Mars Extant-Life Campaign Using an Approach Based on Earth-Analog Habitats

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Abstract. The Mars Robotic Outpost group at JPL has identified sixteen potential momentous discoveries that if found on Mars would alter planning for the future Mars exploration program. This paper details one possible approach to the discovery of and response to the "momentous discovery" of extant life on Mars. The approach detailed in this paper, the Mars Extant-Life (MEL) campaign, is a comprehensive and flexible program to find living organisms on Mars by studying Earth-analog habitats of extremophile communities.

Signs of life on the martian surface are exceedingly scarce. The martian surface is too cold, too dry, and the air too thin to support the kinds of flourishing biological communities we know on Earth. But even on Earth, places exist that are too hot, or too cold, or too dry, or too salty to support familiar animals and plants. Yet these places still support life—extremophile life. The MEL campaign has identified thirteen habitats on Mars similar to habitats on Earth that support such extant extremophiles. From orbital surveys, through regional surveys and on-site traverses, the search will focus on sites increasingly likely to harbor martian life.

The MEL campaign integrates six phases of exploration, from robotic, planet-wide, orbital surveys, through regional, aerial surveys, to intensive, on-site searches, to fully automated labs in robotic outposts, and ultimately to human-run analyses on the martian surface and the full attention of Earth-based labs on returned samples. The approach adopted for the MEL campaign is one that is flexible and open to momentous discoveries and will have the ability to shift or adjust its focus and assets to new or unanticipated developments.

1 Introduction

The MEL campaign proposed in this paper comprehensively integrates six phases of exploration, from robotic, planet-wide, orbital surveys; through regional, aerial surveys; to intensive, on-site searches; to fully automated labs in robotic outposts; and ultimately to human-run analyses on the martian surface and the full attention of Earth-based labs on returned samples. Figure 1 details the decision tree for this multi-mission, multi-decade integrated search for life in Earth-analog habitats.

Tools, and by extension, robots, have always served to increase the researcher's grasp and view. They are an enabling technology for exploring and studying remote objects. There can be no debate about robots *versus* humans (Do we send a pick or a geologist to study a mountain?) just a question of how best to allocate very limited and very valuable resources.

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Robots are already on Mars. After operating as individual instrument platforms future robotic missions will eventually operate more complex outposts. Robots can run several bases more cheaply than one crewed by humans. They can develop a number of attractive sites and give the first human-run expedition a real choice for a successful base. Robots will continue to serve the human expedition after it arrives.

