing the probability that various types of missions might contaminate with Earth life any liquid water, either naturally occurring or induced by human activities, on or within specific target icy bodies or classes of objects;

• *The range of values that can be estimated for the above factors based on current knowledge, as well as an assessment of conservative values for other specific factors that might be provided to missions targeting individual bodies or classes of objects; and*

• *Scientific investigations that could reduce the uncertainty in the above estimates and assessments, as well as technology developments that would facilitate implementation of planetary protection requirements and/or reduce the overall probability of contamination.*

Time line for the report

November 17, 2011 - Organizational teleconference - 1

December 15, 2010 - Organizational teleconference - 2

January 31-February 2, 2011 Meeting-1 Keck Center, Washington DC

March 16-18, 2011 - Meeting-2 Beckman Center, Irvine

May 13, 2011 - Telecon

June 14-16, 2011 – Meeting-3 Beckman Center, Irvine

August 2011 - Draft Report

October, 20011 – Sent to Reviewer

November 2011 – Reviews Received

December 2011 – Initial committee response, Report revisions

December 21, 2011 – Review Coordinator's Initial Comments

January 2012 – Revised Report, Response to Reviews to Review Coordinator

February 2012 - Response to Review Coordinator and Report Revision

March 2012 – Report approved for Release

April 2012 – NASA Briefing

Major Recommendations:

- The committee does not support continued reliance on the Coleman-Sagan formulation to estimate the probability of contaminating outer solar system icy bodies.
- Planetary protection decisions should not rely on the multiplication of probability factors to estimate the likelihood of contaminating solar system bodies
- Replace the Coleman-Sagan formulation with a series of binary (i.e., 99.99% confident yes/no) decisions that consider one factor at a time to determine necessary level of planetary protection*

*Multiple factors that guide a single binary decision point can be multiplied if they are completely independent and their values and statistical variation are known.

PRESENTATIONS TO COMMITTEE ON PLANETARY PROTECTION STANDARDS FOR ICY BODIES IN THE OUTER SOLAR SYSTEM

NASA HQ Briefing:
- Needs and Expectations
- NASA's Outer Solar System Program

Planetary Protection Briefing:
- COSPAR
- Prior NRC Planetary Protection Studies (Mars, Europa)
- Planetary Protection for Europa Missions
- Coleman-Sagan Formulation

Icy Body Briefing:
- Jovian Systems and Radiation Environments
- Satellites of Saturn, Uranus and Neptune
- Trojans, Centaurs and KBOs

Geology of Icy Bodies Briefing:
- Europa, Enceladus, Titan, Triton, Trojans, Centaurs and KBOs
- Surface-subsurface transport

Biological Science Briefing:
- Temperature Limits for Life
- Microbial life in Glacial Ice
- Microbial tolerance – Psychrophiles, Heat Resistance, Radiation Resistance
- Subterranean Biospheres

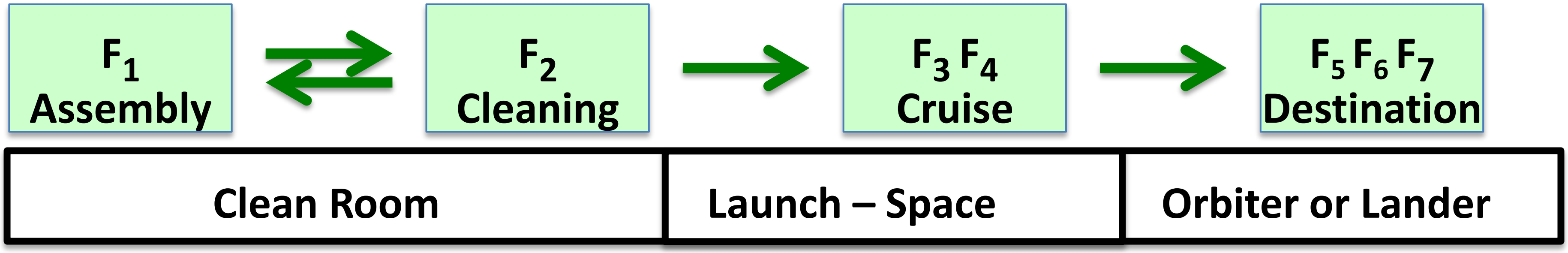
Technology Briefing:
- Future Instruments for Icy Bodies
- Electronic Parts and Spacecraft Reliability
- Sterilization Techniques

Coleman-Sagan probabilistic estimate of contamination

Multiply together:

F_1 = Estimates for the number of organisms on the spacecraft
F_2 =Bioload reduction treatment fraction
F_3 =Cruise survival fraction (surviving the space environment)
F_4 =Radiation survival fraction
F_5 =Probability of landing at habitable site
F_6 =Burial fraction (Protection against radiation)
F_7 =Probability of growth (**Pg**)

Result must fall below **10^{-4}** = less than one live organism capable of growth delivered to the target body in 10,000 missions



Coleman-Sagan probabilistic calculation for mixed community

(Think Europa 2000 report – but current COSPAR policy uses similar but simplified version)

N_{Xs} defines the number of viable type – x organisms delivered to target body

$N_{Xs} = N_{X0}\, F_1\, F_2\, F_3\, F_4\, F_5\, F_6\, F_7$

P_c = Sum (N_{XS} in the limit of a small value (e.g., 10^{-4})

2000 EUROPA report N^{Xs} (summed across four physiological classes) =3.8×10^{-5}

N_{X0} = Number of viable cells on the spacecraft before launch

F_1 = Total Number of Cells Relative to Cultured Cells

F_2 = Bioburden Reduction Treatment Fraction

F_3 = Cruise Survival Fraction

F_4 = Radiation Survival Fraction

F_5 = Probability of Landing at an Active Site

F_6 = Burial Fraction

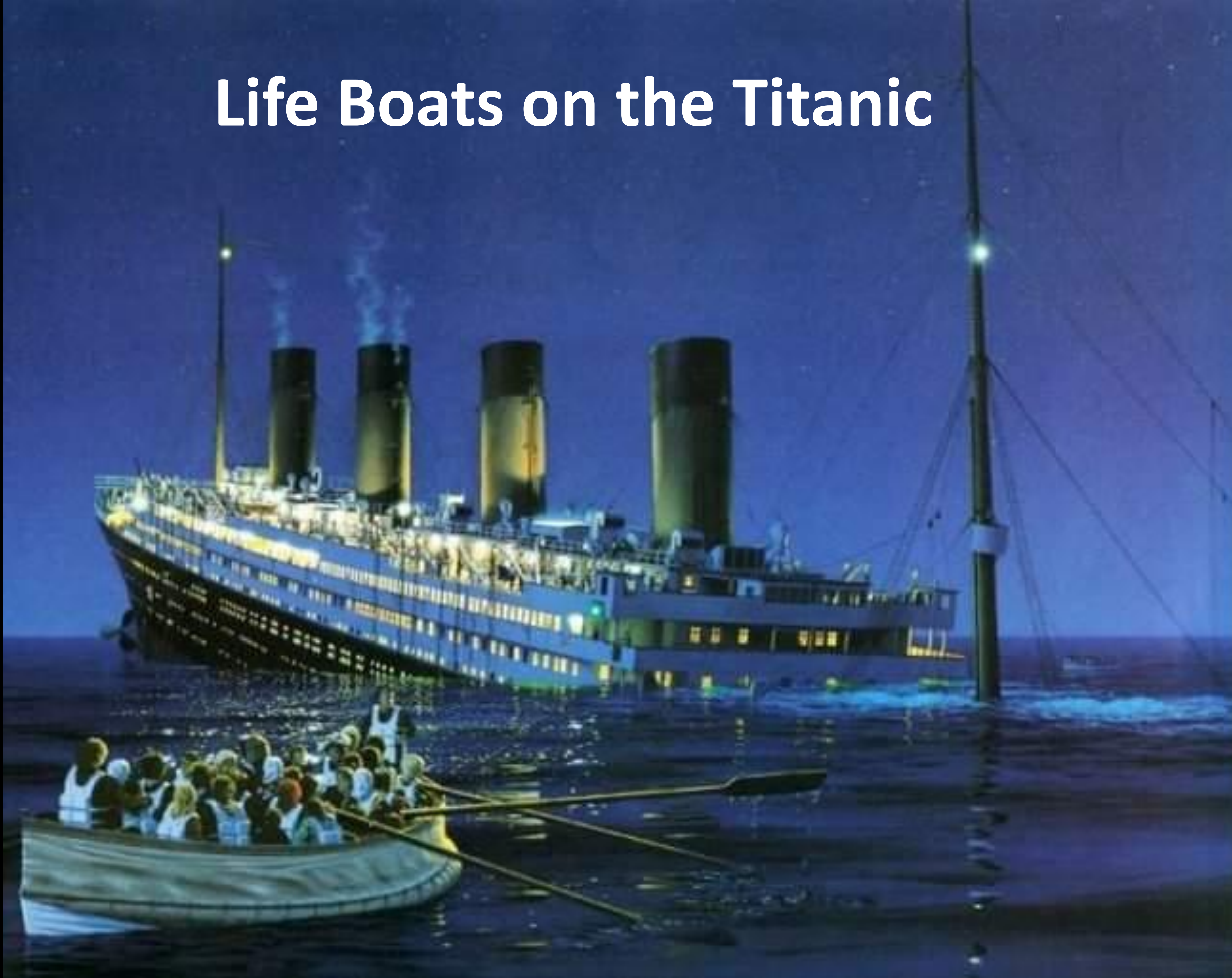
F_7 = Probability that an Organism Survives and Proliferates = Pg

- F_{7a} = *Survivability of Exposure Environments*
- F_{7b} = *Availability of Nutrients*
- F_{7c} = *Suitability of Energy Sources*
- F_{7d} = *Suitability for Active Growth*.

