Science in the Wild: Technology Needs and Opportunities in Scientific Fieldwork

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Abstract.

Considering that much contemporary natural science involves field expeditions, fieldwork is an under-studied topic. There is also little information technology specifically designed to support scientific fieldwork, aside from portable scientific instruments. This article describes a variety of fieldwork practices in an interdisciplinary research area, proposes a framework linking types of fieldwork to types of needs in information technology, and identifies promising opportunities for technology development. Technologies that are designed to support the integration of field observations and samples with laboratory work are likely to aid nearly all research teams who conduct fieldwork. However, technologies that support highly detailed representations of field sites will likely trigger the deepest changes in work practice. By way of illustration, we present brief case studies of how fieldwork is done today and how it might be conducted with the introduction of new information technologies.

Key words:

Collaborative work; mobile professionals; scientific field expeditions; remote communications; requirements analysis; information technology design.

1. Introduction

After a couple of days of driving equipment-loaded vans, an international team of researchers arrives at a wind-blown spot on the Pacific coast of Mexico. One of the younger researchers puts on a wet suit and wades into the water, taking samples of bacterial growth beneath the brine. How could devices such as bar code readers make it easier for the scientists to keep track of the samples? What could happen if there was a local network collecting data from sensors, and the network were left in place to beam data back to their lab?

A team of geology students takes a trip to Texas to measure and describe layers of rock in a canyon. The majority of their work consists of making two-dimensional maps of three-dimensional rock faces. What could happen if the data were collected in three dimensions?

Field scientists collect data and samples outdoors, typically in groups, and often in remote locations. (See, e.g., (Compton, 1972; Kent, 1997; Smith, 1996).) The purpose of this article is to develop a framework for addressing needs and opportunities for innovative information technology (IT) to support field-based scientific research.

We focus on practical means of representation, communication and coordination in scientific fieldwork. How is knowledge developed and shared among members of a field trip? How are activities in the field, on one hand, and in the office or lab, on the other, integrated--before, during and after an expedition?

There are few studies focusing on these questions. Historical accounts primarily document fieldwork practices in the nineteenth century and earlier

(Kuklick, 1996). While there is a body of relatively contemporary "laboratory ethnographies", they do not deal with field trips as a part of laboratory work. (See, e.g., (Cambrosio and Keating, 1988; Knorr-Cetina, 1981;Latour, 1986; Lynch, 1985; Star, 1983); see also (Barley and Bechky, 1994)). Information technology research and development oriented toward scientific work has also focused on laboratories. Such efforts include research on electronic notebooks, which attempt to replace paper scientific and engineering record books with digital files (Sachs and Meyers, 1996), and laboratory information management systems, which are databases recording information about laboratory samples. (Brown and McLaughlin, 1997; McDowall, 1993).

There are, however, relevant studies. Goodwin has analyzed an example of oceanographic research on a ship, and the varying frames of reference that scientists with different backgrounds use as they collaborate. He shows "how multiple kinds of space--including the sea under the ship, graphic representations, the work space of the lab, and embodied participation frameworks for the organization of tool-mediated human interaction--are constituted through a range of temporally unfolding, work-relevant, situated practices." (Goodwin, 1995, 237). In another article, Goodwin (1994) examines professional cultures of visualization used by archeologists and others. Roth and Bowen (forthcoming), also focusing on issues of professional visualization, describe the complexity of coordination that takes place in ecological fieldwork. Clancey (1999) argues that broadly ethnographic methods can be applied to the design of computational systems intended to support scientific fieldwork. Similarly, McGreevy (1994) makes a case for qualitative field studies of field geologists as an approach to information technology design. There are also many handbooks describing practical procedures in various disciplines (e.g., Compton, 1972; Tucker, 1996; Lock, 1998; Smith, 1996).

This article is based on interviews, lab visits, field studies, and a year of participation by the first author in the technology services and planning group of a large research consortium. The consortium, called the NASA Astrobiology Institute, represents a highly interdisciplinary field, and for this reason we believe is a good starting place for understanding a variety of scientific work practices.

We begin the article with an overview of fieldwork, particularly in the context of astrobiology. Then we develop an analysis of fieldwork practices. By way of illustration, we present two brief case studies. At the close of the article, we turn toward the future: What are the most promising opportunities for information technology? How can studies of work contribute to better technological support for scientific fieldwork?

2. Overview

Field research means different things to different people. For an astronomer, a "field trip" can mean a flight to an observatory. But the practical challenges involved in a trip away from one's home office or lab are only the beginning of the problems of field research.

