3

Image Processing

Drawing As and Its Consequences

The SOWG meeting has just ended, and the chatter of the Rover teleconference line is muted by the gentle sounds of classical music, piped into the office via satellite radio. I am sitting with Ben at his desk at a US Geological Survey branch office.[1] A Rover science team member, Ben has worked at the USGS for many years as a planetary scientist trained in geology. He is peering intently at a Pancam image of a rock at the edge of Victoria Crater that he recently requested that *Opportunity* photograph with the Pancams in thirteen filters (fig. 3.1). During the SOWG that planned the maneuver, the rock was given the target name Cercedilla. A black-and-white image of the rock is splayed across his dual screen display. To Ben, Cercedilla looks suspiciously like a piece of rock thrown outward from the deep innards of Victoria Crater during the impact that formed it: in geological terms, Cercedilla may be a piece of crater ejecta. If this is indeed the case, it would be useful for a geologist like Ben, who wants to know more about the deeper (and therefore older) layers of Mars that the crater's formation exposed.

Fortunately, *Opportunity* was commanded to take images of Cercedilla through each of its thirteen filters. Over the next two hours of

Figure 3.1. Cercedilla, single-filter Pancam view, filter L5. *Opportunity* sol 1184. Courtesy of NASA/JPL/Cornell.

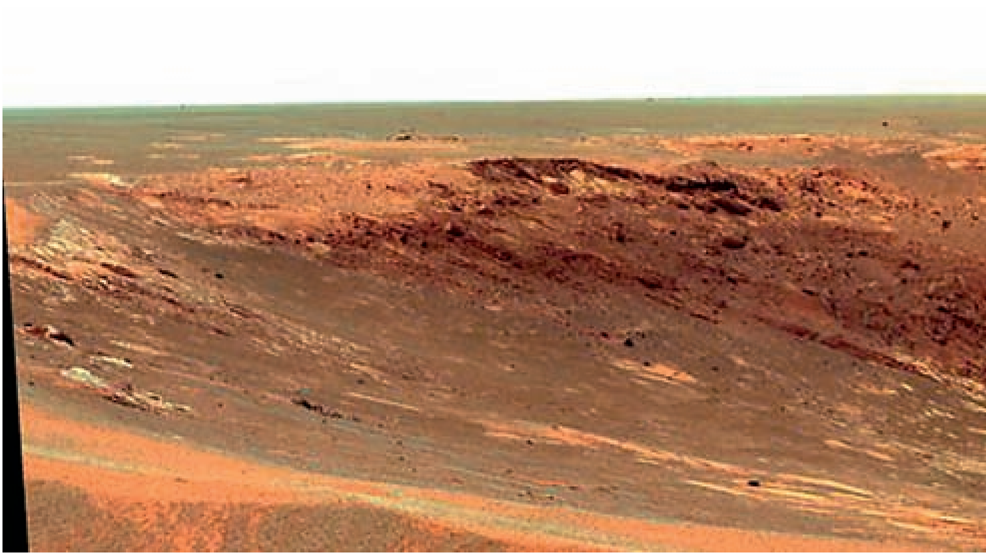
digital work, then, Ben will use these images to "characterize" Cercedilla: that is, to analyze its geological characteristics. To do so, he will compose and recompose the image of Cercedilla into various visual forms. Ben's work will involve software tools, screen work, gesture, and talk as ways of making sense of the digital image on his screen.[2] But all his work will also actively disambiguate, at each click, an otherwise ambiguous image. As an observer, then, Ben is not passive: he actively composes the image into something meaningful. The image that results records and embeds that legibility within its frame, so that the classifying, sorting out, and discriminating work of observation both arises from and is recorded in the work of digital image processing.

In this chapter I will describe the practical work of image processing—activities, forms of talk, interaction, imaging conventions, and instrumental techniques—that Rover scientists use to make sense of digital visual materials.[3] At Ben's desk, we will witness how interpretation, skilled vision, and the expert work of discriminating between kinds of objects are crafted into and through scientific images as they are processed.[4] This is *drawing as* in action. And it is through these practices of *drawing as* that other scientists will come to see the object of interest in just the same way. Turning from Ben's work with Cercedilla back to Susan's work with Tyrone, I will discuss how the work of visual composition presents implications for further observations, representations, and interactions among members of the Mars Rover team.