Current knowledge does not confidently assign values within factor of 10

Not all bioload reduction factors are independent

Life Boats on the Titanic



Life Boats on the Titanic

$$N_B = N_0 \prod F_i$$

N_B = number of lifeboats

N_0 = total number of passengers and crew (2,240)

F_1 = boats per person (1/20)

F_2 = probability of hitting an iceberg (1/50)

F_3 = probability of sinking upon hitting an iceberg (1/2)

N_B =2240 x 0.05 x 0.02 x 0.5 = 1.12

A perfectly reasonable calculation that shows the expected number of lifeboats needed per voyage.

However, sinking of a passenger ship is a singular catastrophic event (not unlike an irreversible contamination of a planetary body);

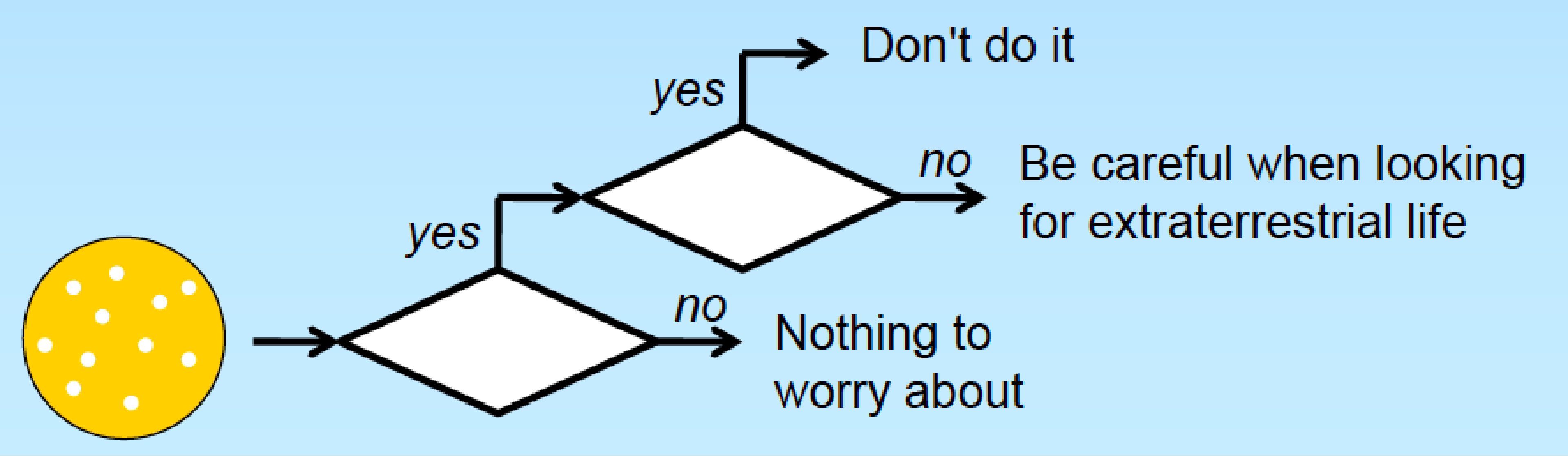
long-term expected average isn't a useful measure!

Recommendation: *Planetary protection should not rely upon the multiplication of bioload estimates and probabilities to calculate the likelihood of contaminating solar system bodies with terrestrial organisms UNLESS scientific data unequivocally define the values, statistical variation and mutual independence of every factor used in the equation.*

Need to answer (qualitatively) two questions:

A. Is there a non-negligible probability that terrestrial microbes would survive the launch, voyage and landing?

B. Is there a non-negligible probability that terrestrial microbes would be able to proliferate?

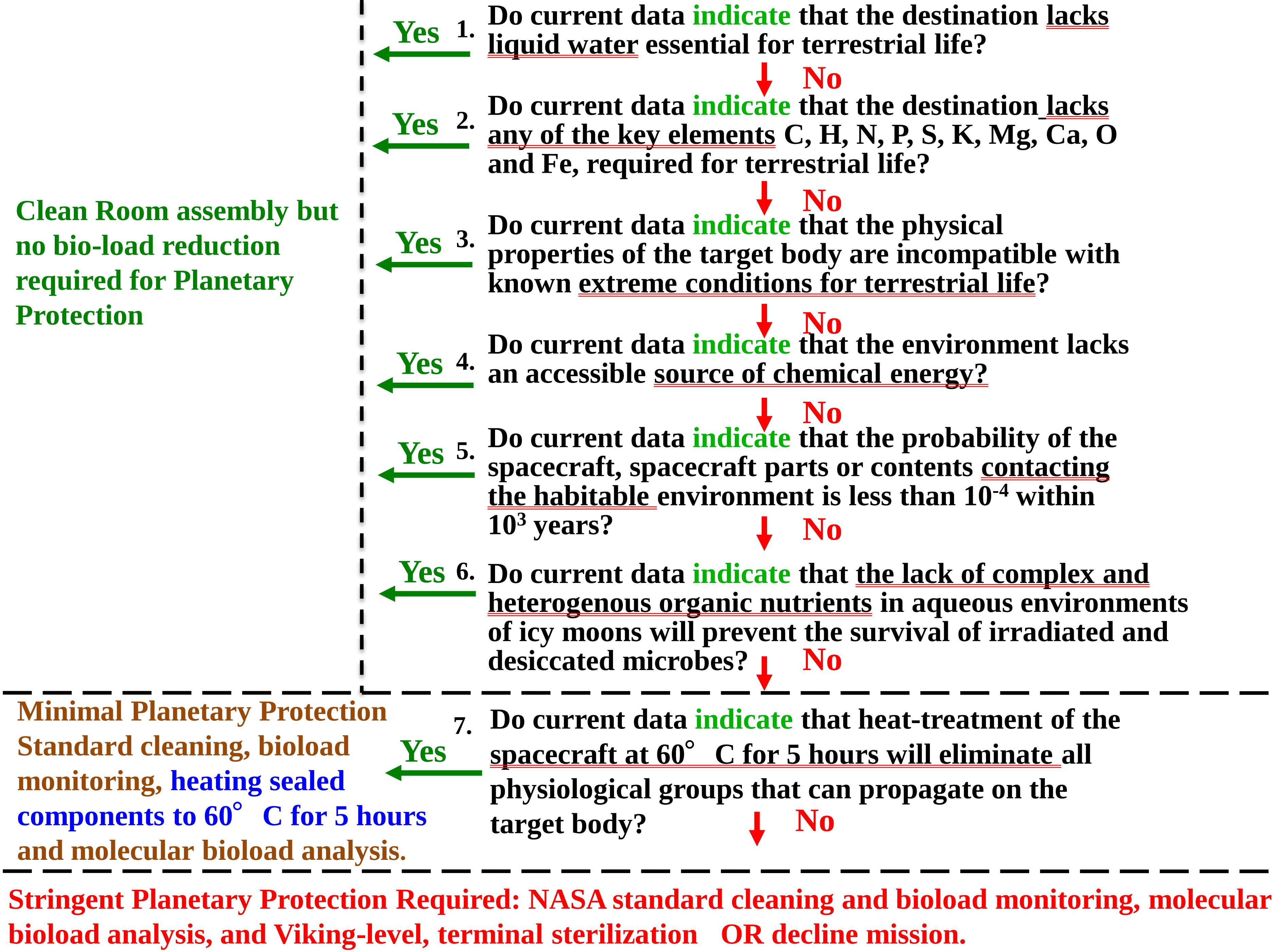


Binary Decision Trees

Recommendation: *Planetary protection should employ a series of binary decisions that consider one factor at a time to determine the appropriate level of planetary protection procedures*.

Caution: Operators in true decision trees represent "Or" rather than "And" operations. Probabilities for different decision points must not be multiplied to arrive at a probability.
Exception to this rule: Within a single binary decision, if their values are known with high level of confidence, multiple factors can be multiplied to arrive at a probability.

Evaluating the Biological Potential in Samples returned from Planetary Satellites and Small Solar System Bodies
NRC –Space Studies Board 1998



1. Do current data indicate that the destination lacks liquid water essential for terrestrial life?
Yes
No
2. Do current data indicate that the destination lacks any of the key elements C, H, N, P, S, K, Mg, Ca, O and Fe, required for terrestrial life?
Yes
No
3. Do current data indicate that the physical properties of the target body are incompatible with known extreme conditions for terrestrial life?
Yes
No
4. Do current data indicate that the environment lacks an accessible source of chemical energy?
Yes
No
5. Do current data indicate that the probability of the spacecraft, spacecraft parts or contents contacting the habitable environment is less than 10-4 within 103 years?
Yes
No
6. Do current data indicate that the lack of complex and heterogenous organic nutrients in aqueous environments of icy moons will prevent the survival of irradiated and desiccated microbes?
Yes
No
Clean Room assembly but no bio-load reduction required for Planetary Protection
7. Do current data indicate that heat-treatment of the spacecraft at 60° C for 5 hours will eliminate all physiological groups that can propagate on the target body?
Yes
No
Minimal Planetary Protection Standard cleaning, bioload monitoring, heating sealed components to 60° C for 5 hours and molecular bioload analysis.
Stringent Planetary Protection Required: NASA standard cleaning and bioload monitoring, molecular bioload analysis, and Viking-level, terminal sterilization OR decline mission.