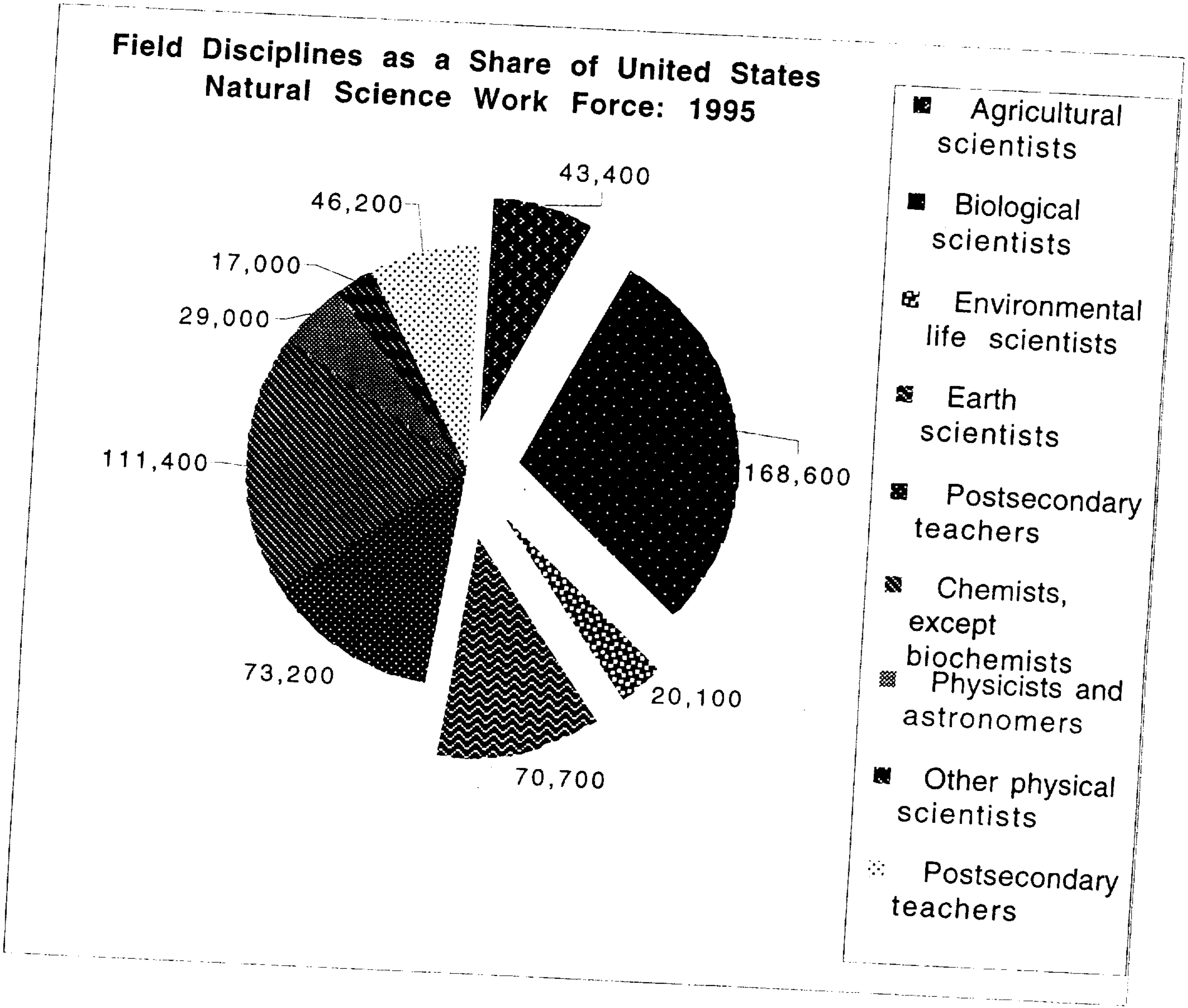
Our working definition, reflecting the discussion below, is that fieldwork is an activity which involves three core elements: (1) *collecting data* (2) *outdoors* (3) *using mobile objects*. Data collection is distinct from physical sample collection, although most fieldwork involves sample collection and samples must be accompanied by at least the information on a label. The fact that fieldwork takes place outdoors (in a non-built environment) has implications for its practice and for the support that can be offered by information technology. The use of mobile objects includes, for example, annotating a map.

Since many field sites are remote, expeditions often present considerable challenges in transportation and communication. Field trips can mean traveling long distances and staying overnight or longer with a group, so it is common for there to be more frequent communication among researchers at field sites, although the communication may be highly focused on the immediate tasks at hand and within specific work groups.

2.1 FIELDWORK IN THE NATURAL SCIENCES

It is difficult to estimate the total number of scientists and support personnel who engage in fieldwork. However, the maximum number of scientists who are likely to engage in fieldwork can be estimated by disciplinary affiliation (NSF, 1998). In the following table, the natural science work force in the United States is divided into persons in disciplines that may include fieldwork, such as "agricultural scientists" and those who likely do not, such as "chemists". The share of technical personnel who may engage in fieldwork thus is slightly more than one half of the total natural science workforce.

Figure 1: Field Disciplines as a Share of U.S. Natural scientists.[i]



Field travel became more convenient with the invention of the automobile and the jet, and we see no signs of it disappearing in the foreseeable future. Field techniques are an established part of the scientific curriculum in scientific training programs. The increasing availability of satellite and other remote image data may spur greater travel and exploration. (Conant, 1994)

2.2 FIELDWORK IN ASTROBIOLOGY

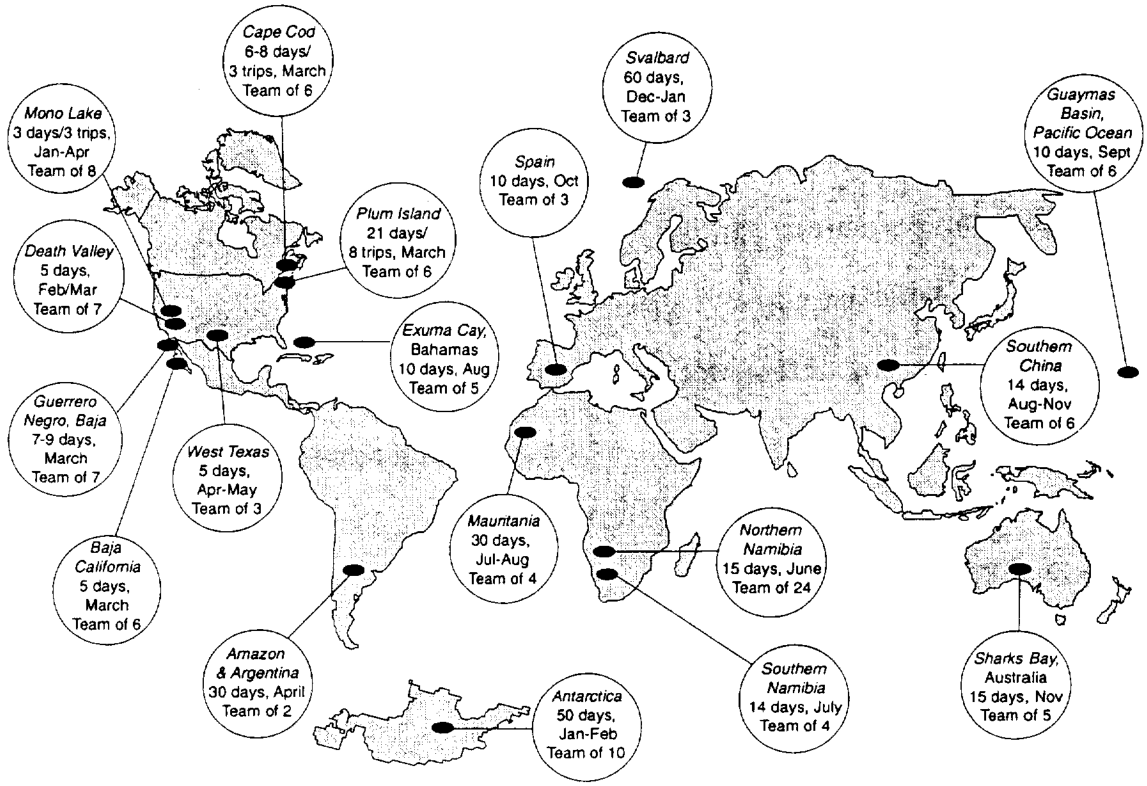
"Astrobiology" as a term came into prominence in the last several years, particularly in the United States, as an expansion on the field of "exobiology" (Showstack, 1998). Major questions addressed by astrobiology include the following: How did life on earth begin? Is there life elsewhere in the universe? What makes a planet habitable for human beings, and how common are these worlds? (Hornek, 1995; Raulin-Cerceau et al., 1998) Not surprisingly, such a broad research agenda draws from many fields of natural science and engineering, including chemistry, geology, biology, zoology, atmospheric and ocean sciences, computer science and engineering, astrophysics and astronomy. (Cady, 1998; Jones-Bey, 1998; Lawler, 1998; Raulin, 1998; Winn-Williams and Murdin, 1998).