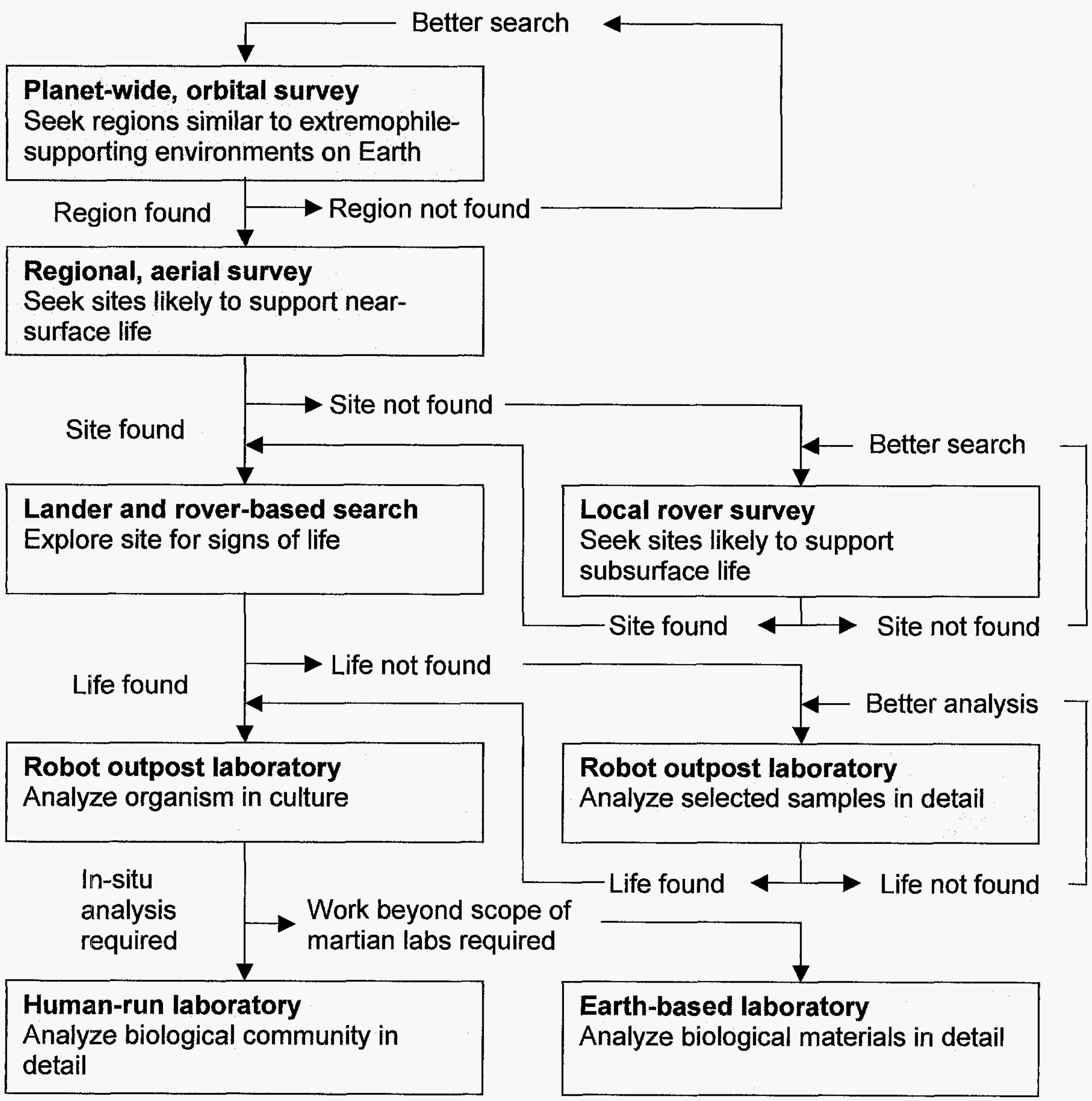

Figure 1: Decision tree for integrated search

Robots, as *intelligent agents*, will do dull, repetitive tasks—running transects, setting up and monitoring sensor nets, identifying and collecting promising samples—easily, without getting bored, distracted, or fatigued. Human time, after all, is just too valuable to waste, and must be saved for tasks requiring real discretion and deliberation.

Robots, as *teleoperators*, will do the dangerous work, like studying sites on cliff faces, or with unconsolidated, shifting soil, or with deadly concentrations of toxins. They can slip down cave mouths or into sinkholes too deep or too tight for humans. They can operate farther and longer than life support systems can sustain human traverses.

The six phases of exploration include

1. Planet-wide, orbital surveys
2. Regional, aerial surveys
3. Local, lander- and rover-based searches
4. Robot outpost laboratory studies
5. Earth-based laboratory tests on samples transferred to Earth
6. Human-run analyses at a Mars-based laboratory

Signs of life on the martian surface are exceedingly scarce. The martian surface is too cold, too dry, and the air too thin to support the kinds of flourishing biological communities we know on Earth. But even on Earth, places exist that are too hot, or too cold, or too dry, or too salty to support familiar animals and plants. Yet these places still support life—extremophile life. The MEL Campaign seeks to identify habitats on Mars similar to those on Earth that support extant extremophile life. Where martian conditions parallel terrestrial conditions, they may support communities of the martian equivalent of our bacteria or archaea or perhaps organisms even more active and complex. Earth-analog sites include

