PAST GEOLOGICAL EXPLORATION OF THE EARTH AND FUTURE GEOLOGICAL EXPLORATION OF THE PLANETS. Graham Ryder, Lunar and Planetary Institute, Center for Advanced Space Studies, 3600 Bay Area Blvd., Houston, TX 77058-1113.

The necessary predominance (and predilection) of sophisticated analyses of samples and observations from spacecraft characterizes the current exploration of the solar system, and appears to dominate some thinking about the future (e.g. [1]). However, exploration must eventually include *in situ* geological exploration of the planets (e.g. [2]), unless we are content to remain largely uncertain of inventories, histories, and processes. Many reviews (e.g. [3-6)] refer to geology, but their subject is generally either geomorphology or the geology of the very last events. Much of geological history is hidden within rock units. The geological exploration of planets must be undertaken with an understanding of how geological knowledge has been obtained on the earth, taking into account current and reasonably-soberly-projected technologies. A case study of the acquisition of geological knowledge in the classic area of NW Scotland provides a background for understanding some limitations of remote-sensing, spot landers or observations, and transect investigation. Terrestrial experience clarifies limitations in potential robotic investigation and the necessity of iteration, and suggest that human presence will be necessary [2] if geology is to be adequately understood. Non-epistemic factors will undoubtedly have a powerful influence on the methodology and schedule of planetary geological exploration.

Current Exploration Methodology and Limitations: Undeniably spectacular advances were made during the Golden Age of Planetary Exploration (e.g. [7]) in promoting the planets from obscure tiny discs to describable and "comfortably familiar" [4] bodies. The objectives of the exploration of the solar system include understanding the evolution of planets, and much of this is, or is interpreted from, their geological history. However, most of our information has come from observations made at a distance of several tens of kilometers at least, from flybys or orbit; only a few spot landings have provided direct contact information. We use landforms, supplemented to some extent by a little information on physical and chemical characteristics of the surface at a fairly gross scale, to interpret the geology [8]. This has been supplemented for Mars by meteorites from unknown locations. Our information about the Moon is more advanced, including observations by humans at the surface, sample analyses, and some *in situ* geophysical measurements. Nonetheless, if we studied the Earth only in that way, we would be far from understanding even the major processes currently operating. For processes and events that took place epochs ago a close investigation at the surface is necessary. Plate tectonics was not discovered from orbit and even if orbital data available in the '60s had suggested plate tectonics, it could not have been confirmed without contact investigations. Geological processes that took place in the Silurian Period cannot be determined from orbit, nor in any but the most superficial way from the analysis of samples alone.

Particularly important questions pertain to choices among conflicting hypotheses, iteration of observations, and knowing when a controversy is resolved. Sparse data lead not only to little constraining and multiplicity of concepts but allow no means of checking which (if any) are correct; they also of course hide real complexity. Thus even for the Moon we have no way to know whether its history prior to about 4.0 Ga was rather simple or rather complex, what tectonic and magmatic processes dominated, or whether a readable record even exists. Even for a subject as simple (?) as the origin of lunar granites, we have virtually no testable concept of generation of magma, crystallization processes, depth or size of magma bodies, or physical and tectonic aspects of intrusion (indeed, we do not know that intrusion, in the sense that there was magma movement, occurred at all). Yet these would be seen as essential components of studies of terrestrial granitic rocks.

In this age of detailed chemical and isotopic measurements on samples, it is easy (apparently) to overlook the geological context that must be determined both to obtain relevant samples and to interpret the data, and which is fundamental in its own right. The geological context has inevitably been derived from geological field work, which never has been (and is not now) foremost a sample collecting expedition. To properly plan future planetary exploration, one must be aware of how geological knowledge has been, is, and can be obtained, and both the advantages and limitations of particular strategies and techniques. It is important to know how geology is done (and not done), and the comparative information and cognitive response acquired with orbiting sensors, landed robots, and human sensors and manipulative abilities. The comparative information levels of *in situ* analysis, sample returns, selected transects, and detailed geological mapping must be assessed. Yet with the

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growth of Planetary Geology as a distinct field, increasing numbers of participants have little or no significant experience of terrestrial field studies such as geological mapping. Studies of how geological knowledge has been obtained on the earth provide the basis for understanding both the advantages and the limitations of possible methodologies of constructing planetary geological knowledge.

Acquisition of geological knowledge in NW Scotland: Oldroyd [9] made a definitive study of how the structure and geological history of the classic NW Highlands of Scotland were deciphered (up to ~1890). His study documents participants, methodologies, and controversies. I have used both his analysis and my own conclusions from visiting important sites at Assynt and Eriboll to attempt to construe how the geological history of the area might have been addressed by hypothetical planetary-style exploration. I have been more concerned with the cognitive aspects of field work than with the mechanical ones, and attempted to imagine what the participants might have been thinking when they made their observations. This was difficult insofar as it is almost impossible to suppress knowledge that those participants did not have.

NW Scotland is an appropriate example: classic significance, Oldroyd's study [9], my familiarity with it, reasonable exposure, general lack of fossils, and remoteness (though it is accessible). As now recognized, pre-Cambrian Lewisian gneiss is overlain by Torridonian arkosic sediments and then quartzite and limestone of Cambrian age. Overthrust from the east are the Moines (mainly meta-shales and -sandstones). All dip roughly to the south-east. The interpretation of the units and their relationships, hence the essential geological history, went through several shifts before the true nature was recognized. Although units could be reasonably described and correlated, there were two *main* sources of contention: a) whether the Moine and the Lewisian (modern names) were the same, b) the nature of the boundaries between units. Murchison inferred a continuous upward succession, at least partly for non-epistemic reasons, and was able to override objections about overlying metamorphic rocks and the need for faults; this extension of "Siluria" held sway for twenty years. Lapworth (among others) used a different working hypothesis, different methodology (including the use of right-way-up structures and exceptionally detailed mapping) to show that the boundary between the Moine and the rocks to its west was a zone of thrusting, with several thrust planes and numerous imbricate sheets. However, the resolution was a compromise as well as a new creation, and depended on the acquisition of better and more relevant data.

The distinction of the Moine from the Lewisian could probably not be made from orbital geochemistry. While ground chemical traverses could probably distinguish all the main units, the relationships could not be seen without examination of the boundaries themselves and the detailed mapping of their outcrop. Murchison saw the Moine thrust; he just never recognized it from his spot checks. It would have been clear to him perhaps if he had followed its trace and not been led too strongly by preconception.

Conclusions: Knowledge results from an interplay of data and cognition, and scientists are continuously involved in a series of feed-back loops within an agonistic field. The problem of underdetermination (sparse data) is particularly well demonstrated in historical geology, which is different, both methodologically and epistemologically, from most other sciences. Critical evidence for genetic interpretation (such as the nature of a boundary) might exist only in a few spots, and not be apparent in a broad view e.g. a rover traverse or a brief field survey. This was one of the reasons that Murchison was wrong in his interpretation of NW Scotland: generalized theory-induced limited sections and no detailed mapping. Many critical types of information, such as the nature of a contact, are unlikely to be definitively acquired with remote sensing, even from smart and sophisticated robots of a type we can reasonably envisage. One can argue that the planets have a more simple geological history than does the earth, and that less detail is necessary to understand them, but unless we do the detailed studies, we will not know that they are indeed more simple.

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