The NASA Astrobiology Institute is a consortium involving NASA, universities, and other research organizations located in the United States and Europe. It was founded in 1998 in order to promote, conduct and lead multidisciplinary research, and promote education in the field. Our observation and the opinion of leaders in the field is that the disciplinary composition of the Institute mirrors the wider field of astrobiology.

Among eleven "lead organizations" in the United States, eight are engaged in projects involving field research. By way of learning more about a sample of these projects, we gathered information on plans for the 1999 calendar year at four of these institutions: Harvard University, Jet Propulsion Laboratory (JPL), NASA Ames Research Center, and the Marine Biological Laboratory (MBL).

In total, there are about thirty trips planned by researchers at the four institutions, ranging from short hops with a few people to extended treks with large teams. The geographic distribution is global. The environments are highly diverse and include desert, tropical rainforest, sea floor, salt marsh, and arctic tundra. (See Figure 2, "Selected Expeditions, 1999".) Considering that researchers spend a great deal of time arranging, preparing for and analyzing results from field trips, it is clear that the sheer effort related to fieldwork is an important part of these researchers' work.

Figure 2: Selected Expeditions, 1999



At Harvard, four of eight astrobiology projects are field-based. Researchers have the goal of better understanding the co-evolution of Earth and life through time. This involves multidisciplinary investigations of the geological record, in places such as South China, Norway's Svalbard, and several locations in West Africa. A project at UCLA has a similar goal and also involves geological fieldwork, in Greenland and Australia.

Most of JPL's astrobiology researchers are involved in field studies, and they take about one field trip per month. Under the heading of "life in hostile environments", such as deserts or high-salinity bodies of water, their fieldwork also consists of taking measurements of the environment (temperature, humidity, pH), and then collecting, identifying and studying organisms which exist under those conditions. During the current, first year of the grant, investigators have been conducting this kind of research in the Salton Sea, the Mojave desert, Mono Lake and Death Valley. All of these trips are to areas in a roughly 300-mile radius of Los Angeles, but in 2000, JPL investigators may travel also to the Siberian permafrost and the Atacama Desert in Chile.

Within the Ames astrobiology group, about 40% of the activities are field-based. Under the heading of research on habitable planets one project will be conducting ecological fieldwork in South America. Several other field-based projects take place under the heading of the biological origins of life, mainly by biologists, geologists and paleontologists. Like the JPL group, researchers will be obtaining environmental measurements and samples, though studying different organisms in different locations: Wyoming's Yellowstone National Park, Mexico's Baja California, and the Bahamas.

Astrobiology research at the Marine Biological Laboratory in Woods Hole, Massachusetts is concerned with understanding microbial biodiversity through molecular biological techniques. The fieldwork mainly consists of sample collection, but also involves collection of environmental information about the locales from which the organisms are harvested, similar to the information collected by JPL and Ames. They carry devices into the field such as thermometers, oxygen sensors, and portable flourometers.

3. Varieties of fieldwork

Within the expeditions we have described, there are four major types of fieldwork within the consortium: ecological, microbiological, geochemical and stratigraphic geological. Although we use disciplinary labels, what matters in this case is not the conceptual background of particular researchers, but the sort of practical methods, techniques and devices they use.

3.1 TYPES OF PRACTICES

There is only one example of ecological fieldwork: namely, the trip by Ames researchers to South America. This project is intended to measure the extent and type of vegetation across contiental regions. The fieldwork consists mainly of calibrating remote sensing data from satellites with observations made on land. The two researchers will go to three different regions of the continent, walk to spots that appear to their experienced eyes to represent typical levels of vegetation, and make measurements with a light reflectance meter. Gross locational information is sufficient. A laptop is used to capture the readings from the meter in all of the locations, and location is noted in a notebook with pencil.

Since microbiology is defined in large part by laboratory techniques, microbiological fieldwork is typically oriented toward retrieving samples. Time in the field is typically brief when the location is near, and often more time is used for transportation rather than research. For instance, MBL trips to locations on or near Cape Cod will last one day. JPL trips often take place over a long weekend consisting mainly of driving. Ames trips to Mexico are unusual in that the researchers settle for a week or more nearby because the distance is so great from their home laboratory. The Ames group takes samples and puts them in glass tanks to make mini-laboratories at a makeshift laboratory in the field. Using hand-sized sensors, data is collected daily from the tanks and from the field sites. All of the groups will sometimes leave equipment in the field in order to perform extended field experiments. Microbiological fieldwork is frequently conducted in groups of several members, and coordination of information after trips is typically ad hoc and dependent on face-to-face interaction.

Geochemical fieldwork, as exemplified by Harvard and UCLA projects, is also oriented toward retrieving samples. The aim is to chemically analyze rock specimens. However, in contrast to microbiological fieldwork, more specific location is generally important because rock samples differ by their specific setting. For this reason, geochemists carry more information into the field and more information home. Much of this information is locational. They carry documentation to help them navigate to field sites. They use handheld (currently low-accuracy) global positioning system (GPS) devices to get in the right vicinity and then consult maps, notes and photos to pinpoint, and later document, field sites. Also in contrast to the microbiologists we studied, the geochemists take longer trips, to more remote locations, in more difficult terrain.

Stratigraphic geological fieldwork, represented by researchers at Harvard and their associates, is concerned with representing layers of rock. Researchers gather a great deal of image data, in precise relation to location. Samples are often also gathered for laboratory analysis, but the field studies are based almost entirely on what skilled researchers see and record when they walk around in various locations. Going into the field, researchers typically carry topographic, satellite and other maps, photographs, articles describing an area, along with tools for generating new annotations, photos and maps. Such tools include cameras (digital and analog), surveying instruments, pens and pencils, and handheld GPS devices. Since they spend longer periods in the field together and often share the work of collecting data, stratigraphers appear to often get to know the inquiries and observations of others on an expedition.