Image Work and the Dawn of Aspect

To understand how work with images can be considered scientific, it is helpful to review the way planetary scientists characterize their cameras and the images these instruments produce.[5] Central to this story of digital imaging in planetary science is the digital photographic plate: the CCD, or charge-coupled device. Instead of a light-sensitive plate that changes color with exposure, scientists describe electrical detectors that precisely count the number of photons that hit them. The standard explanatory analogy is the water bucket: in this account, detectors sit passively like buckets, counting the drops of water (photons) that fall into them.[6] As the "buckets" are tallied up, the resulting numerical value is expressed as a pixel value. This pixel data can be displayed either as a number or as a value of a shade of gray in a spectrum from black (zero photons) to white (many). As other analysts of digital imaging have described it, then, the digital image is both pictorial and numerical.[7]

According to Rover scientists, CCD-collected pixels represent both photon quantity and quality. When paired with optical filters, pixel values reveal information about an imaged object's ability to reflect light in a particular wavelength. This can be used as a diagnostic tool to identify mineralogical composition. As raw data, each individual image frame just looks like a black-and-white picture in which each pixel corresponds to the number of photons collected through the filter of choice. But combining these filtered images in an image processor through red, green, and blue data channels produces varying color images of the Martian landscape. Because the more extreme colors are produced by wider disparities



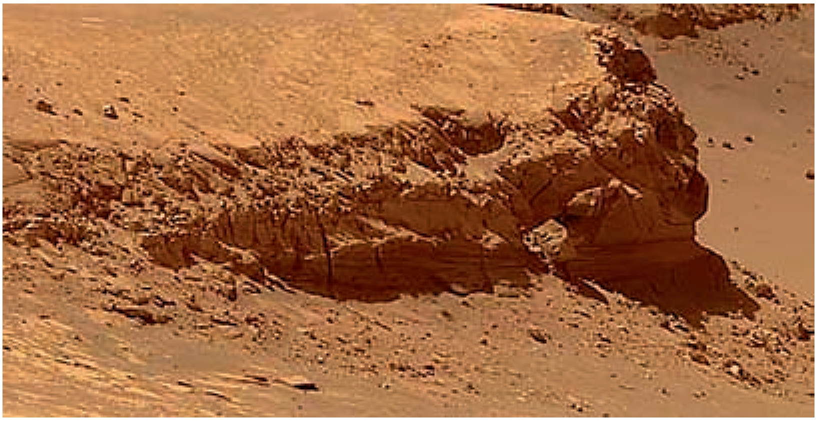
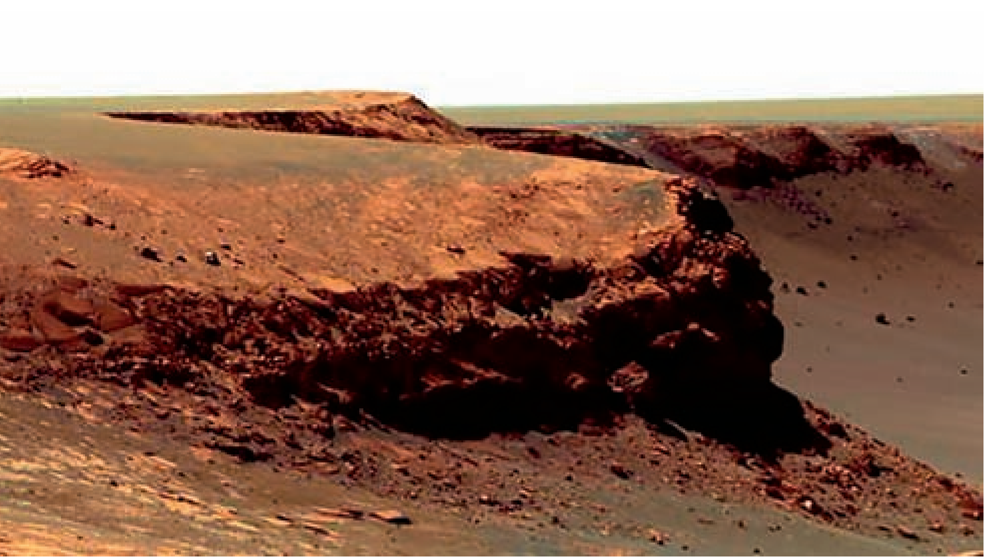


Figure 3.2A. Pancam observation of Cape Verde assembled in L257 false color. *Opportunity* sol 952. Courtesy of NASA/JPL/Cornell.