Decision Points for Planetary Protection

7 decision points (Chapter 3)

Decision Point One: **Availability of Liquid water**
Decision Point Two: **Availability of ~70 key elements (C, N, P, O, H, S, etc.)**
Decision Point Three: **Physical and chemical extremes e.g. -15°C > Life <122°C**
Decision Point Four: **Chemical energy (electron donors e.g. Fe^{2+}, SH^-, organic carbon, coupled with electron acceptors e.g. CO_2, SO_4^{2-}, O_2, H_2O_2)**
Decision Point Five: **Probability of contacting with potentially habitable regions $<10^{-4}$ over a 1000 year time frame**
Decision Point Six: **Nutrients sufficient to recover from radiation/desiccation**
Decision Point Seven: **Heat treatment (e.g., 60°C for 5 hours) cannot eliminate physiological types that might grow on the target body**

Recommendation: *NASA should adopt a binary hierarchical decision-making framework where affirmative answers to any decision point would eliminate further requirements for planetary protection.*

Period of protection:
Committee on Planetary Protection Standards for Icy Bodies in the Outer Solar System (Icy Bodies Committee)

COSPAR Policy:
Initially recommended planetary protection extend through period of exploration
Current definition: 50 years after a Category III or IV mission reaches target
(But planetary exploration is a young science with missions planned for decades)
Icy Bodies committee considers 100 years too short

2000 *Europa* Report:
explicitly assumes planetary protection borders on perpetuity
Icy Bodies committee expresses concern that indefinite time horizon will lead to ad hoc practical solutions.

Icy Bodies Committee
No sound basis for recommendation of 10,000 years or more
Impossible to estimate timeframe of exploration of the solar system:
Assume the period of protection will extend for the next millenium

A Geophysical Perspective and Inventory of Habitable Environments on Icy Bodies relative to Decision Points 1-5
(Water, Key Elements, Physical parameters compatible with life, Chemical Energy, Contact with habitable environments)

> **(Special emphasis on Decision point 5-Contacting Habitable Environments)**

Survey of icy bodies to delineate areas of concern for planetary protection where preponderance of geophysical and chemical data indicates potential habitability for terrestrial life and evidence of resurfacing in the last 10^8 years.

A Biological Perspective relative to Decision Points 1- 4 and emphasis on 6 and 7 (Water, Key Elements, Physical parameters compatible with life, Chemical Energy, Complex Organics and nutrients, Survival at 60°C)

A Geophysical Perspective and Inventory of Habitable Icy Bodies

Decision point 1: - Liquid water:

Europa, Ganymede, Callisto, Titan, Enceladus, possibly Dione

No significant liquid on small, irregularly shaped icy bodies

Decision point 2: - Key Elements and their bioavailability:

Insufficient data to constrain presence/absence but C, S, and N likely present as ice, clathrates or simple organics

Chemical modeling predicts all Phosphorus on Titan sequestered in phosphine instead of phosphate.

Decision point 3: - Physical constraints

Temperature ranges are better constrained than key elements

Liquid water in contact with ice hovers at freezing point:

- Pure water -20°C at 100 km
- Ice+salt or ice+ammonia at temps as low as -97°C

Ice constrains the temperature of water

Contact with warmer rocks at great depth can lead to porous convection and broad down-wellings and focused up-wellings

Mixing of the hydrothermal fluids minimally increase temperature of surrounding oceans

Decision point 4: Chemical Energy

Great uncertainty about availability of redox couples and maintenance of energy through geochemical cycles

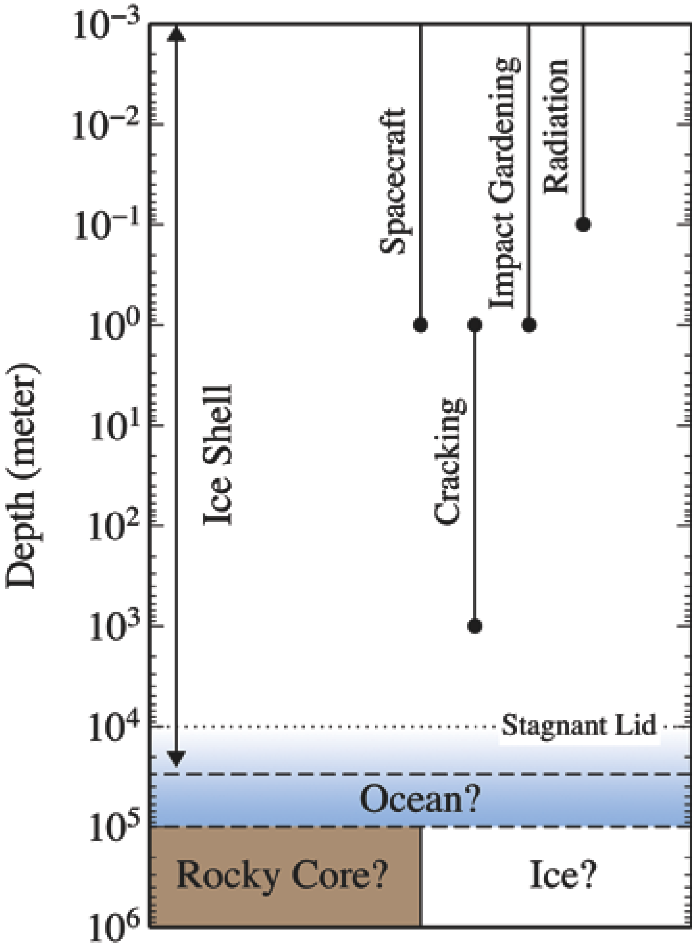
Radioactive decay could hydrolyze water for chemical energy

Decision Point 5—Contacting Habitable Environmemnts

Floating outer ice is a formidable barrier to microbial invasion

Vertical transport and concerns about planetary protection:

- **Top Down and Bottom up vertical transport**
- **Limits to the vertical range**



Impact Gardening
- **Europa most vulnerable**

Tensile Fractures
- **At some depth fails in shear instead of tension; forms slope rather than crack**

Cryovolcanism -Europa, Ganymede, Enceladus, Titan, Ariel, and Triton
- **Material flows towards surface.**
- **Drain back events rare**

Near-Surface Melting
- **Requires 10^3 higher heat flow than in the south polar terrain of Enceladus**

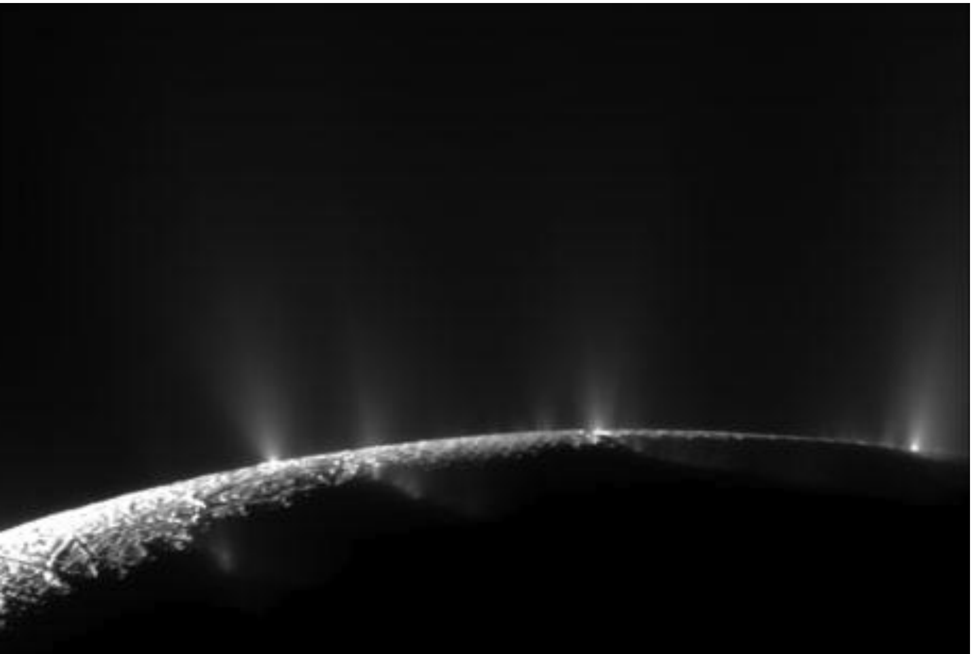
~10 to 100 km thick ice shell (e.g. Europa, Enceladus, Titan, and Triton