Some of these contrasts among types of fieldwork are summarized in Table I, "Fieldwork Practices".

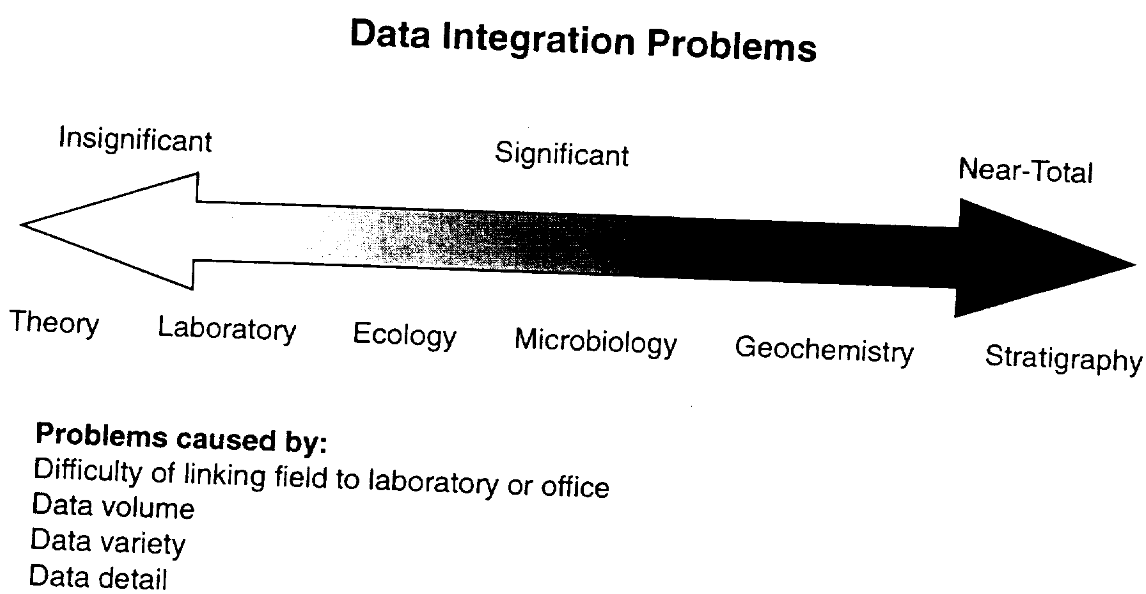
Table I: Fieldwork Practices

Type	**Purpose**	**Central Object(s)**	**Example Trip**
Ecology	Calibrate remote sensing data	Luggage-sized light meter	South America (NASA Ames)
Microbiology	Sample organisms	Portable sensors	Cape Cod (MBL)
Geochemistry	Analyze rock samples	Handheld GPS, photos, maps	Western Australia (UCLA)
Stratigraphy	Produce maps of outcrops	Handheld GPS, photos, maps	Western Texas (MIT)

3.2 TYPES OF TECHNOLOGY NEEDS AND OPPORTUNITIES

These different types of fieldwork face different problems integrating field activities with the activities of the lab or home office. These problems of integration which incorporate as a spectrum include at least the following four dimensions: the logistical difficulty of linking field data and objects to laboratory or office; the sheer volume of data generated in the field.; the variety of types of data from the field; and the specificity of field context information. (See Figure 3, "Data Integration Problems".)

Figure 3: Data Integration Problems



By definition, scientists engaged in theory or doing laboratory work have no problems of integration with field activities. The ecological fieldwork we have described has relatively limited problems of integration. Thus, for examples, getting reflectance readings from forests back to the office involves challenges—researchers can attest to many problems of the usability and portability of their equipment—but they are not major stumbling blocks. The volume and variety of the data is moderate, since it is represented in a few graphs or a few long series of numbers. It is not necessary to have highly specific information about field sites; noting rough location in a region suffices.

3.2.1 Logistics and project management tools

The microbiological fieldwork described in this survey presents slightly more intense problems of integration between the field and the lab. First, there are more logistical challenges because there are more objects (i.e., samples) and more equipment to transport and keep track of.

Second, data variety and detail are somewhat greater. Field researchers note a few or several different types of sensor measurements in their notebooks, and associate them with particular samples. Field locations are described in slightly greater specificity (a particular area of a specific body of water, for example). Selected aspects of the field context—the sensor measurements—are noted, along with ad hoc descriptions of samples that seem remarkable. For example, a researcher might write in her notebook that a particular sample seems "leathery". Opportunities to share and reconcile data and project information among team members appear to be limited in the field, and can be difficult to coordinate afterward because of the reliance on ad hoc and face-to-face interactions.

Third, the overall difficulty of linking activities in the field to activities in the laboratory is greater. This is not only because of the greater practical complexity of field data (variety, detail and sometimes volume), but also because of the greater complexity of laboratory work, which typically involves several people, using sevral instruments, and multiple and often poorly connected media and information technologies. Even for a small team working solely in a laboratory, it can be difficult to access and coordinate the plethora of hand-written notes, email, text documents, and data files and images. When scientific work is carried out in larger teams or in field locations these problems are particularly acute.

For these reasons, the clearest and most distinct needs are for tools that help link field data and samples to activities that precede and follow them in the lab, or what we would summarize as "logistics and project management tools". Examples of such tools would include the following:

- Sample tracking system (such as bar-coding)
- Logistics tools (such as checklist and planning appliances)
- Tools for sharing technical information in workgroups (groupware)
- Tools for organizing and documenting field trips as part of larger projects (groupware/workflow systems)

Such tools will of course be easier to use and may be more readily adopted if they are presented in physical forms appropriate to sometimes messy work outdoors, such as ruggedized electronic or hybrid (paper-electronic) notebooks. Our finding regarding sample labels, in microbioloby and the other disciplines, was that there are no label format standards between individuals and they consulted under a variety of circumstances. Thus, sample-labeling systems should allow human-readable text and should be completely user-defined.

3.2.2 Mobile communications

The geochemical fieldwork we studied also has as its central goal the retrieval of samples, but goes about acquiring samples in settings that have important practical implications. The geochemists can profitably use logistics and project management tools, but can more profitably make use of better mobile communications. The reason is that their fieldwork is somewhat more information-intensive: they rely on high levels of documentation going into the field and leaving it. They also take longer trips to more remote locations, putting them further out of touch with possible sources of information. Examples of mobile communications tools that they could use would include the following:

- More accurate GPS
- Satellite communications (for voice and data such as email, web, weather information services)
- Networked information systems to prevent data loss.