Figure 3.2B. Pancam observation of Cape Verde assembled in Approximate True Color with adjusted contrast. *Opportunity* sol 952. Courtesy of NASA/JPL/Cornell.

in pixel values between the filtered images across these channels, the resulting colors are taken to be clues to the object's chemical and mineralogical qualities.

On the Rover mission, the Pancam's thirteen carefully chosen color filters enable the team to take many filtered images of Mars from the same camera angle. These filter sets are considered particularly useful for seeing particular



kinds of features and are often combined and recombined in the course of mission operations depending on which features individual scientists most want to see. For example, a soil scientist interested in the composition of the terrain of Cape Verde, a promontory on Victoria Crater, assembled the left Pancam second, fifth, and seventh filters (abbreviated L257) in false color; this combination was judged helpful for revealing a wide range of textural and compositional differences (fig. 3.2A). The resulting picture was well received by soil scientists and doubled as a good image for planning a drive into the crater, since it highlighted different types of soil that might be hazardous or safe for rover wheels. But another geologist pointed to the same transformed image and said: "We think we're getting all this [great data], but look, what do we get [points to shadowed region]? Artifact soup." This scientist was most interested in characterizing the crater's stratigraphy: for him, "lighting and geometry" were more important than compositional difference, since they would allow him to measure the exact shapes, sizes, and depths of the crevices on the cliff face. He therefore combined the filtered frames that showed the least variation in pixel values and adjusted the lighting saturation to better reveal these distinctions (fig. 3.2B).

In these two renderings of the same image we see a switch between the artifact and the object of scientific analysis: composition and texture at the expense of lighting, or stratigraphy at the expense of composition. The pair of images also demonstrates how the selection and combination of raw images varies based on the image processor's intent: exactly what they want to see. But the flexibility to see it both ways is crucial to the science and operations of the mission. The geologist would not be satisfied with the soil scientist's picture, and a rover driver could not hope to identify slippery soil in the geologist's image. Both representations were derived from exactly the same dataset, the same set of pixels, but as a result of the choices of the image processor, a different set of features is revealed or subdued each time. The result of this plethora of possibilities is that one is often confronted with an image of an object on Mars repeated through different filters or processing algorithms. With so many possible viewings, it is clear that there is no one best way of picturing Mars. Rather, such images represent different ways of seeing and knowing the Martian surface.

In fact, the key to understanding rover images is that they are never singular views. Image processors combine multiple images over and over again to craft new visualizations of Mars. This is not a response to resource scarcity. Rather, the Rover scientists I studied explain that it is always necessary to see different things in the same image. For example, as discussed in chapter 2, when calibrating images that return from the panoramic cameras a human operator works in tandem with the computer to locate and eliminate light pollution, scattering, and dust across Pancam images. The resulting equation is applied across the board to an entire suite of images to systematically subtract a value from all pixels so that the images are corrected for dust and atmospheric conditions on any given day. But one person's artifact is another's data: many of the atmospheric scientists rely on these dust values to understand the atmosphere and Martian weather patterns, and soil scientists try to understand the optical quality of the dust itself. They therefore use the output from the calibration procedure to get the dust information and would rather see the dust than the image it obscures.[8]

The multiple views that result are therefore not an attempt to home in on a better representation of Mars in some absolute sense, or to produce incommensurable representations of the planet. Instead, digital image-processing techniques enable a switch between the artifact and the object of scientific analysis: composition and texture at the expense of lighting, or stratigraphy at the expense of composition. This ability to see the same visual data in different ways recalls the famous phrase *seeing as*, proposed by philosopher Ludwig Wittgenstein in the mid-twentieth century.