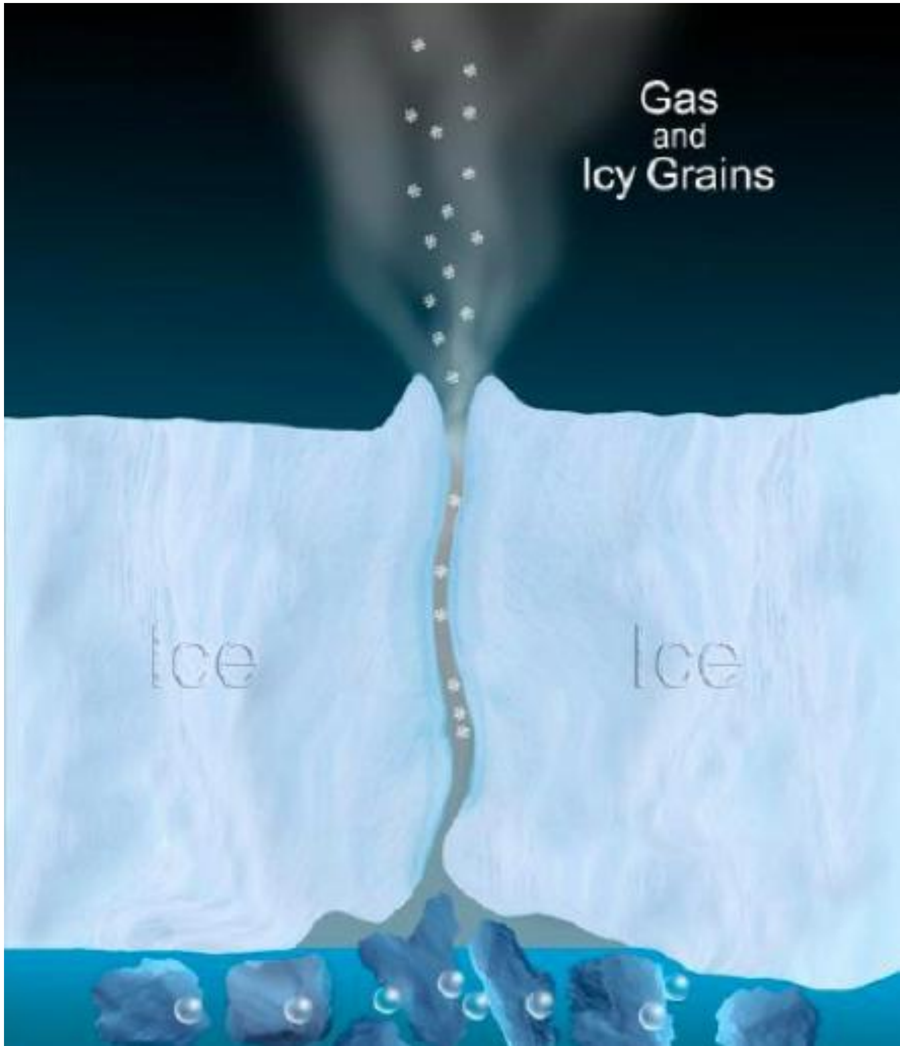
Plumes on Enceladus: A vertical transport "worst case scenario"

- **Dust and vapor emerging from major cracks at south pole**
- **Contains water vapor, simple organics, ice grains with salty cores**

Ideas for formation:
- **Condensing vapor from a deep water body?**
- **Throttled escape from pressurized caverns full of liquid water?**

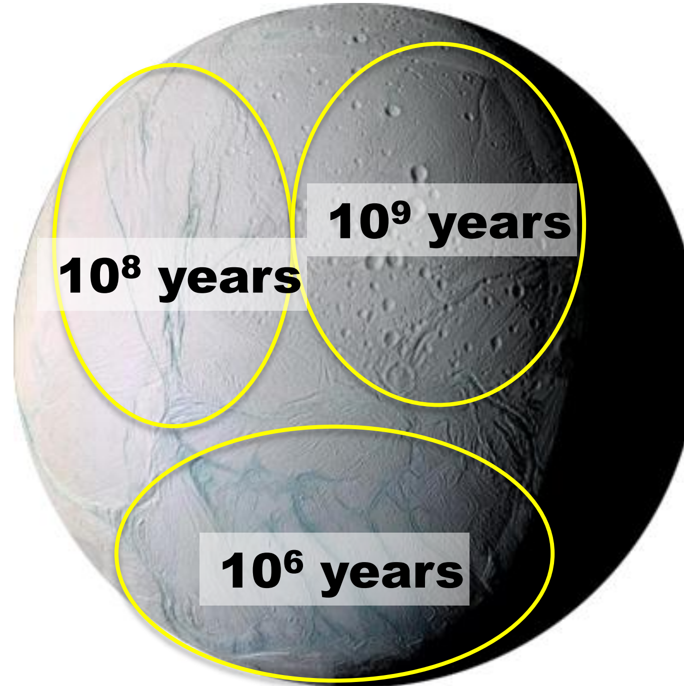
Fractures provide a direct conduit from the subsurface to the surface



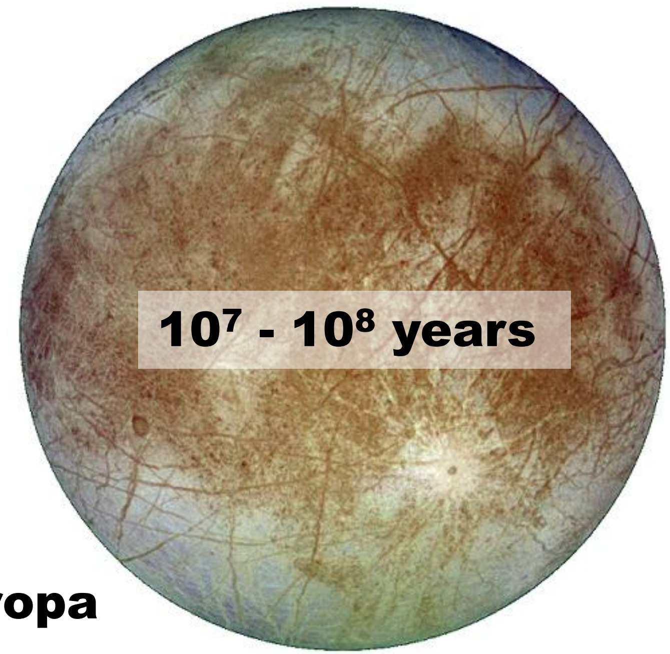


Youngest limit of surface age estimates

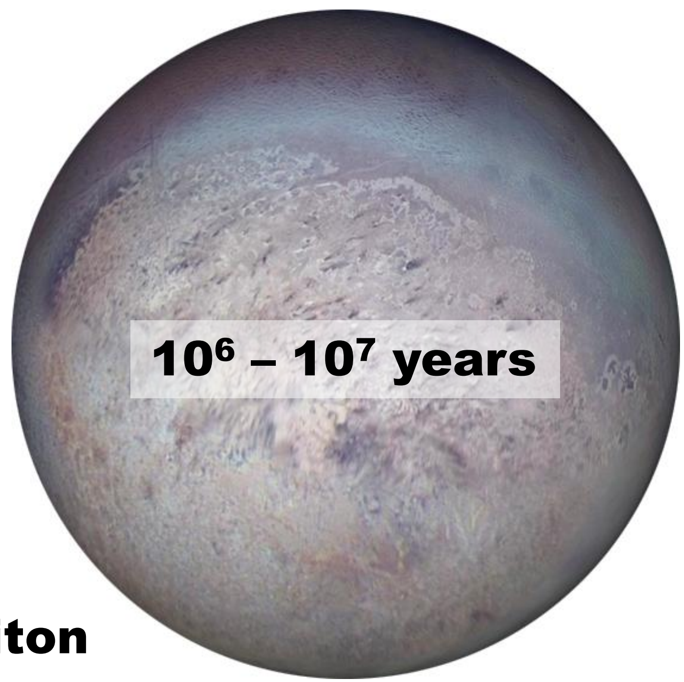
Three bodies of concern for geologically recent activity



Enceladus



Europa



Triton

A Geophysical Perspective and Inventory of Habitable Environments on Icy Bodies

Recommendation: **Evidence of widespread resurfacing activity within the past 10^8 years requires that NASA evaluate planetary protection requirements for Europa, Enceladus, and Triton using a hierarchical decision-making framework .... must demonstrate that their plans for missions to these bodies have less than a 10^{-4} chance of contacting an area of active surface-subsurface transport within the next 1,000 years.**

Finding: The possibility for active transport of contaminants into a habitable portion of Titan's interior over a 1000 year timescale is more remote than 10^{-4}, removing Titan from high levels of concern for planetary protection. Titan's average surface age appears to be older than the 10^8 year cutoff, and though putative cryovolcanic features have been found, all firm evidence for current geologic activity on Titan is driven by exogenic processes involving the methane cycle and windblown sediment, none of which is habitable for terrestrial organisms.

A Biological Perspective - Decision points 1-4 are Geocentric

Decision point 1: - Liquid water: All life has absolute requirement for liquid water

Jupiter's moons Europa, Ganymede, Callisto

Saturn's moons Titan, Enceladus, and possibly Dione

Decision point 2: - Key Elements and their bioavailability:

Life requires C, H, N, O, P, S, Mg, Ca, Na, Fe and 70 other elements can serve essential roles in protein-mediated catalysis

Insufficient data to constrain presence but chemical modeling predicts all Phosphorus on Titan sequestered in phosphine

Decision point 3: - Physical constraints

Microbial growth at or above -15°C although metabolism can persist at -20°C. Upper temperature limit 122°C

Geophysics suggests liquid water at 100 km or as Ice+salt or ice+ammonia will maintain temperatures below -20°C.

