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Scale versus detail in water-rock investigations 1: A process-oriented framework for studies of natural systems

Richard B. Wanty, Byron R. Berger, and Michele L. Tuttle
U.S. Geological Survey, M.S. 973 Denver Federal Center, Denver, CO 80225, USA

ABSTRACT: Studies of water-rock interaction rarely explicitly address the antithetical properties of scale and detail. Explicit treatments of these properties usually rely on statistical methods and focus independently on geological, hydrological, or geochemical data. While these approaches have the power to draw conclusions from large data sets, they lack predictive capability when data sets from other areas are considered, or when perturbations (e.g., climate changes) are imposed on existing data. However, when processes and properties of natural systems are understood, such a predictive capability may be gained.

We propose a framework for considering the interaction of scale and detail of spatial and temporal properties of natural systems and processes, applied to mineralized rocks. Weathering of ore-related minerals, especially sulfides, provides the opportunity to trace flow along specific fracture sets, and demonstrates the isolation of some sets from others. Case studies presented in this paper, and its second part (by Berger et al. this volume), demonstrate scale-dependent phenomena in natural systems. Although our approach is qualitative, it allows for an efficient design of field and lab studies, and results in a fully integrated study of natural systems, as it includes geological, hydrological, and geochemical factors.

1 INTRODUCTION

An assumption implicit in all environmental studies is that the collected samples represent the system under study at some spatial or temporal scale. Few studies ever test this assumption. Similarly, if a new area is to be studied, there exists no reliable protocol for defining a sampling strategy that will guarantee a representative sample set. Statistical methods are available to generate spatially unbiased (objective) sampling networks (cf. Miesch 1976), which have the advantage of producing unbiased geochemical baselines. However, such methods put little weight on important geologic variables such as lithology and structure. As a result, statistically designed, objective sampling grids provide no predictive capability for areas exceeding the study boundaries, or for other sampling times within the study area.

In a coupled hydrologic-geochemical process-oriented approach, the researcher's objective is to test hypotheses related to the relative importance of various properties of the system. Therefore, sampling strategies will necessarily be subjective, as greater sample density will be required in geologically or hydrologically complex areas, or in areas with strong geologic or geochemical gradients. The problem the researcher faces, then, is to correctly recognize these complex areas, based on existing information or preliminary geologic, hydrologic, and geochemical reconnaissance studies. Prior geologic knowledge (usually in the form of geologic maps or reports) of a study area is a great advantage.

This research strategy introduces the dilemma of scale of studies versus detail. In general, scales of study can be increased at the expense of detail, or vice versa. Given limited fiscal resources, a delicate balance exists between scale and detail. A budget might allow for the collection and analysis of a finite number of samples, so the spatial density of those samples is critically important.

This paper presents a discussion and examples focusing on fractured, mineralized rocks, but the philosophical approach is general and broadly applicable. The presence of mineralized rocks documents a paleohydrologic system that could still be active today (it should be noted, however, that the driving forces behind fluid flow may be different; the former thermally driven flow system might now be gravity driven). Further, mineralized rocks may behave as localized sources of solutes in the weathering environment, providing a suite of "natural" tracers whose migration and attenuation in streams and ground water can be followed.

Because of our focus on a specific mineral deposit type, the hydrologic regimes we will discuss in this and the following paper (Berger et al. this volume) are primarily fracture controlled. Conceptual and numerical models of fracture-controlled flow are still in development. In general, stochastic or deterministic models of fracture flow can be constructed using either a continuum approach or a discrete fracture network approach (Hsieh 1998). The model fracture networks rarely provide an exact match to a field situation (nor are they intended to); rather, they are constructed to match field data (e.g., aquifer tests) or observations. These models seem to have limited accuracy in that they fit the overall features of a flow system without matching the fine detail present in most aquifers. More importantly, though, because these models are usually based on statistical representations of field data, no reliable predictive capability is expected if the study area is expanded.

From the analysis of spatial scales of various natural properties and processes presented in this paper, it should be possible to design more efficient field studies, as well as to assess the degree to which collected samples represent a natural system. An outgrowth of this approach is to suggest a strategy for field sampling that locates areas where geochemical and hydrologic gradients exist.