Wittgenstein illustrates *seeing as* with optical illusions involving ambiguous pictures, called gestalt figures in psychology, such as the duck/rabbit, the profiles/trophy, or the old woman/young woman pairs (fig. 3.3). He notes that people

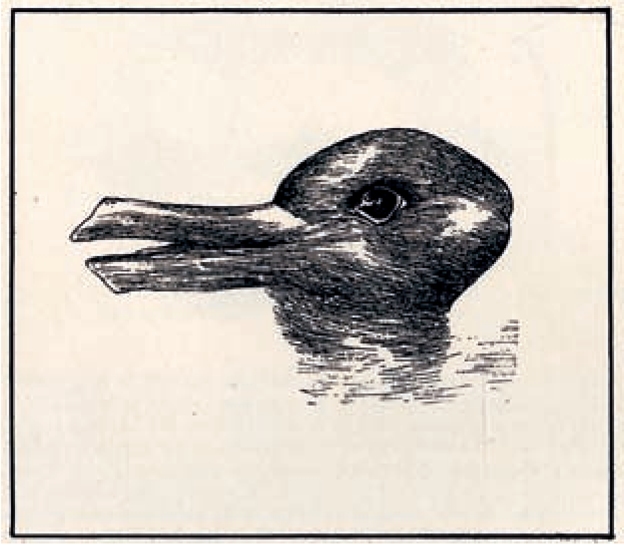


Figure 3.3. The duck/rabbit. Jastrow, "Mind's Eye," 312.

do not usually say "I see it as" about their visual experiences—they just see. But the ability to say, "I see it as" arises in situations where there is some ambiguity about which features are salient: which elements form the background and which the foreground. This is the case with the gestalt figures. While the image does not change, in appreciating its same components in a different way you may suddenly experience a different observation, where the foreground and the background, or the artifact and the object, shift. This is when people stop saying, "I *see* a duck" and start to say, "I *see* it *as* a duck." Wittgenstein calls this moment "the dawning of aspect": a change in the organization of visual experience. Although the object does not change, this change of aspect produces a different observation, "quite as if the object had altered before my eyes."[9]

Like the duck/rabbit, we might *see* Cape Verde *as* a stratified cliff face or *see* it *as* composed of different soils. Unlike Wittgenstein's examples, however, these *seeing as* experiences are not "found" but crafted, the result of image processing. These actions and interactions compose the image into something meaningful, distinguishing foreground from background and object from artifact. Thus an interpretation or skilled vision is crafted into the image from the outset, so that the resulting picture incorporates elements of what it ought to be *seen as*. This is the work of *drawing as*.

Making It Pop Out

To witness *drawing as* in action, let's return to Ben's desk at the USGS, where he is squinting at the image of Cercedilla on his screen. With each transformation of the image, Ben attempts to disambiguate the visual experience of Cercedilla by isolating a single aspect of it at a time, blinding or curtailing alternative aspects. He purposefully includes particular features that he considers salient and simultaneously excludes or silences other features, relegating them to the background.

For example, one way to see Mars is by combining a set of filters through red, green, and blue channels in an image-processing program,[10] producing what the Rover team calls an Approximate True Color (ATC) image: "an estimate of the actual colors you would see if you were there on Mars."[11] This does not mean that true color images are any more "true" than other kinds of images. It is a technical term that refers to a particular combination of filters that approximates the range and type of light sensitivity exemplified by the human eye. The result is a Mars that looks reddish brown.

Ben, however, is not interested in what a human eye could see on Mars. Instead, he is interested in seeing which parts of the rock reflect light differently, since this could be a clue to mineralogical composition. He therefore asks the computer to show him aspects of Mars that the human eye cannot see but the rover's filtered cameras can: the near-infrared region spectrum of light. He loads the Pancam image-processing software and selects several filtered frames of Cercedilla pictures from among the Pancam thirteen-filter set that bear no relation to the human eye's sensitivity. As he combines these images through red, green, and blue channels in his image-processing software, the image of Mars on his screen brightens with bright yellow, blue, and purple (fig. 3.4): a false color image.

False color, to the Rover scientists, does not imply a false image; nor is the image artificially painted to produce spectacular views. Rather, the colors arise from a mathematical relation between pixels across the included image frames, enabling the viewer to see when objects in the scene reflect light in different wavelengths. Thus the distribution of colors in a false color image demarcates, highlights, or otherwise identifies invisible features of the imaged terrain. As one graduate student I interviewed explained, pointing at a false color image that presented Martian thermal data, "That is something you *cannot* see, so it looks like something you *can* see."[12]

As Ben describes it, putting an image into false color like this brings out new features that are otherwise invisible. In false color, "a lot of these . . . rocks suddenly pop out that weren't there before." This kind of talk is not unique to Ben but is echoed across the mission. Rover scientists frequently explained to

Figure 3.4. Cercedilla in a false color view, from a combination of filters. Author's photo.