Cannot rule out local warmer temperatures fueled by porous convection from warmer rocks at depth and upwelling.

Decision point 4: Chemical Energy

Life requires chemical energy – redox couples - Electron donors (e.g., Fe^{2+}, SH^{-}, organic carbon) and electron acceptors (e.g., CO_2, SO_4^{2-}, O_2, H_2O_2). All could be present on icy bodies.

Radioactive decay could hydrolyze water for chemical energy

A Biological Perspective relative to Decision Points 6, 7
A few guiding principles for Planetary Protection.

1. The vast metabolic and physiological diversity of microbes allows the colonization of diverse environments

2. Niche competition constrains optimal microbial growth of individual microbes to a limited range of conditions.
   e.g. microbes that grow optimally at −15°C do not survive at 122°C

3. The environmental source of organisms on the spacecraft and will dictate their ability to grow at low temperatures of icy moons (e.g., at 0°C or below)

3. Microbes have evolved specific survival tactics necessary to tolerate explosure to radiation or extremely low vacuum

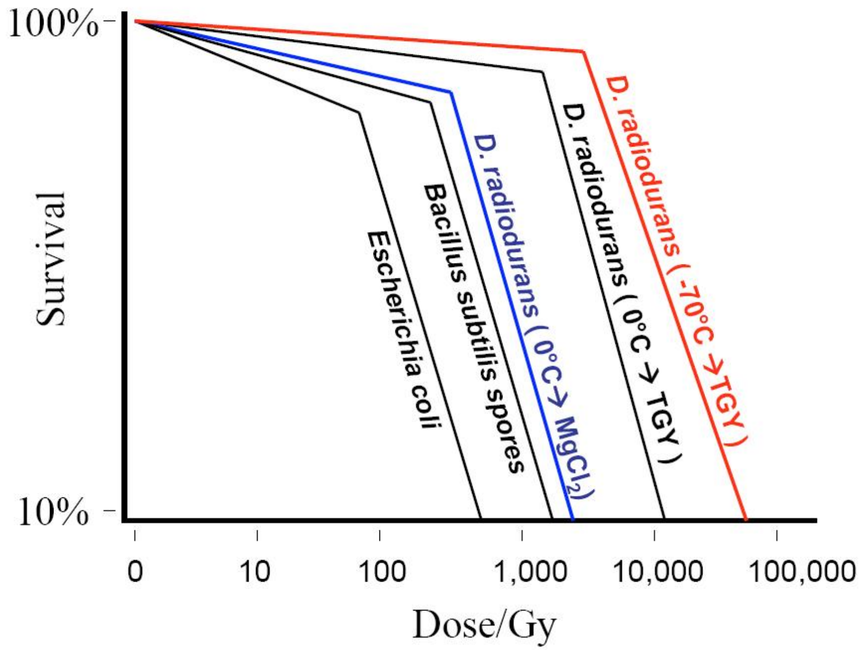
4. Heat tolerance correlates with growth temperature.

A Biological Perspective

Decision point 6: - **Complex and Heterogeneous Nutrients**

Bacteria and Archaea on spacecraft or surfaces of icy moons will experience high levels of radiation flux. Microbes in concealed or radiation-protected components could survive.

Only microbes that are radiation resistant e.g. *Deinococcus radiodurans* are likely to remain viable.



The ability to repair damage from radiation exposure requires complex, heterogeneous nutrients including complex forms of carbon that to the best of our knowledge are not available on Icy Bodies in the outer solar system.

A Biological Perspective

Decision point 7 – Minimal Planetary Protection

The Geophysical perspectives indicates persistent temperatures will not exceed 0°C or lower. The known lower temperature limits of terrestrial life is -15°C.

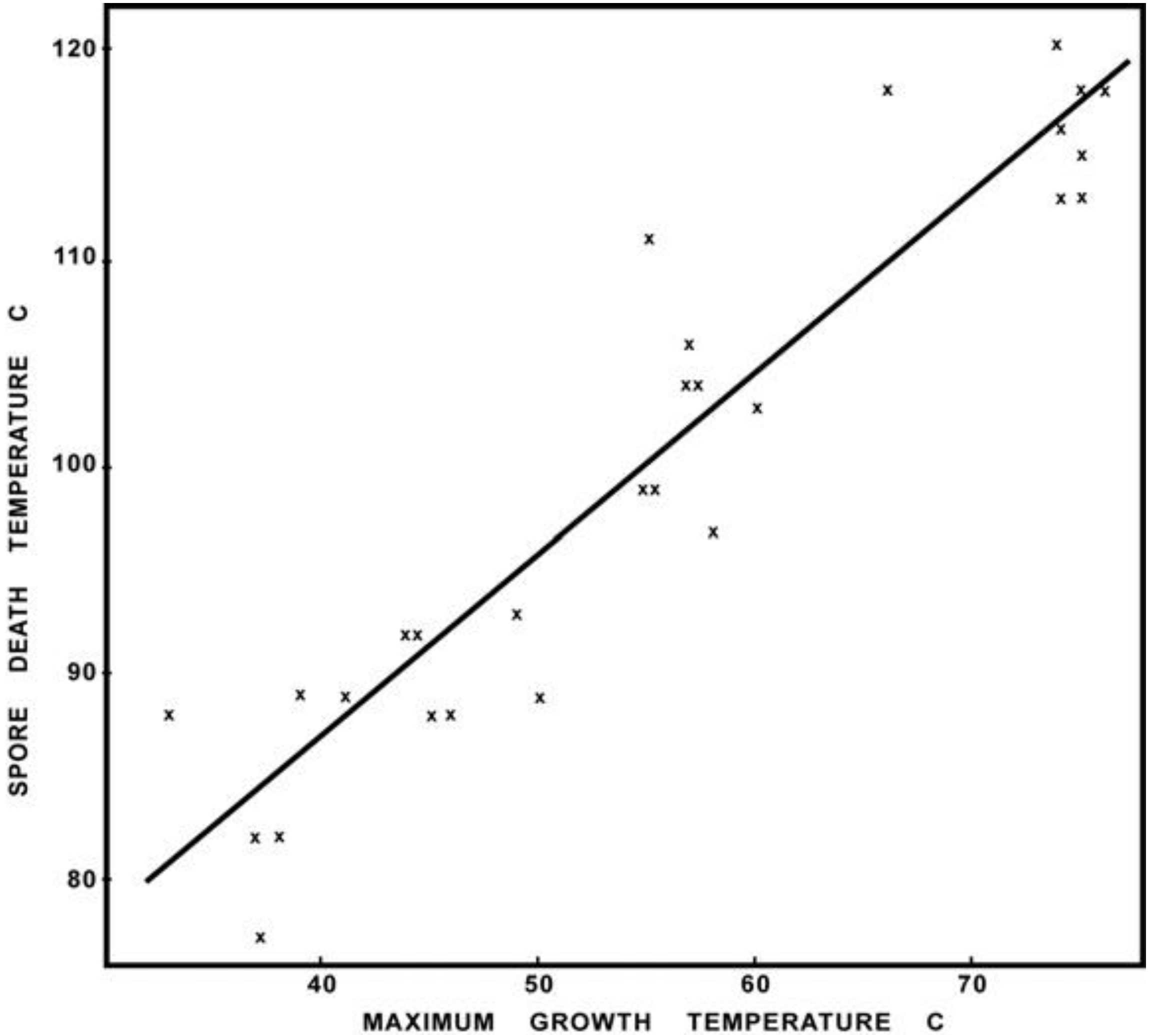
The maximum temperature range of growth for Psychrophiles and facultative psychrophiles lies between −5°C and 40°C.

Non-spore-forming psychrophiles will not survive short (minutes) exposure to temperatures greater than 20°C.

Non- spore-forming facultative psychrophiles will not survive short-time exposure to temperatures above their maximum growth temperature (>20°C to 40°C).

Psychrophiles and Facultative psychrophiles are not adapted at the molecular level to grow or survive at temperatures much more than 10°C above their maximum growth temperature

Heating to 60°C for 5 hours will provide sufficient bioload reduction for non-spore-forming psychrophiles and facultative psychrophiles.



Typical spore forming bacteria exhibit D_{10} value for heat inactivation of 10 minutes at approximately 40°C above the maximum growth temperature.

Spores from psychrophilic bacteria are likely to be rendered inactive at 40°C above their maximum growth temperature

Concluding remarks:

Finding: If the preponderance of data eliminates presence of liquid water, the likelihood of bioavailable phosphorus, sources of redox-couples for energy, or complex organics required for radiation resistance on icy bodies in the outer solar system, planetary protection will only require routine spacecraft cleaning and minimal monitoring.