The last example is particularly relevant for researchers who work in treacherous terrain, for example, where one could lose a notebook down a crevice or in the ocean. In any case, field researchers such as geochemists can make better use of such technologies if the physical interfaces to information technologies allows hands-free operation, particularly on difficult terrain. Examples of such interfaces would include voice-to-text annotation and pen-based computers.

3.2.3 Advanced data systems

Stratigraphic fieldwork presents a cluster of extreme data integration problems. For field geologists who make maps of rock layers, collecting and managing data pose major challenges. The data consist of many images and other graphical information, and samples are often associated with the field data as well. There are multiple types of data, including analog and digital data. For instance, field geologists often take instant photographs, paste them in their notebooks, and make notes on them. The volume of the data varies, but typically is a detailed and annotated two-dimensional representation.

Most importantly, the field data is highly specific. It is not an overstatement to say that the entire field site itself is the focus of inquiry. The researchers may or may not take samples as well, but the main things they carry home are descriptions of outcrops.

All of these considerations contribute to the fact that geological data is frequently subject to interpretation among experts. Even expedition team members will argue over what they thought they saw at a particular location. The collapsing of three-dimensional experiences into multiple, overlapping, two-dimensional summaries means that data is frequently lost in transit to the office.

The ideal would thus be to enable the collection and manipulation of three-dimensional data over entire field sites. There are two main technologies that would enable such capabilities:

- Three-dimensional (3-D) reflectorless GPS
- Geographic information systems (GIS) for 3-D "virtual field sites"

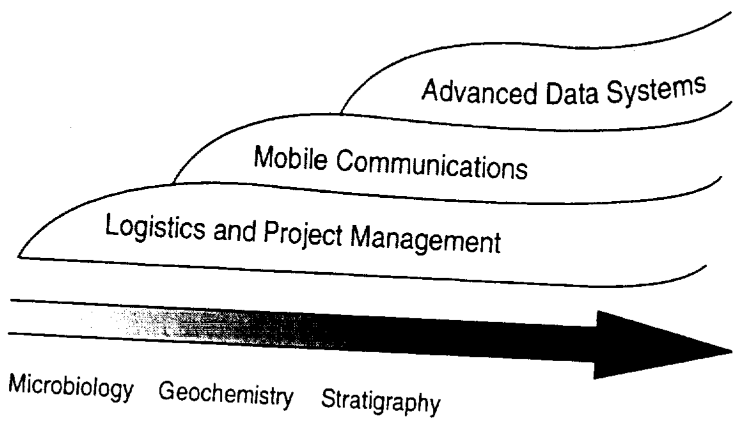
Reflectorless GPS units use laser range finders to bounce a signal off of an inaccessible rock face in order to gain its position and to map the geological section in 3-D. This 3-D manipulation, along with other data organization and displays, is performed using a computer GIS. Stratigraphers can also benefit from project and logistics management tools and mobile communications. Indeed, the implementation of 3-D GIS in the field would call for pen-based annotations in the field.

3.2.4 Summary

In short, the three types of information technology needs and opportunities we have identified build on each other in a step-wise fashion. (See Figure 4, "Example Technology Opportunities".) Project and logistics management tools are generic to fieldwork, and thus will be immediately useful to the largest number of scientific personnel. Mobile communications will be critically useful for a smaller number of researchers, but will be facilitated by the use of project and logistics management tools.

Advanced data collection and manipulation techniques are most specific, but also build on the capabilities of the other two types of technologies. Advanced data manipulation techniques will probably require greater changes in work practice, and thus will have a slower rate of adoption and design development. However, they also promise the most impressive leaps forward in making fieldwork more efficient, enjoyable and scientifically rigorous.

Figure 4., Example Technology Opportunities



4. Case studies

In this section, we will present brief case studies of work practice in disciplines that we take to be illustrative of three different points in the spectrum of data integration problems.

Field microbiology we take as exemplary of problems common to all fieldwork: logistical and project management problems. Better design and use of information technology in such settings will result in incremental improvements in efficiency and ease of conducting fieldwork.

Geochemistry is representative of opportunities to improve fieldwork through mobile communications.

Studies of geological strata we take as exemplary of problems associated with the most extreme forms of fieldwork: problems of collecting large and heterogeneous amounts of field data. Better design and use of information technology in such settings will result in radical transformations of how research groups can visualize, interpret and inter-relate field observations.

In each case study, we present what we regard as critical issues in work practice. We describe a "day-in-the-life" of some researchers and describe how that day would be different if new technologies were introduced. These narratives are from actual field trips, interviews with experienced researchers, and literature discussing standard work practices in the fields.

4.1 MICROBIOLOGY

Figure 5, Snapshots from Microbiology Fieldwork

The work of microbiology revolves around laboratory techniques. Fieldwork is typically limited to the retrieval of organism samples, which are then cultured, or studied directly, in the lab. Beside keeping track of samples, there are logistical problems associated with preparing for a trip and transporting people and equipment, and problems of communication and coordination among project participants.

In microbiology labs, logistical and project management is often chaotic. In the field, this situation is more pronounced. Following is an example from a real expedition conducted in the summer of 1999. (For illustrative photographs, see Figure 5, "Snapshots from Microbiology Fieldwork".)

A group of researchers interested in an unusual microorganism took a trip from the United States to a coastal area of Mexico. They spent a week preparing. After flying in from their home institutions to the nearest airport, they loaded rented vans with equipment, and started driving early one morning. They met with customs and other officials along the journey, and arrived that evening. The next day, one half of the group met with local officials while another half started preparing equipment. By afternoon, part of the group was able to go to the field sites.

They first covered the seats of the van with sheets of plastic to keep them from getting wet. Driving in a van near the water, they would repeat the following three steps several times:

1. Select and note location.

2. Check and note salinity and temperature of the water.

3. Take and note samples (sometimes labeled).

At each step, the content of the notes was passed by word of mouth and transcribed into most individuals' notebook: rough location of samples, along with temperature and salinity of water, and sometimes a description of the sample such as "dark green". They also took 35 mm photographs of the samples.

There was constant banter and questioning. Temperature and salinity are shouted, often at a distance. More detailed information and speculation were discussed at closer range. Several individuals (especially grad students) keep notes from their own point of view. Some people were simply after samples, and didn't need to take notes.

At a makeshift laboratory, work was conducted in a manner similar to that at the home laboratory. Mainly the researchers analyzed samples using gas chromatography equipment. The chromatographic readings would be saved on computer disks and printed out and pasted into notebooks.