- *Humid subsoil*—Evidence exists on Mars for a diurnal cycle that condenses liquid water at dawn on surfaces and within near-surface soil wherever and whenever atmospheric pressure exceeds 6.1 mb and the temperature climbs above 0°C [http://biospherics.com/mars/spie2/spie98.htm]. On Earth, extremophile communities are known that can exploit such transient supplies of water [http://seti.org/litu/projects/highlights/licancabur.html, http://astrobio.net/news/article233..html, http://www.lpi.usra.edu/science/kirkland/Workshop3/analog_sites_data.htm, http://spaceref.com/news/viewpr.html?pid=2173]. Photosynthesizers protected by ferric salts [http://www.astrobio.net/news/article613.html] could grow close to the surface and make oxygen available to consumers and reducers. While initial consensus on the Viking labeled-release experiment was that an inorganic reaction generated a false positive for both landers, a reconsideration of the original data in the light of new Mars developments persuaded Gil Levin to conclude that the original experiment was successful [http://biospherics.com/mars/spie/spiehtml.htm]. Powerful SEMs and transmission electron microscopes (TEMs) could identify the martian equivalent of bacteriophages (ubiquitous in terrestrial soils), if they exist [http://www.sciencenews.org/articles/20030712/bob9.asp].
- *Seasonal winds carrying dust and spores*—In season, martian winds blow dust all over the planet. For any soil-dwelling microbes, dissemination by wind would confer a real advantage. Such spores would need to tolerate high UV intensities and extreme dryness. Interestingly, for terrestrial organisms, these two adaptations go hand-in-hand [(http://www.nature.com/cgi-taf/DynaPage.taf?file=/nature/journal/v409/n6823/full/4091092a0_r.html]. Earth air is

always full of spores from a variety of organisms both prokaryotic and eukaryotic, from bacteria to fungi, mosses, and ferns.

- *Biocrusts on rocks*—Gil Levin tracked diurnal and seasonal changes in the color of rocks at the Viking I site in Chryse Planitia [http://biospherics.com/mars/color/color.htm]. He suggested the cause was biological activity. On Earth, lichens and desert varnish coat rock faces and thrive on airborne nutrients [http://www.desertusa.com/magdec97/varnish/dec_varnish.html, http://www.highmars.org/niac/niac06.html].

- *Endoliths in porous sandstone*—Martian sandstone is known from lithified dunes—but eolian, rather than aqueous deposits. Such a lithified dune field is known in Herschel Crater [http://mars.jpl.nasa.gov/msss/camera/images/1_31_00_dunes/paleodunes/14_sandstone_1071.pdf]. On Earth, Antarctic endolithic algae and lichens grow within porous, translucent sandstone protected from desiccation and UV radiation—a natural greenhouse [http://www.newscientist.com/hottopics/astrobiology/likenothing.jsp, http://www.geocities.com/exobiologie/Abstracts/Abstract_09.html, http://unisci.com/stories/20021/0116024.htm].

- *Buried lakes*—Even an ice-covered lake may give a heat signature if warmed from below (like Licancabur lake in the high Andes, +6°C on its bottom [http://space.com/searchforlife/licancabur4_021111.html]). Unfortunately, with Mars Odyssey's THEMIS, lots of noise from the wide variability in the heat capacity of rock, sand, and fines complicates data. A record of *sun glints* on Mars, especially in equatorial areas of high hydrogen concentration (Mars Odyssey) suggest areas of ground frost and sources of abundant, near-surface water [http://skyandtelescope.com/news/current/article_600_1.asp]. On Earth, Antarctic and high Andean lakes support algal mats and plankton, with rotifers and tardigrades. While martian lakes would be dust covered, precluding photosynthesis, active, anaerobic life may still be possible [http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1393.pdf].

- *Sub-glacial hotspots*—Volcanic features abound on Mars, and some show similarities to sub- and periglacial features, like the pseudocraters and catastrophic flood plains known on Earth [http://www.euromars.org/Iceland/Bo2506.htm, http://www.journalnet.com/articles/2004/03/11/news/local/news08.txt]. On Earth, without photosynthesis, communities are anoxic. Still, this does not mean simple communities; even the predatory niche does not require O_2—*Giardia*, a nonpathogenic protozoan is an anaerobic bacterial predator [http://www.nature.com/cgi-taf/dynapage.taf?file=/nature/journal/v426/n6963/full/426127a_fs.html].

- *Deep, hot, wet rocks*— Deep, volcanically heated, water-saturated regolith is a possible site of most ancient life [http://www.people.cornell.edu/pages/tg21/DHB.html]—very similar to deep-Earth environments, but for extant life, accessible only with deep drilling. On Earth, sulfur-oxidizing chemolithoautotrophs are the energetic base of SLiME (subsurface lithoautotrophic microbial ecosystems) communities [http://www.pnl.gov/news/1995/95-23.htm, http://nsf.gov/od/lpa/news/publicat/frontier/7-97/7extreme.htm, http://www.sciencenews.org/pages/sn_arc97/3_29_97/bob1.htm]. Some derive their energy from the oxidation of iron or sulfur compounds. Methanogens use hydrogen gas directly and release methane, which has been detected in the martian atmosphere [http://www.jmcgowan.com/mars_reprint.PDF].