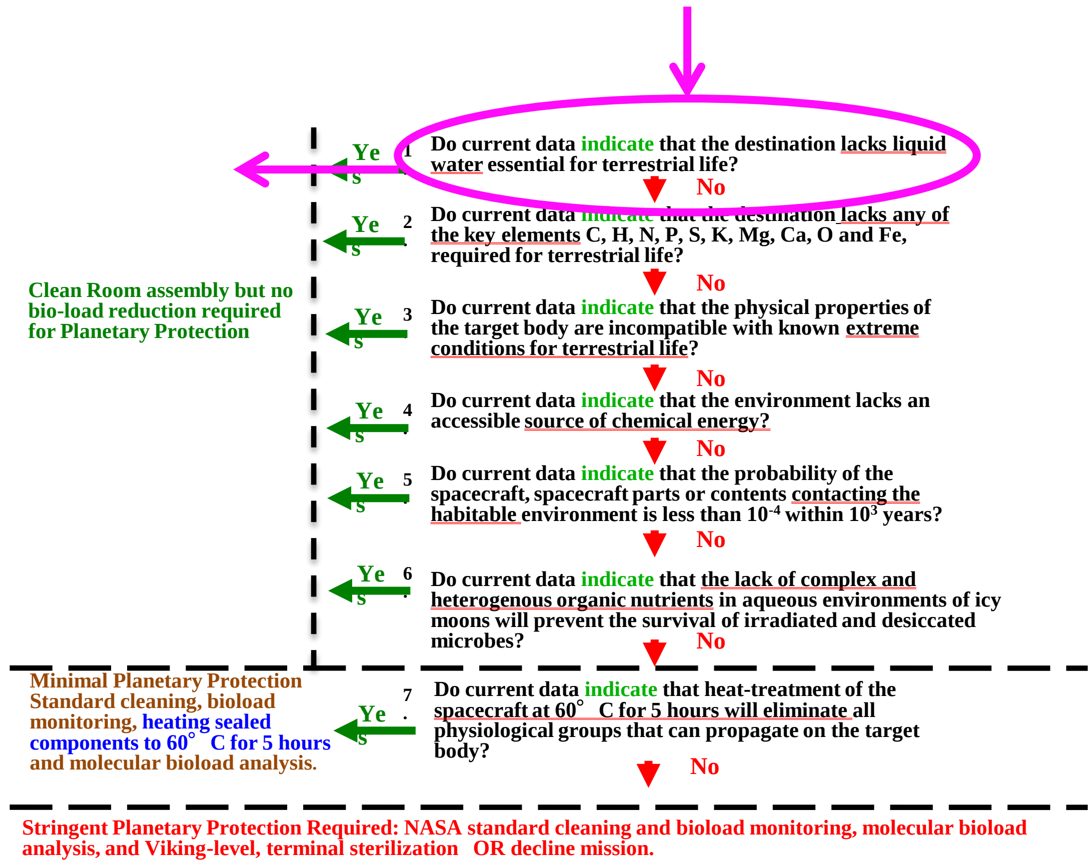
Recommendation: Molecular-based inventories of bioloads including both living and dead taxa must be collected in order to document the range of physiological capabilities of potential contaminants in component and spacecraft assembly facilities.

Recommendation: If the probability of contamination exceeds 10^{-4} after treatment at 60C for 5 hours, full Viking-level, terminal sterilization planetary protection must be undertaken.

Examples of Implementation

Example 1: Comet lander

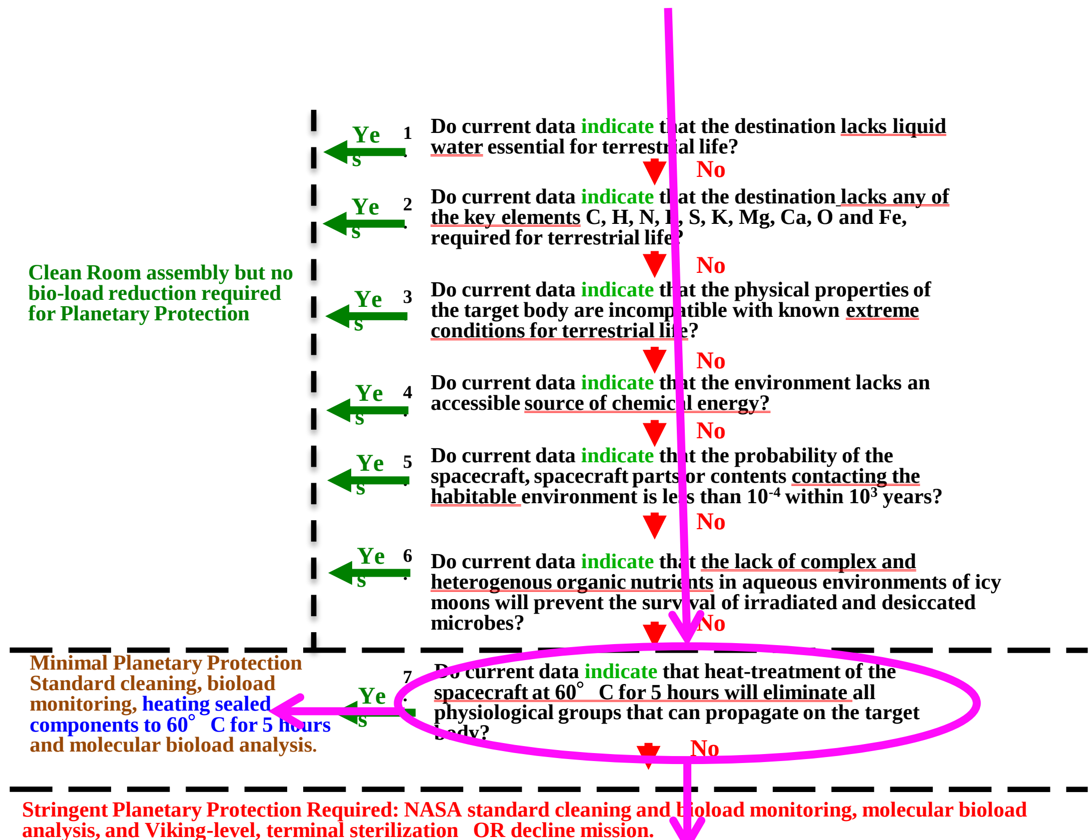
- Current data indicates that the destination lacks liquid water.



Examples of Implementation

Example 2: Enceladus geyser surface lander

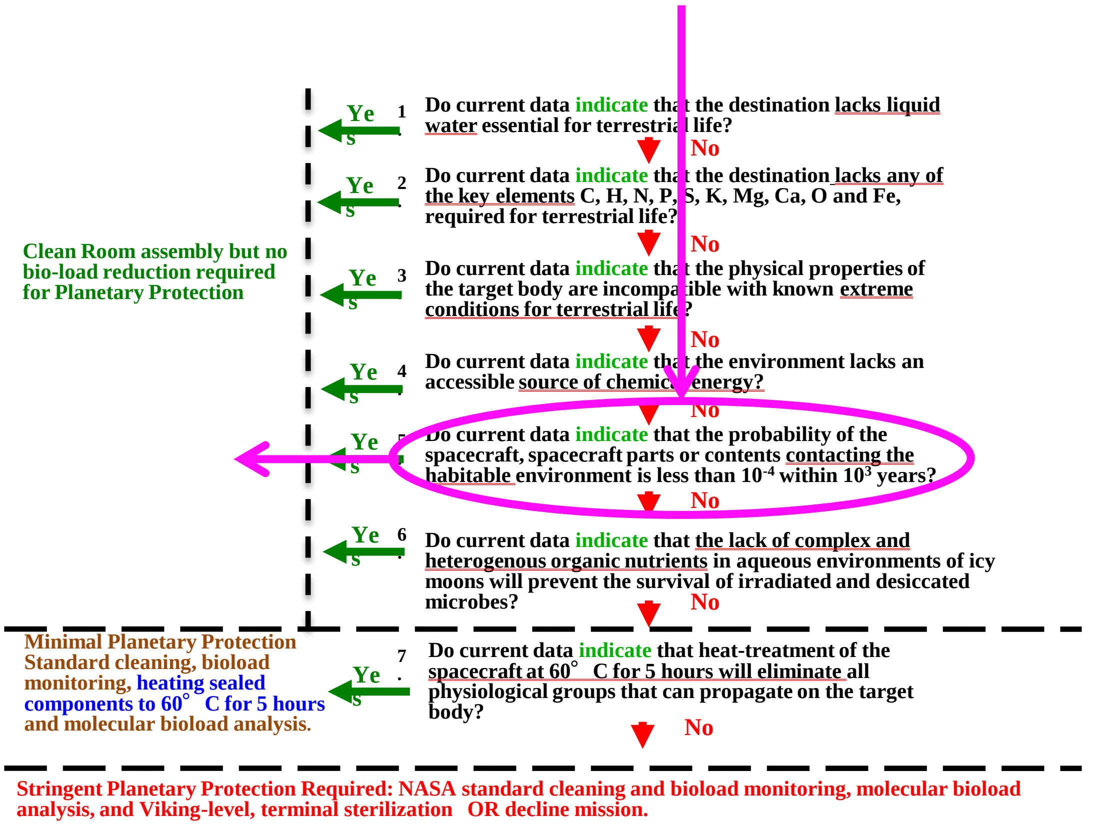
- Current data indicates that the destination has liquid water.
- Current data do not indicate a lack of key elements, incompatible physical properties, or a lack of chemical energy sources.
- Open conduits exist between subsurface and surface at landing site, so chance of encountering habitable environment within 1000 years is more than 10^{-4}.
- Current data has nothing to say about nutrients.
- Planetary protection measures required; the necessary measures are subject to further study of mild heat treatment.