Some data is subsequently transcribed into personal computer spreadsheets or databases when putting together a publication. A few researchers like to have the data in personal computer applications beyond what they want to publish. Separate project groups share information within themselves on an ad hoc basis. Most of the collaboration and sharing takes place after trips, since the trips are rather crammed with getting data (the most important results of an expensive activity).

How could this trip have been made easier using information technology? Putting aside the many other innovations that could be imagined and could be useful, we will tell the same story adding logistical and project management tools. We put the story in italics to emphasize its speculative character:

A group of colleagues from several research institutions are on a field trip in Mexico. They are studying salt-water organisms in the field and collect samples of them. More than a year ago, Brendan—"or someone else, I forget who"—started a project file for the *project. They simply called it "Baja 2001", since the group had been going to a particular location, a long drive south of Tijuana, for years.*

Long before the trip, there were many practical details to be coordinated among the thirty people who will spend at least some of the ten days in the field. There are permits to be acquired, equipment to be bought, and inventories to be accounted for—and each person has a different role. They use web-based project management software to make lists of tasks, elect and assign tasks to individuals, and track their progress. Since the software sends email messages, even those who don't use the web portal stay abreast with the tasks and inventories using their usual email program.

Yesterday, a first group of researchers gathered just outside the Mexican border. At customs, it was necessary to find a particular piece of equipment. They searched the group project database, loaded on laptop, for that piece of inventory using a keyword, and see that it is in Box C4. They then quickly retrieved the item for inspection by customs.

Today, the group has unloaded their vans and gotten the permit's they need to start work. Half of the group goes to set up a "laboratory" in a borrowed office. The other half drives a van to the field site to collect samples, observe conditions in which the organisms grow, and check on experiments they left in the field during an earlier trip. At each stop, they use a ruggedized laptop to do three things:

1. Note a location.

2. Note salinity and temperature measurements.

3. Associate location and measurements with one or more samples using a label printed out in the van.

Although most of them are dripping wet after collecting samples, they sometimes also tap out a few descriptive words on the laptop, which they put on a seat they have covered *with plastic. The sample labels use a unique identifier number (machine-readable) and have a few descriptive words (natural language) to help them keep track of what they collected.*

When this information has been uploaded to the central web server, everyone in the project will have access to it. For months before and after a field trip, people in the group search the database for data, samples and other information that interests them, and sometimes browse through to learn about past projects or find out what other researchers are doing.

4.2 GEOCHEMISTRY

Figure 6, Snapshots from Geochemistry Fieldwork

Many specialties in geology involve collecting samples, and documenting each sample in relation to a specific location, often referred to as an "outcrop." Fieldwork involves locating and/or selecting the outcrop, surveying the outcrop, collecting samples, and recording information about the outcrop's location. (See Figure 6, "Snapshots from Geochemistry Fieldwork".)

Geochemistry is a specialty that relies upon laboratory techniques to determine identity and other characteristics of samples. These techniques are not easily transferred into the field however, so the field geochemist must select the samples on the basis of other indicators and consult with each other. The following is an account of a day of geochemistry fieldwork that took place in western Australia in 1999.

Three geologists went to western Australia to examine the Narryer Gneiss Complex. After meeting the night before and discussing the previous day's events, the geologists spent the following morning creating a research plan for the current day using various maps and literature. Then they loaded equipment into the vehicles (including aerial photographs, topographic and geologic maps, rock hammers, compasses, backpacks, hand-lenses, measuring tape, field books, wide arrays of pens and pencils, cameras, sample bags, food and water). Accompanied by local people who came along out of curiosity (and, from the researchers' point of view, helpfully kept tabs on the whereabouts of their group in the bush) the team traveled five hours to the field site.

Once there, they did a distant survey of the outcrops to locate their general position on the maps using hand-held GPS units. Walking closer to the outcrop, the team looked for indicator minerals and measured sections of rock with the measuring tape. They used a big hammer to smash chunks of rock off the face, bagging and labeling each specimen with a marker.

Then they took photos to indicate where the outcrop was located and where the sample was removed. They started with wide-angle photographs including a landmark, and took closer pictures of the sample location, usually using a well know object to indicate scale (a quarter, a fieldbook, or a person). That evening, they loaded about fifty kilograms of specimens into large crates for the journey home.

With the aid of logistical and project management tools and mobile communications technologies, the day might have been a little more productive:

Several colleagues have traveled to western Australia. A debriefing and planning session is held the night before, using a computer to organize and annotate all of the maps, photographic images, and sample descriptions and locations collected the previous day.

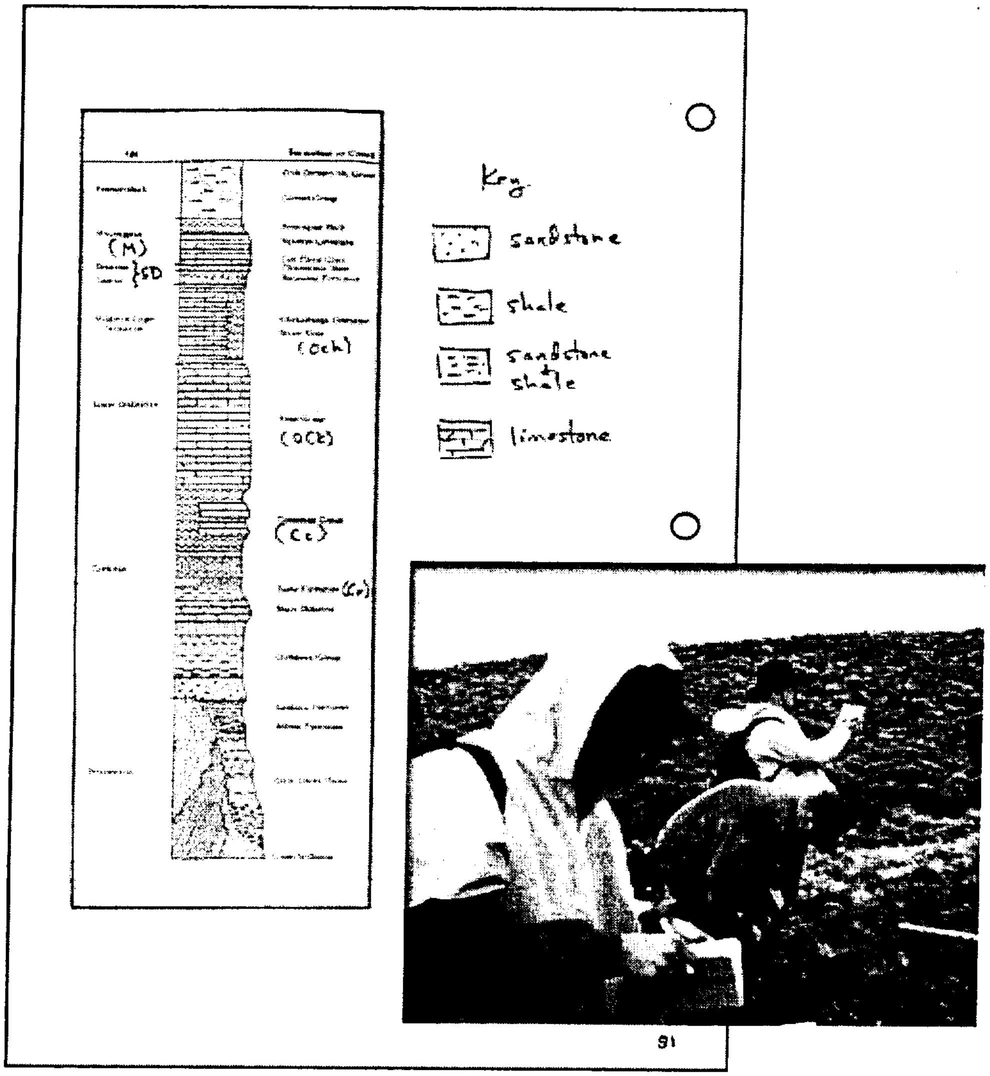
The field site is remote, so the researchers feel better knowing they have a satellite phone to reach help if needed. The common mishap of forgetting a document is a thing of the past now that all of the maps and papers are stored on their portable computers, and accessible over the satellite network.