me that the point of generating false color or stretched images was "to see new things," or to make a hidden feature "pop out." One scientist I interviewed who was looking for sulfate content on Mars explained, "If you get a particular [filter] combination the sulfates just jump out at you. It's like they turn green or blue or something." This change of view does not imply a change in the underlying dataset, only a change in orientation or aspect. As another scientist explained to me, "The data is the same, the difference is in what you see." A Rover Planner on the team echoed this statement: "The image never changes, but you can manipulate the image, and everyone sees something different."[13]

Certain filter combinations have become conventional on the mission, since they are considered particularly good ways of seeing locally relevant details. The most common combination is L257: the left Pancam's second, fifth, and seventh filters. This combination, as the SOWG Chair explained to Cynthia and Alexa in chapter 1, gives a broad enough range of coverage across the visible spectrum to highlight spectrally distinct objects in the terrain. Other combinations are more

Figure 3.5. Blueberries, L257 false color view. *Opportunity* sol 42. Courtesy of NASA/JPL/Cornell.

specific. For example, when *Opportunity* landed on Meridiani Planum, the rover was surrounded by small round marbles of hematite that the team now calls blueberries. The mineral hematite is often formed in aqueous environments and appears to the human eye as dusty gray stone. But because it is slightly less red than most of Mars, combining the images produced by the fifth and seventh filters on the right-eye Pancam (abbreviated "R5-R7") which tend more toward the infrared, makes the hematite light up bright blue in the resulting combined picture. Because this particular visual construal makes the blueberries "pop out," the team calls this combination "the blueberry finder" (fig. 3.5).

Cercedilla also appears to be covered with and surrounded by blueberries, but it is unclear to Ben whether these blueberries are embedded in the rock or sitting on top of it, windblown from across the Meridiani plain. If the rock is crater ejecta, the two possibilities present different likely geological histories for Victoria's deep interior, one involving water, the other not. Ben therefore investigates the blueberries even further to better understand their distribution. Taking his false color image, he heightens the contrast between the different filters, creating a *decorrelation stretch*. "Stretching" here is a technical term that refers to increasing the contrast between pixels, roughly analogous to using the "contrast" tool on Photoshop. In a decorrelation stretch, the scientist increases the contrast in at least one of the combined filtered images by a certain factor but does not necessarily apply the same factor of stretch across the board to the other images in the combination. This changes the "correlation" between the pixels across the image frames. As Ben manipulates the sliders on his screen, Cercedilla brightens as if painted by pop artist Andy Warhol (fig. 3.6). He exclaims, "If you look at it like this [stretched], wow! That's really a different color. Suddenly there's differences in what I thought were really the same [thing]."

Having identified these differences, Ben moves from simply discriminating between colored materials to characterizing them in order to say something about their classification or origin. To do this, he draws on another common approach to image processing: producing a *cube* (sometimes spelled "qub"). Image processors talk about combining filtered image frames almost as if they are creating a stack of semitransparent photographs, layering one on top of the other in perfect alignment. Looking top-down at this pile, the combination of filtered frames produces a colored picture. But looking at the pile from the side, they see individual pixels perfectly aligned, each with a different value. They therefore speak of "slicing through the image cube," generating a graph of pixel values (i.e., how many photons an object collects at a single point) for each filter. These graphs are considered diagnostic for mineralogical composition. Because

Figure 3.6. Cercedilla in a decorrelation stretch. Author's photo.

the object will absorb and reflect different quantities of light wavelengths depending on its particular mineralogical composition, scientists "read the spectral signature"—the graph of pixel intensity at a single point collected through each filter– to make claims about rock composition.

"Using the false colors as a guide," as he puts it, Ben starts by selecting an area of the image of Cercedilla, toward the middle of the telltale circular stamped depression left by the Rock Abrasion Tool as it ground into Cercedilla. The software colors his selection red on the picture, and a graph pops up showing thirteen red points connected by a red line (fig. 3.7). Ben peers at it. "Interesting," he says, and pauses. With his cursor he sweeps over the tail end of the graph. "See the upturn? That's kind of blueberrylike. And it's from this center spot." He moves his gaze and his cursor from the graph to the image, pointing to the swatch of red. "So I'm gonna choose a different color and look at [he selects a region on the edge of the RAT hole in green] that." Thirteen green points show up on the graph alongside the red but do not follow the characteristic blueberry curve. He