Examples of Implementation

Example 3: Jupiter orbiter

- Could crash on Europa. Data indicates Europa's subsurface could be habitable.
- Given current knowledge of resurfacing timescales, a random location on Europa's surface has < 10^{-4} chance of transport to a habitable environment in 1000 years.
- Orbital calculations show 10^{-2} chance of hitting a random location on Europa within 1000 years.
- These two factors are independent, and we can reasonably estimate the range of variation, so they may be multiplied.
- Much less than a 10^{-4} chance of contacting a habitable environment in 1000 years.



Necessary Research

Recommendation: The D value times for heat inactivation of spores from psychrophilic and facultative psychrophilic spore forming bacteria should be determined at different temperatures, specifically between 40° and 80°C. These analyses should include isolated psychrophilic and facultative psychrophilic bacteria from high latitude soil, water and cryopeg samples, as well as isolated facultative psychrophiles from temperate soils, spacecraft assembly sites, and the spacecraft itself.

Recommendation: Studies should be undertaken to better understand the environmental conditions that initiate spore formation and spore germination in psychrophilic and facultative psychrophilic bacteria so as to compare these requirements with the characteristics of target icy bodies.

Recommendation: Searches should be undertaken for unknown types of psychrophilic spore-formers, and to assess if any of them have different tolerances than known types.

Recommendation: Research should be undertaken to characterize the protected microenvironments within spacecraft and to assess their microbial ecology.

Necessary Research – Continued

Recommendation: Research should be undertaken to determine the extent to which biofilms might increase microbial resistance to heat treatment and other environmental extremes encountered on journeys to icy bodies.

Recommendation: Technologies should be developed to directly detect and enumerate viable microorganisms on spacecraft surfaces.

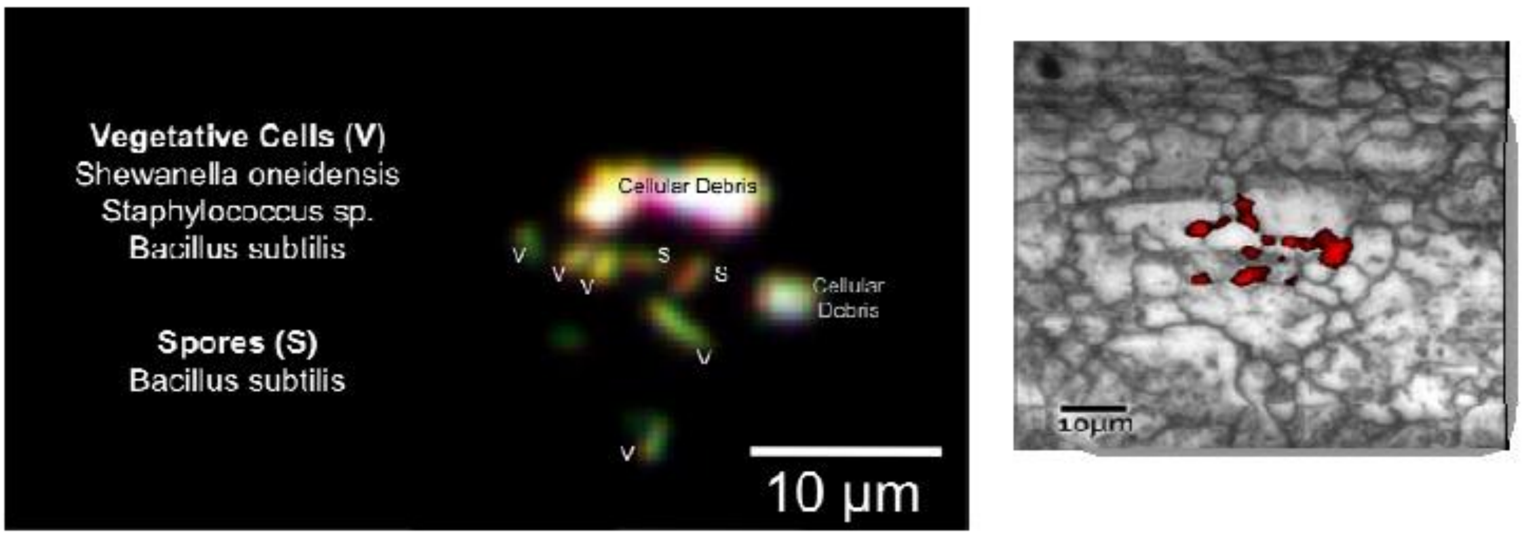


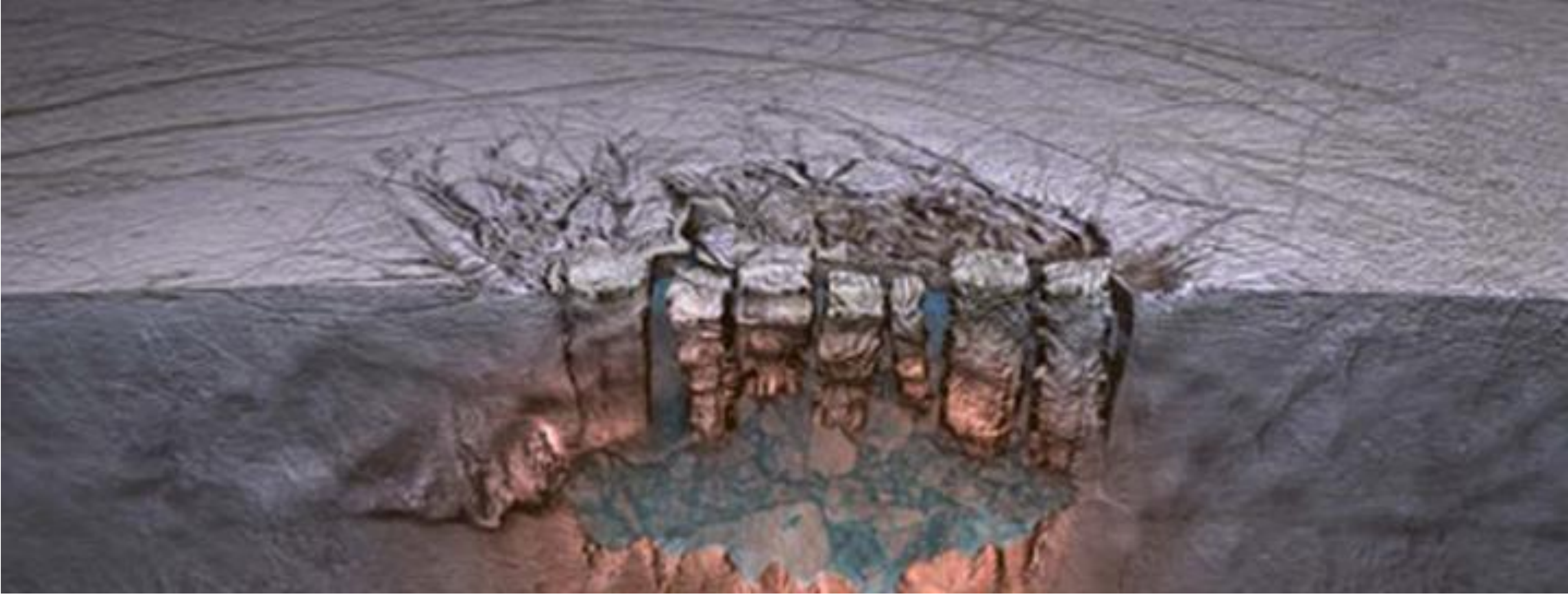
FIGURE 6.1 Vegetative cells and spores on same plate; Vegetative cells "hiding" on plasma-cleaned surface. Images courtesy of R. Bhartia, JPL.

Necessary Research – Continued

Recommendation: Research should be undertaken to determine the concentrations of key elements or compounds containing biologically important elements on icy bodies in the outer solar system through observational technologies and constraints placed on the range of trace elements available through theoretical modeling and laboratory analogue studies.

Recommendation: Research should be undertaken to understand global chemical cycles within icy bodies and the geological processes occurring on these bodies that promote or inhibit surface-subsurface exchange of material.