- *Snowpacks*—MGS images show recent gullies on mid- and high-latitude, pole-facing crater rims developed from melting snowpacks [http://www.jpl.nasa.gov/releases/2003/21.cfm]. Mars Polar Lander, had it been successful, could have imaged such snow packs. On Earth, the watermelon snow alga (*Chlamydomonas nivalis*) [http://uwadmnweb.uwyo.edu/botany/fac/tvogel/snowalg2.htm] thrives at freezing temperatures and supports a diverse community of psychrophilic annelids like *Mesenchytraeus* (segmented worms), collembolans, and midges like *Diamesa*, which is active at –16° C. Martian "animals" would depend on O released by local photoautotrophs. While the expected O_2 concentration would be slight, some Chironomid midge larvae (*Chironomus plumosus*) can grow and develop in O_2 concentrations as low as 3 ppm [http://ufbir.ifas.ufl.edu/Chap20.htm].

- *Glacier snouts*—Glacial features like moraines, eskers, and erratics are known on Mars, also lobate flows from high-latitude craters that may be masses of soil-covered ice [http://space.com/scienceastronomy/mars_earth_021030.html, http://uark.edu/misc/csaps/Research/current_research/marston_res.html, http://www.lpi.usra.edu/meetings/5thMars99/pdf/6237.pdf]. Glacial lifeforms on Earth settle in meltwater pockets on the glacial surface and support a diverse community of psychrophiles [http://www.nichols.edu/departments/glacier/iceworm.htm, http://www.ecology.bio.titech.ac.jp/Study/glacio_bio/algae.html].

- *Hydrothermal vents*—Active thermal springs are a best bet to support living organisms [http://nai.arc.nasa.gov/library/downloads/annual_abstracts/BOOK-2of6.pdf]. The enormous variety of hot springs in Yellowstone National park provide many interesting analog sites. Fossil remains of impact-induced hydrothermal features in the Mars-analog Houghton crater in the Canadian arctic are currently being studied [http://spaceref.com/news/viewnews.html?id=459]. Volcanic vents on Mt. Erebus in the Antarctic build 10-m ice chimneys from condensing steam. The hollow interiors support thriving photosynthetic microbial communities [http://www.spacedaily.com/news/mars-life-03f.html]. Water vapor in the frigid Martian atmosphere should do the same, but, because of the lower g, on a larger scale [http://mars.astrobio.net/news/article104.html]. On Earth, a variety of thermophilic bacteria, archaea, and even eucaryotes thrive in mineral-rich acidic hot springs [http://helios.bto.ed.ac.uk/bto/microbes/thermo.htm]. *Cyanidium caldarium*, a rhodophyte (red alga—a phototrophic eucaryote), will grow in a solution of 0 pH, at a temperature of 55° C, and 100% CO_2 atmosphere.

- *Sinkholes and cave mouths*—Caves are a good bet to support living organisms. Martian gravity (0.38 g) allows deeper, more extensive caves than Earth. Higher temperature and pressure at depth can support more Earth-like conditions than on the surface. On Earth, terrestrial caves support highly diverse microbial communities; analogous conditions should exist on Mars [http://www.nasa.gov/vision/universe/solarsystem/cave_slime.html]. Deeply fractured limestone, extensive subsurface aquifers, and CO_2-rich atmosphere make caves likely.

Volcanic slopes show chains of pits that resemble collapsed roofs of extended tubes. Sulfate-type excavation may be present [http://www.pitt.edu/~cejones/Geology0802/10_GroundwaterCaves.pdf]. Carbonate deposits should be visible to Odyssey's THEMIS; other mineral signatures to Mars Express.

- *Ejected basalts*— Possible site of most ancient life—very similar to deep, sub-surface Earth environments. Rocks thrown up by impact may contain fossils or other traces of extinct life. A search for the source crater of the famous martian meteorite ALH84001 has yielded a pair of relatively fresh (16 MYA) impact sites in old, Noachian terrain, one east of Hesperia Planitia and another south of Schiaparelli Crater, where material was recently "unearthed." [http://www.lpi.usra.edu/meetings/lpsc97/pdf/1661.PDF] Beagle 2, which, regrettably, failed, had a corer/grinder and optical microscope, which could have resolved bacteria-sized objects 4 μm across [http://www.daviddarling.info/encyclopedia/B/Beagle2.html]. On Earth, such rocks may hold hydrogen-metabolizing subsurface lithoautotrophs—carbon-fixing rock dwellers.