2 SPATIAL SCALES OF NATURAL PROPERTIES AND PROCESSES

Figure 1 shows a number of properties and processes found in water-rock systems, and the scales at which we observe them. The list is not comprehensive, but demonstrates the wide range of spatial scales over which commonly studied natural system properties and processes occur. Some 16 orders of magnitude of distance are shown on the scale bar. The approximate spatial extent over which each property or process is relevant is shown by the horizontal bar. At the top of the figure the line labeled 'deposit drainage' demonstrates that the spatial extent of drainage from mineral deposits, from chemical genesis to physical transport, may span most of the spatial range shown in the figure. The focus of this paper is on mineral deposits, but the concepts presented are applicable to a wide variety of systems. Therefore, the 'deposit drainage' line could alternatively be labeled 'water-rock interactions.'

Figure 1 is organized so that the properties, processes, and observations are shown from top to bottom in the rough order of geology → chemistry → hydrology → ecosystems. Each horizontal line in the figure is meant to show the actual process or property, but in fact, these lines also may be considered to show the spatial extent or relevance of conceptual or numerical *models* of the properties. The geologic properties and processes are shown at the top because conceptual models of geologic environments provide an overall context within which hydrogeochemical systems can be studied. By understanding the overall geologic systematics, more reasonable model fracture networks might be constructed at a number of spatial scales, and the results of a truly geologic-integrated study might enjoy greater predictive capability. Further, an understanding of the geologic systematics might facilitate a more efficient field sampling strategy.

3 STUDY DESIGN AND OBSERVATIONS AT VARIOUS SPATIAL SCALES

Figure 1 may be used as a guide for organizing investigations of water-rock systems. By determining which processes and properties may be important in a field study, the appropriate sampling strategy may be developed. For example, a study of regional ground-water chemistry and flow in a fractured intrusive rock might include an area up to several tens of kilometers, but to assess flow in individual fracture sets in that area, there must be detailed areas within which several samples are collected within meters or tens of meters of each other.

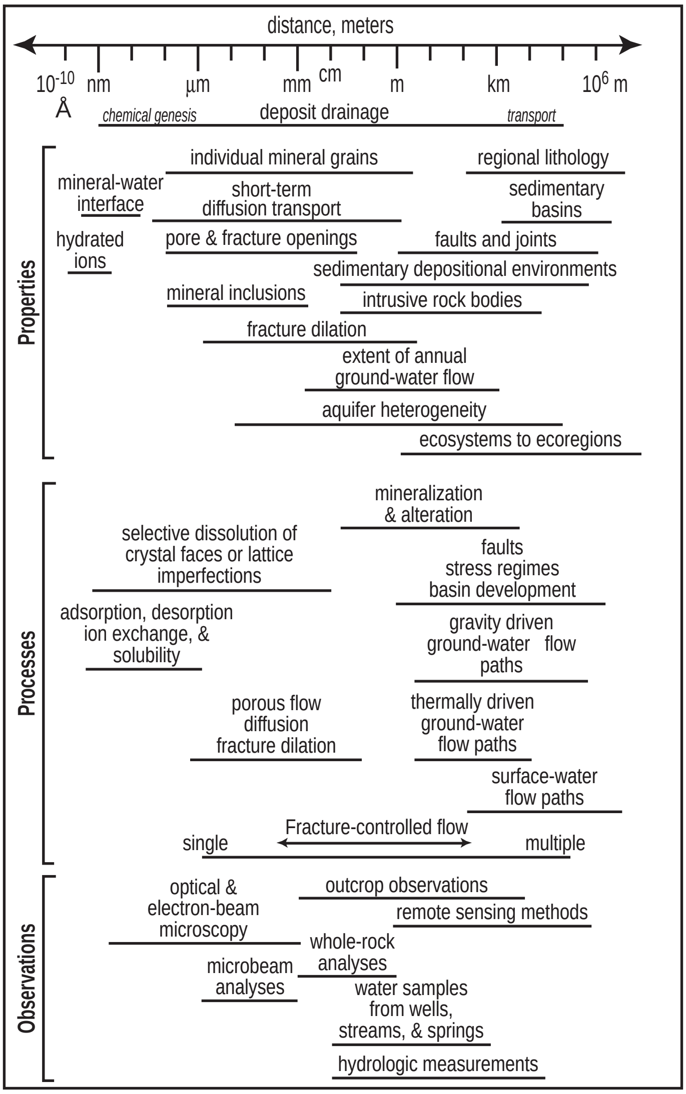

Figure 1. Relevant spatial scales for properties, processes, and observations in systems of interest in water-rock investigations.