Approaching the outcrop, the team sets up their GPS base station. The base station will be used as a reference point to improve the accuracy of their hand-held units in analysis at home. A preliminary position can be located using the base station GPS and then the location and a digital photograph of the outcrop is marked on the digital maps on their backpack computers. They set up real-time web-based camera so researchers who were unable to travel to the field can also see the proceedings at the site. At one point, the scientists contact their colleague at UCLA to ask for her comments and advice.

As the geologists begin to look more closely at the outcrop face, photographs of where samples were located are taken with the digital camera. The photographs are automatically time-stamped and referenced to the geologists' position, using 3-D GPS, and uploaded to *the network. Notes about the samples collected are jotted down in pen-based notepads, automatically linked to sample labels.*

4.2 STRATIGRAPHY

Figure 7, Snapshots from Stratigraphic Fieldwork



In contrast to geochemistry, and other sample-oriented fieldwork, stratigraphy produces detailed renderings of field sites. Stratigraphers meticulously describe layers of rock, and relate this information to rock samples, maps, photographs, and drawings of other relevant features and spatial relationships. (See Figure 7, "Snapshots from Stratigraphic Fieldwork".) Below is an example of a stratigraphy field trip from the past year.

Ten geology students led by a professor stayed in a motel near canyons in west Texas. Each morning, the group loaded equipment and supplies on their belts and backs: rock hammers, bottles of acid, binoculars, pens and pencils, field notebooks, compasses, hand-lenses, grain size charts, and their lunch and water. Each student also carried a Jacob staff (a stick about one meter long) and a topographic map with a transparent overlay taped on a board measuring about 1 by 1.5 feet.

After an hour drive over dirt roads, the students and their belongings pour out of the van. Following a quick debriefing, the apprentice geologists chose the side of the canyon that would be easiest to climb and began to look for definite layers to note. After a while, they debated and decided on the straightest path up the cliff as to not skew their Jacob staff measurements. Then, splitting into pairs, they set off to the foot of the canyon to begin taking thickness measurements, detailed descriptions of the rocks, and representative samples from each layer.

These descriptions, which were recorded with crude drawings in the field books, included details about the sediments that the rock was composed of and specific features such as fossils or ripple marks that might indicate the environment under which these layers were formed. A chain of historical events began to come together in the students' notes as they slowly made their way up the canyon wall. Their slow work in the sun was punctuated by frequent mad chases down the canyon after tools, samples, notebooks and maps that had fallen out of their reach.

New information technology could not only aid in the ways in which the data is collected, but also could change how it is organized and displayed for further use. Here is the same story, with key technologies added to enable three-dimensional data collection and manipulation:

A group of ten geology students are heading out to a remote desert canyon. After an hour drive over dirt roads to the site, the students have a quick debriefing and begin to set up the GPS total station and the differential GPS station. The base GPS units are placed at the base of the canyon wall to ensure the greatest stability and to receive the most constant readings. The geologists take a few moments to size up the sides of the canyon and then split into two groups. One group will use the total GPS station and reflectorless laser range finder to measure the steeper side from the base of the canyon wall. For the adventurous types, more traditional fieldwork will be done by climbing the side that is less steep. Using hand-held GPS units and the real-time corrections from the differential GPS, they measure and describe the different layers of rock.

Seeking out the best exposures of the layers, both parts of the team start at the foot of the canyon wall measuring the layers, writing notes, and selecting representative samples from each layer. Each of the layers is given a name and the designations are spoken on a voice communications system—and sometimes shouted between the two teams throughout the canyon. The voice descriptions are also recorded and transcribed into text on the climbing teams' backpack computers--freeing up their hands to collect samples and steady themselves on the rocky terrain. Their backpack systems also include digital cameras, which they use to photograph details about the rocks such as fossils or ripple marks that might indicate the environment under which these layers were formed.

From these descriptions, a chain of historical events was beginning to come together in the students' notes. These histories may be confirmed when the data from the two groups *is later compared and the information is compiled in a GIS and then used to produce a 3-D representation of the canyon and its geologic features.*

5. Conclusion: Implications for Research and Design

The brief case studies we presented were intended to illustrate the analysis of how specific classes of work practice require different classes of information technology innovation. They suggest how certain types of technology may most profitably be applied to the varieties of fieldwork that are practiced today. Project and logistics management tools are generic to fieldwork, and thus will likely be useful to the largest number. Mobile communications are also widely valuable. Advanced data collection and manipulation systems will be useful to the most specific classes of researchers. Such systems will probably require greater changes in work practice, but promise revolutionary improvements in how fieldwork is done. Finally, these three classes of technologies will probably be most useful in combination.