- *Shoreline sediments*—Shorelines are prime locales for fossils, especially if they consist of layered sediments from carbonate-sequestering microorganisms. Orange carbonate granules are prominent in ALH84001 [http://nai.arc.nasa.gov/news_stories/news_detail.cfm?ID=198]. On Earth, sites may include off-shore reef builders, associated communities like stromatolites or microbialites. Such colonies of mat-forming cyanobacteria are ancient (to 3.5 billion years), widespread, and extant (Shark Bay, Western Australia). Early martian conditions may have paralleled conditions on Earth and supported the evolution of such complex communities.

- *Lakebed evaporates*—Evaporite deposits may yield included fossils, if not dormant spores. Many craters show evidence of flooding: inflow and outflow channels, deltas, and shorelines [http://marsoweb.nas.nasa.gov/landingsites/nai/cabrol.ppt).]. MER A, *Spirit*, at Gusev Crater, has identified the evaporite mineral goethite [http://news.bbc.co.uk/1/hi/sci/tech/4094437.stm]; Mars Express is capable of identifying mineral signatures from orbit. Many possible dry lakes, of a variety of sizes, ages, latitudes, and elevations are known. MER B, *Opportunity*, seems to have landed on what was once the shoreline of a salty sea [http://www.nasa.gov/lb/vision/universe/solarsystem/Mars-more-water-clues.html]. On Earth, halophiles (organisms that require a salty environment) like *Duniella salina* thrive in hypersaline lakes. Some may leave resistant spores (like the reported 250-million-year old *Bacillus*) in brine inclusions on evaporation of habitat [http://www.nature.com/cgi-taf/DynaPage.taf?file=/nature/journal/v407/n6806/abs/407897a0_fs.html]. Acid-saline lakes in Western Australia are currently studied as Mars-analogs [http://www.lpi.usra.edu/meetings/lpsc2003/pdf/1690.pdf], as is California's Mono Lake [http://science.nasa.gov/newhome/headlines/ast11jun99_1.htm].

2 Integrated Search-for-Life Campaign

2.1 Global, orbital surveys

Planet-wide surveys: the initial search for extant life will examine multi-spectral and high-resolution orbital imaging to identify regions of interest. In particular, the orbital recon will focus on such features as

- Thermal signatures of "hot spots" (IR spectra)
- "Fresh" volcanic and hydrothermal features (hi-res imaging)
- Sub-surface water deposits (neutron spectrometry, radar)
- Recent gullies and other fresh, depositional features (hi-res imaging)
- Water-laid minerals (gamma-ray spectrometry)

2.2 Regional, aerial surveys and ground-based networks

Subsequent recon may involve flying drones or dirigible balloons for slow, close observations of promising sites. On-board instruments can sample the atmosphere for gaseous signatures (recent identification of methane) or even scatter a network of microprobes for long-term monitoring of transient or cyclical phenomena. In particular, aerial surveys can focus on such features as

- Hydrothermal vents, sinkholes, gullies, springs, evaporite beds, and fossil reefs (microbialites).
- Seismic signals revealing depth and extent of aquifers.
- Transient signatures of volcanic and biogenic gases, including water, methane, and oxygen.
- Spectra of redox-sensitive minerals and complex organics.

2.3 Rover- and lander-carried tests for life

Rovers and landers can physically manipulate samples *in situ*. Suitably designed instruments can collect beneath the soil surface, core into rocks, drill to great depth, and plumb the voids of caves and vents.

Rover- and lander-carried instruments must be of limited size and limited power; samples must be small, easy to process, and require short processing times.

Such *in situ* tests should demonstrate the unequivocal presence of life by including procedures that actually plate out and culture microbes to identifying living organisms, not just biologically important molecules (see http://books.nap.edu/books/0309083060/html/12.html#pagetop, http://www.uark.edu/misc/csaps/Research/current_research/kralres.html).

Some possible investigations include

- A full inventory of large organic molecules (gas chromatography–mass spectrometry).