BACKUP SLIDES

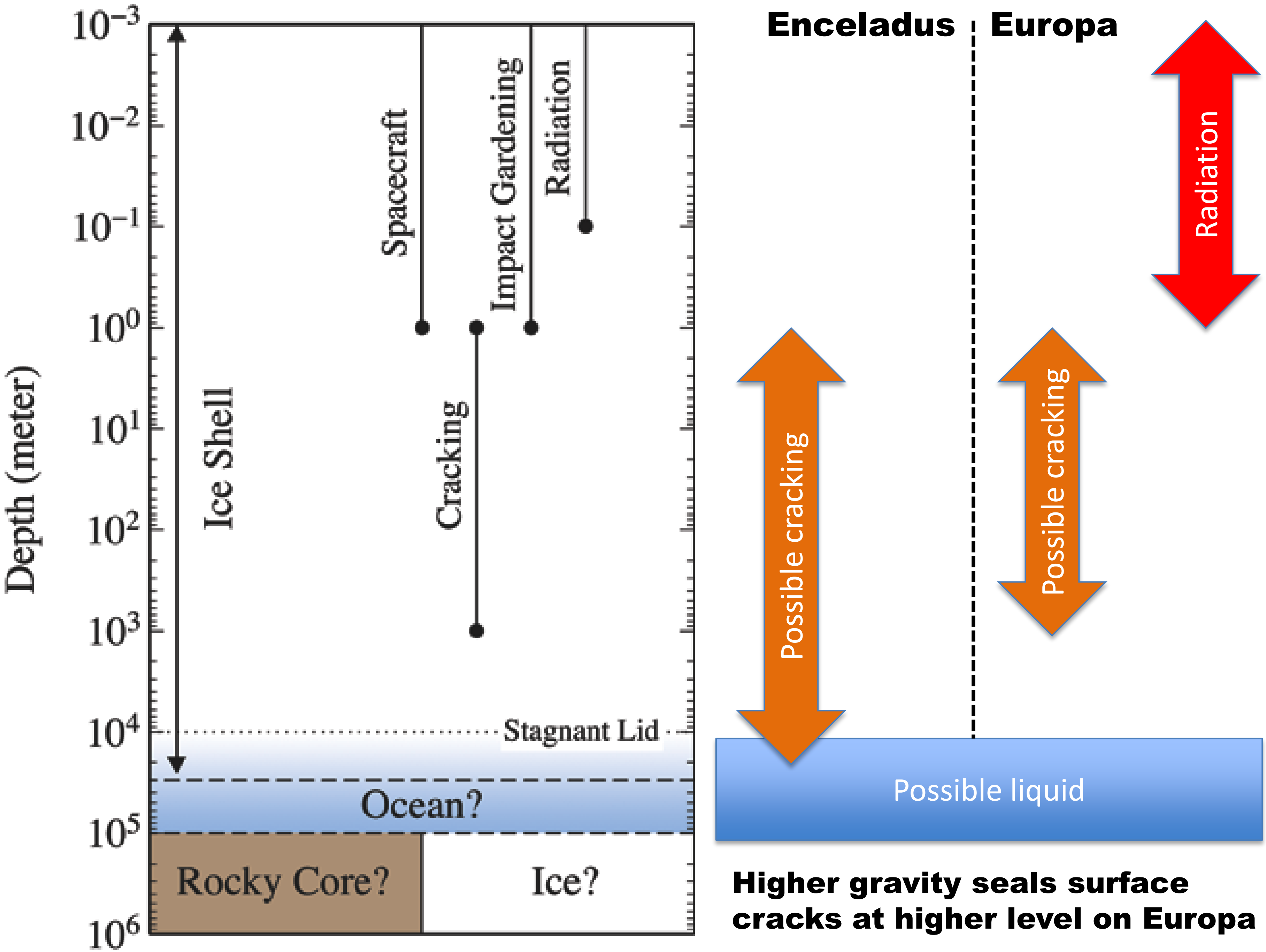


Europa "great lakes" model

Misconception: This model makes it easier to transport liquids from the surface to the ocean.

In fact, the model (as published) *requires* 10s of km of ice below the lakes and doesn't work if the liquid in the lake is in communication with the ocean.

If this model is correct, near-surface brines are *trapped.*


Enceladus
Europa
Depth (meter)
10−3
10−2
10−1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Ice Shell
Spacecraft
Impact Gardening
Radiation
Cracking
Stagnant Lid
Ocean?
Rocky Core?
Ice?
Radiation
Possible cracking
Possible cracking
Possible liquid
Higher gravity seals surface cracks at higher level on Europa

Triton

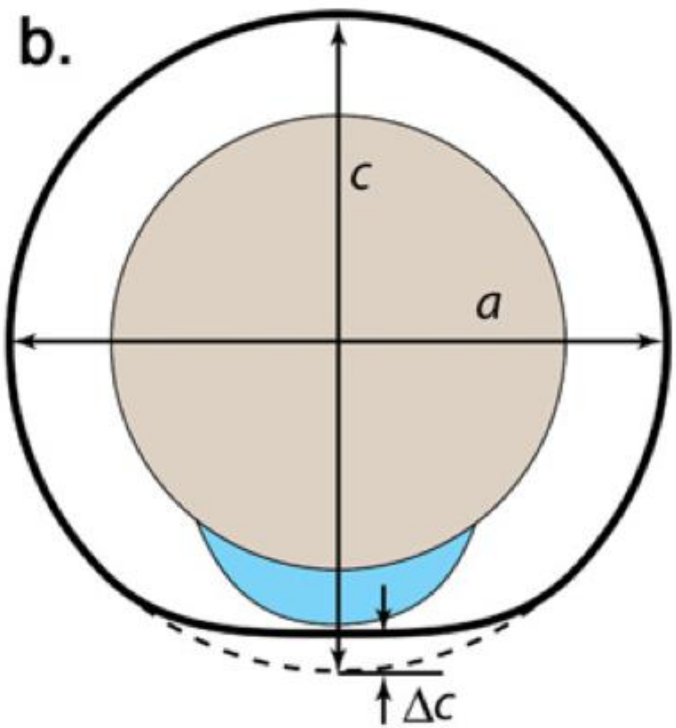
Enigmatic geology

Surface may be *very young*

Most surface activity may be driven by cycling of icy materials other than water (e.g. N_2, CH_4, CO, etc.)

Ice shell thickness on Enceladus could be highly variable

Huge contrast in heat flow at south polar terrain may imply thin ice shell (<10 km?)



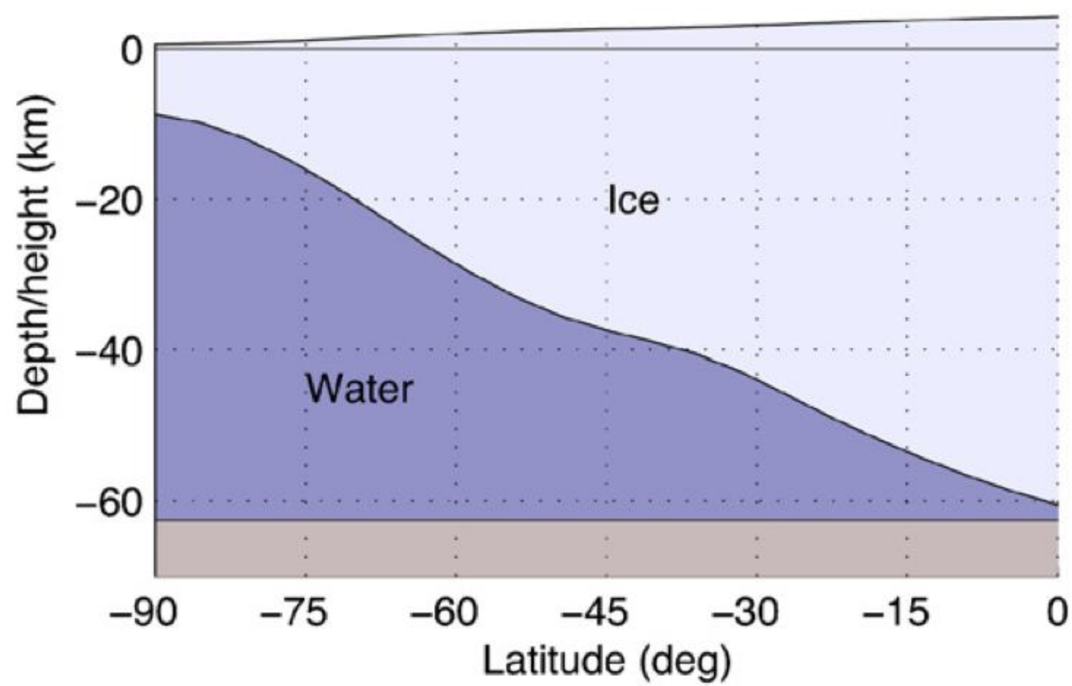


TABLE 1.1 COSPAR Planetary Protection Categories

	Category I	Category II	Category III	Category IV
Type of Mission	Any but Earth Return	Any but Earth Return	No direct contact (flyby, some orbiters[1])	Direct contact (lander, probe, some orbiters[1])
Target Body[2]	Group 1	Group 2	Group 3	Group 4
Degree of Concern	None	Record of planned impact probability and contamination control measures	Limit on impact probability Passive bioburden control	Limit non-nominal impact probability Active bioburden control
Planetary Protection Policy Requirements	None	Documentation: PP plan, Pre-launch report, Post-launch report, Post-encounter report, End-of-mission report	Category II plus: Documentation: Contamination Control, Organics inventory (as necessary) Implementing procedures such as: Trajectory biasing, Cleanroom, Bioburden reduction (as necessary)	Category III plus: Documentation: Probability of contamination analysis plan, Microbial reduction plan, Microbial assay plan, Organics inventory Implementing procedures such as: Partial sterilization of contacting hardware (as necessary), Bioshield, Monitoring of bioburden via bioassay

Group 1: Flyby, Orbiter, Lander: Undifferentiated, metamorphosed asteroids; Io;

Group 2: Flyby, Orbiter, Lander: Venus; Moon (with organic inventory); **Comets**; Carbonaceous Chondrite Asteroids; Jupiter; Saturn; Uranus; Neptune; **Ganymede***; **Callisto**; **Titan***; **Triton***; **Pluto/Charon***; Ceres; **Large Kuiper-Belt Objects**

Group 3: Flyby, Orbiters: Mars; **Europa**; **Enceladus**

Group 4: Lander Missions: Mars; **Europa**; **Enceladus**