Our main goal, however, has been to begin to develop a framework for understanding and studying scientific fieldwork for the purpose of designing responsive information technology. Toward this goal, we underscored the usefulness of informing technology design with work practice studies centered on understanding practical activity. We have proposed a working definition of fieldwork. Perhaps most importantly, we have proposed numerous specific hypotheses to be refined and tested by further research

Technologically, we have limited our horizons to capabilities that are commercially available today, and will require no major innovations. Some of the most novel implications of the study of fieldwork, however, have to do with technologies that will make it possible not only to bring back better information from the field, but to have multimedia telematic access to field sites. Eventually, telepresence, robotics, telemetry and virtual field sites may trigger some of the most significant shifts in how fieldwork is done since widespread use of jet travel.

Persons Interviewed

Following is a list of key informants for this study:

NASA Ames Research Center:

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University of Colorado:

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Harvard University:

Bowring, S.; Erwin, D.; Grotzinger, J.; Hoffman, P.; Knoll, A.; Thurmond, J.

Jet Propulsion Laboratory:

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University of California, Los Angeles:

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Marine Biological Laboratory:

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REFERENCES

Barley, S. R., & Bechky, B. A. (1994). In the Backrooms of Science: the Work of Technicians in Science Labs. *Work and Occupations, 21*(1), 85-126.

Brown, D., Williams, A., & McLaughlin, D. (1997). A Web-based Information Management System. *Trends in Analytical Chemistry, 16*(7), 370-380.

Cady, S. (1998). Astrobiology: A New Frontier for 21st Century Paleontologists. *SEPM-SOC Sedimentary Geology, 13*(2), 95-97.

Cambrosio, A., & Keating, P. (1988). Going Monoclonal: Art, Science and Magic in the day-to-day use of hybridoma technology. *Social Problems, 35*, 244-260.

Clancey, W. J. (1999). Visualizing Practical Knowledge: The Haughton-Mars Project . Manuscript, NASA Ames Research Center, Computational Sciences Division.

Compton, R. R. (1972). *Geology in the Field*. New York: John Wiley & Sons.

Conant, F. P. (1994). Human Ecology and Space Age Technology. *Human Ecology, 22*(3), 405-413.

Goodwin, C. (1995). Seeing in Depth. *Social Studies of Science, 25*(2), 237-274.

Goodwin, C. (1994). Professional Vision. *American Anthropologist., 96(3):606-633.*

Horneck, G. (1995). Exobiology, the Study of the Origin, Evolution, and Distribution of Life Within the Context of Cosmic Evolution- A Review. *Planetary and Space Science, 43*(1-2), 189-217.

Jones-Bey, H. (1998). SPIE Maintains Stride; Astrobiology Picks Up Pace. *Laser Focus World, 34*(9), 16...

Kent, M., Gilbertson, D. D., & Hunt, C. O. (1997). Fieldwork in Geography Teaching: a Critical Review of the Literature and Approaches. *Journal of Geography in Higher Education, 21*(3), 313-332.

Knorr-Cetina, K. D. (1981). *The Manufacture of Knowledge: An Essay on the Constructivist and Contextual Nature of Science.* Oxford: Pergamon Press.

Kuklick, H. (1996). Science in the field. *Osiris, 11*, 1-265.

Latour, B., & Woolgar, S. (1986). *Laboratory Life.* (second ed.). Surrey: Princeton University Press.

Lawler, A. (1998). Astrobiology Institute Picks Partners. *Science, 280*(5368), 1338.

Lock, R. (1998). Fieldwork in the Life Sciences. *International Journal of Science Education, 20*(6), 633-642.

Lynch, M. (1985). *Art and Artifact in Laboratory Science: A Study of Shop Work and Shop Talk in a Research Laboratory.* London: Routledge and Kegan Paul.

McDowall, R. D. (1993). A Matrix for the Development of a Strategic Laboratory Information Management System. *Analytical Chemistry, 65*(20), 892-901.

McGreevy, W. M. (1994). An Ethnographic Object-Oriented Analysis of Explorer Presence in a Volcanic Terrain Environment. NASA TM-108823. NASA Ames Research Center, Moffett Field, California.

Mecham, M. (1998). Space Science Studies Come to the Internet. *Aviation Week and Space Technology, 149*(1), 59.

National Science Foundation, (1995). 1995 SESTAT (Scientists and Engineers Statistics Data System) Surveys of Science and Engineering College Graduates. *Science and Engineering Indicators*. National Science Foundation, Science Resources Studies Division.

Nealson, K. H. (1997). The Limits of Life on Earth and Searching for Life on Mars. *Journal of Geophysical Research, 102*(E10), 23675-23686.

Nerem, R. S., Dam, T. M. v., & Schenewerk, M. S. (1998). Chesapeake Bay Subsidence Monitored as Wetlands Loss Continues. *EOS, Transactions, American Geophysical Union, 79*(12), 149,156.

NSF. (1998). *1995 SESTAT (Scientists and Engineers Statistics Data System) Surveys of Science and Engineering College Graduates* (Science & Engineering Indicators): National Science FoundationScience Resources Studies Division.

Raulin, F. (1998). From Exobiology to Cosmobiology at LISA and Elsewhere. *Biological Sciences in Space, 12*(2), 66-72.

Raulin-Cerceau, F., Maurel, M.-C., & Schneider, J. (1998). From Pansermia to Bioastronomy, the Evolution of the Hypothesis of Universal Life. *Origins of Life and Evolution of the Biosphere, 28*, 597-612.

Roth, W.-M., & Bowen, G. M. (forthcoming). Digitizing Lizards: The Topology of 'Vision' in Ecological Fieldwork : *Social Studies of Science*.

Sachs, S. R., & Myers, J. (1996,). *Working Group Report on Electronic Notebooks.* Paper presented at the Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises (WETICE'96), Stanford University.

Showstack, R. (1998). The Search for Life in the Universe Spurs Development of the Field of Astrobiology. *EOS, Trasnactions, American Geophysical Union, 79*(12), 149, 158.

Smith, R. L. (1996). *Ecology and Field Biology*. New York: Harper Collins.

Star, S. L. (1983). Simplification in Scientific Work: an Example from Neurosciences Research. *Social Studies of Science, 13*, 205-228.

Tucker, M. E. (1996). *Sedimentary Rocks in the Field.* (2nd*). Chichester, England ; New York: Wiley.

Wynn-Williams, D., & Murdin, P. (1998). Exobiology in the UK. *The Journal of Royal Astronomical Society, 39*(6), 29.

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