To assure that the best set of representative samples are collected, geologic, hydrologic, and geochemical investigations must be conducted simultaneously. Observations by the geologist determine the sites where the hydrologists and geochemists focus their attention. Also, the latter may find an important site (e.g. a spring, a site where water flow or chemistry changes abruptly, etc.) to which the geologist should focus attention. There must be continuous interaction among all members of the field party. This interdisciplinary and iterative approach carries through all phases of the study.

According to Deaton & Winebrake (2000), complex environmental systems are more readily understood by considering the whole system first, then focusing on details. Thus, the areas selected for detailed study are chosen within the context of the larger system. One strategy for conducting field work, which fits within this approach, is to use geologic parameters (bounding faults, lithologic terranes, etc.) to delimit a study area, then determine hydrologic boundaries from topographic maps. If possible, the field party should walk the length of surface-water drainages, monitor flow, some chemical parameters such as conductivity or pH, and pay attention to rock outcrops or rocks in the streambed. If changes in any of these properties are observed, appropriate samples should be collected. An example is given in the next section.

From the point of view of project management, each item in Figure 1 represents a person's expertise, a facility, or piece of equipment. Thus, Figure 1 may prove to be a useful planning and budgeting tool.

4 CASE STUDY ILLUSRATING MULTISCALE BEHAVIOR

Figure 2 shows an area in the Osgood Mountains of north-central Nevada, USA, where our geologic, hydrologic and geochemical studies identified multiple scales of variability. The following discussion is keyed to the locations marked A - E on the map.

4.1 *Variations at 10's of kilometers*

The Osgood intrusive rocks were emplaced in local extensional zones created by strike-slip displacement on the NW-trending faults shown on the map. A third NW fault is inferred from poor exposures at the surface along the SW margin of the southern intrusive body. These large-scale geologic structures resulted from regional tectonic stresses. The fracture network that resulted from those stresses provides the pathways for present-day ground-water flow.

Locations of surface-water samples collected from the Osgood Mountains are shown by the round symbols in Figure 2. More dilute waters were generally found in the south, and somewhat more concentrated waters were found in the north. This separation is readily apparent at a sample density of 2 km^{-2}, but still apparent at sample densities slightly below 1 km^{-2}. This trend is likely due to lithochemical variations in the Osgood intrusive rocks.