- Test for chirality (http://www.spacedaily.com/news/mars-life-04c.html), especially involving active uptake of stereospecific molecules (http://www.biospherics.com/mars/2000SPIEFinal.html).
- Search for linear ionic polymers (especially involving passage through electrically charged nanopores— http://www.nap.edu/books/0309083060/html/6.html).
- Determination of $^{12}C/^{13}C$-labelled metabolites (mass spectrometry— http://www.lpi.usra.edu/hottopics/psiw/psiw8.html).
- Test for active metabolism (uptake and release of ^{14}C-labelled metabolites— http://www.biospherics.com/mars/2000SPIEFinal.html).
- Observation of growth in nutrient solution (nephelometry).
- Change in redox state of soil substrate (http://www.sciencedirect.com/science?_ob=GatewayURL&_method=citationSearch&_uoikey=B6WVB-46FH763-1T5&_origin=EMFR&_version=1&md5=505adff2e3fa757d560af8be7cfff0ae)
- Test for photosynthesis (http://dsc.discovery.com/news/briefs/20020408/mars.html).
- Immunoassay tests (http://mars.astrobio.net/news/article43.html).
- Close examination of native samples (soil, rock, ice) and products of culturing procedures for cells and biologically interesting structures with optical and scanning electron (SEM) and transmission electron microscopes (TEM).

2.4 Robot outpost tests of rover-collected samples

The robot outpost will operate instruments that are too big for a rover, that need more power than can be supplied by a rover, that must process more samples than can be processed by a rover, or that need more time to process tests than can be accommodated by a rover mission.

If on-site searches detect microfossils or if on-site tests are positive for growth, a rover will transport a sample to the robot outpost for advanced study.

Culturing organisms in the robot lab will determine:

- The basics of martian life cycles—cell division and genetic recombination.
- The basic amino acid spectrum, and fundamentals of martian biochemistry—ATP equivalent, storage and structural molecules, and importance of metals and halogens to biological reactions.
- The details of the genetic code—this will tell if martian life is related to Earth's or not.
- The details of cellular anatomy—cell walls, membranes, organelles, nuclei, etc.
- Knowledge of basic metabolic inputs and outputs.

2.5 Human-run tests at a crewed base

Because the two-way light time loop may be too long, or the decision tree too complex, a trained researcher, on site, can run more tests and make more decisions than robot outpost software can. On-site researchers can also access diverse localities more quickly and easily than a rover. Trained specialists will explore in greater detail the most promising sites, mapping the biological communities in the field and making extensive collections for lab studies. On-site researchers can expand on the knowledge gained form both robot outpost and returned samples, including studies like

- Characterizing biological diversity at each site
- Determining details of community structure (producers, consumers, and reducers)
- Understanding details of biogeochemical cycling
- Working out details of internal metabolic pathways for specific individuals (roles of enzymes, co-factors, energetic reactions, and biosynthesis)
- Determining the nature and activity of the martian genetic code—especially if it is novel and different from our own (replication, transcription, and translation)
- Begin alpha taxonomy—initial classification of organisms

A crewed base will have to deal with planetary protection issues, including both the danger of infection from potential martian pathogens, and the danger of contaminating study samples (and the local environment) with terrestrial microbes (http://astrobiology.arc.nasa.gov/roadmap/objectives/o17_planetary_protection.html).

The cold, dry, high-radiation environment on the martian surface is intensely sterilizing: it will provide a clean buffer for human activities separated from the presumed biologically active zone beneath the surface. Currently, our protocols and hardware are adequate to handle dangerous pathogens in the lab and recover and protect samples from the subsurface, deep rock, and ice (http://isd.gsfc.nasa.gov/Papers/DOC/iaf99_preserv_mars_life.doc).

2.6 Earth-based lab tests on returned samples

Returned samples can be distributed to Earth-based instruments either too big or requiring more energy than can be accommodated at a Mars robot outpost. Returned samples will also be available to instruments or protocols considered long-shots for a robot base and not established there. Dedicated laboratories will perform any tests not practical to perform at that time on Mars, such as

- Genetic sequencing—mapping organism genomes.
- Beta taxonomy—establishing evolutionary relationships among species.

But any returned sample will be of limited size and diversity, particularly if it is collected by a non-roving lander, and not selected by a rover from a variety of sites. A robot outpost will have the advantage of processing a much greater diversity of samples than possible through a sample-return mission.