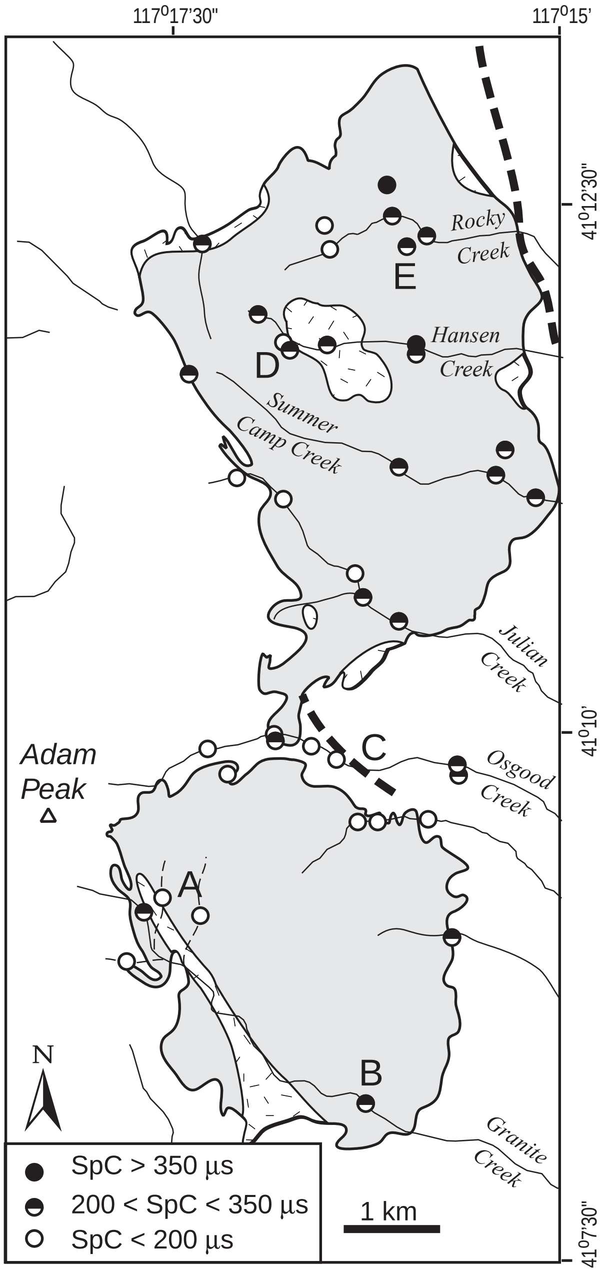

Figure 2. Map of study area showing several scale-dependent phenomena. Shaded area shows outcrop of granodiorite intrusions; patterned areas show zones of sulfide alteration. Heavy dashed lines indicate right-lateral strike slip faults that controlled emplacement of intrusions (geologic map base from Hotz & Willden 1964; alteration zones from Neuerberg, 1966).

4.2 *Variations at 100's to 1000's of meters*

Between points A & B along Granite Creek, changes were observed in the chemistry of surface water. Upstream, near point A, the conductivity values were less than or equal to 210 µs. At point B the conductivity increased to 240 µs and flow increased by more than 5 times. The creek follows an alteration zone, which is defined by an abundance of sulfide minerals in the rocks (Neuerberg 1966). No tributaries to Granite Creek exist other than those shown on the figure, so any chemical changes from A to B must be explained by mixing of the upstream samples at A with ground-water discharge to produce the observed chemistry at B. The small tributaries near A were more dilute than the main stream at A, and so do not account for the increase in solute load from A to B. Therefore, weathering of the altered rocks in the ground-water environment more than doubled the concentrations of Cl, B, K, Ba, Mg, Na, Sr, and Mn. Ground water discharging along this several-km reach of stream bore the chemical signature of the rock alteration.

The spring sample collected at point E is unusual from a geomorphological point of view. The spring is located on a ridge crest, rather than in a valley. The localization of the spring along the ridge is controlled by a zone of EW-trending fractures in the rock that extend to the west for at least several km. Although these fractures are obviously hydraulically conductive, their connection to crosscutting fractures in the area must be limited, or else the spring would not be found on a ridge top.

4.3 *Variations at 1's to 10's of meters*

The fault at point C is one of the principal bounding faults for the Osgood intrusive rocks. In today's stress regime, it is also an hydraulically conductive feature. The fault is regionally extensive (many km), but the hydrologic effects on the creek are localized within a very narrow zone. As the creek crossed the fault, flow increased by more than a factor of 30, and conductivity decreased from more than 300 µs to about 250 µs.

There were two springs at point D, approximately 20 meters apart from each other. Despite their proximity to each other, one had a conductivity of 120 µs, while the other had a conductivity of 280 µs. Because of the thin soil cover, ground-water flow is predominantly in bedrock, and the locations of these springs are structurally controlled. Therefore, the difference in water chemistry is attributed to either differences in residence times of the spring waters in the ground, or to local variations in lithochemistry.

4.4 *Summary of scale-dependent phenomena*

The average sample density in the Osgood Mountains study area was approximately 2 km^{-2}. Many of these samples were collected while walking along the drainages and monitoring conductivity and temperature, and measuring hydraulic heads of ground water beneath streambeds (Wanty & Winter 2000). At the same time, the geologists were nearby observing fracture orientation, density, and offsets (if any). The continuous interaction between geologists and chemists led to many of the observations described in this section. With little prior knowledge of the hydrology of the Osgood Mountains, we collected several important pieces of data that will help unravel the hydrology and chemistry of ground and surface waters in the region. Many of the features described in this paper would have been missed without geologic context or perhaps with a lesser sample density. It should be noted, however, that the sample density was not predetermined. Rather, samples were collected based on observations of geologic, hydrologic, and geochemical parameters as field work progressed.

5 CONCLUSIONS

Consideration of scale-dependent properties and processes should be an integral part of the planning and execution of all water-rock interaction studies. With this approach, appropriate sample densities may be chosen, and appropriate chemical or physical parameters to measure also can be determined. Questions as to whether the results of a study are truly representative of the system are also best answered in the context of scale dependency.

Although not discussed in this paper, temporal scales of variation are equally as important. Environmental systems can vary hourly, daily, seasonally, annually, decadally, etc., so temporal scales of variation should be considered. In dry climate regions, especially, seasonal variations in precipitation may lead to dramatic variations in system hydrology and chemistry. Temporal scales of variation also might be important in problems involving long-term climate change, radioactive waste disposal, and resource assessment, to name a few.

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