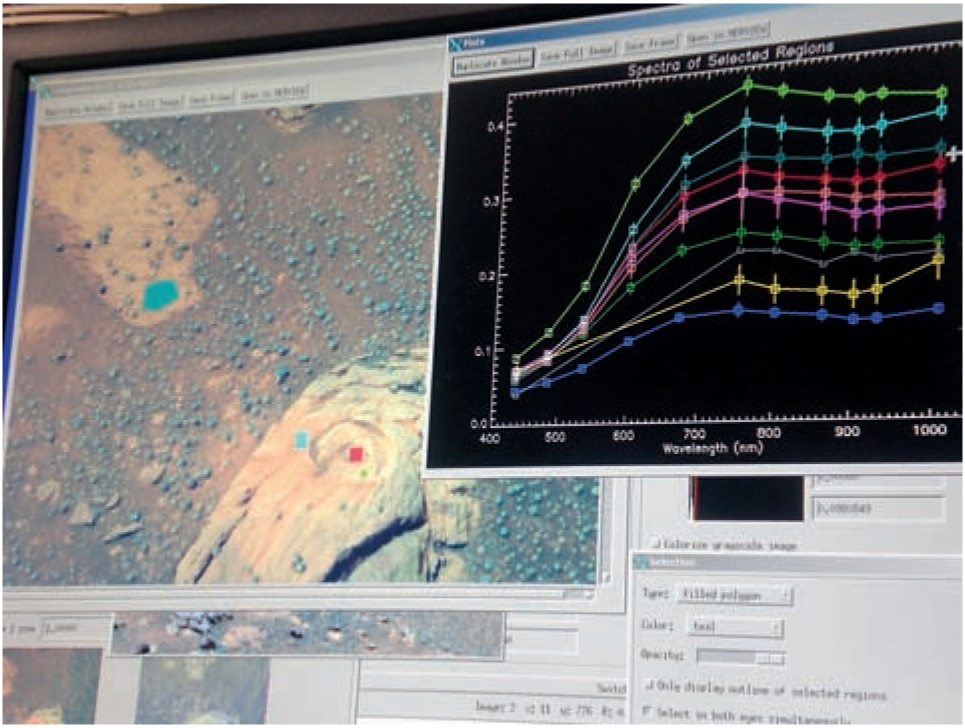
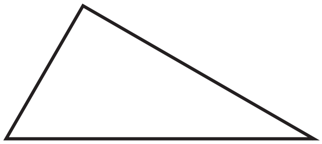


Figure 3.7. Using false colors as a guide, Ben selects areas on the image of Cercedilla to display a graph of pixel values across the thirteen Pancam filters. Author's photo.

gestures again with his mouse, sliding over first the green lines, then the red lines to point out the differences between them. "So there's the difference in spectra between the RAT hole [on Cercedilla] and a spot outside where the Mössbauer [instrument] got its data. And so, why are the spectra so different?"

Over the next hour, Ben transforms the same filtered set again and again. Each single aspect that the resulting image presents to view precludes other ways of seeing and knowing: the slope map image doesn't show him the band depth, the graph doesn't show him where the blueberries are located, and none of these images show him what Mars might look like to the human eye. As one of Ben's colleagues explained, "You have to throw out something in order to make it [the data] understandable." As each new aspect "pops out" I am reminded of Wittgenstein's description of the moment he came to see the duck in the duck/rabbit picture: when a change of aspect in how the elements of the visual field are organized produces a different observation, "quite as if the object had altered before my eyes."[14] The ability to see the photometry or the blueberries is the product of skilled, disciplinary drawing practices that enforce an aspect to organize visual experience and characterize the object in view. The observer sees only the one aspect of the illustration along with the features that the artist or scientist has determined are salient: what is drawn in, not what is drawn out.

Analytically speaking, these are different *drawing as* practices, each producing different possibilities for *seeing as*. It is as if the selection and composition of filters takes the ambiguous duck/rabbit image and resolves it first into just the duck, then into just the rabbit. However, the duck/rabbit example implies a particular ambiguity in which there are only two possible ways of seeing the image. It is perhaps better in this case to consider examples that present many possibilities for *seeing as*. Ludwig Wittgenstein uses the example of the "aspects" of a triangle in this way:



> This triangle can be seen as a triangular hole, as a solid, as a geometrical drawing, as standing on its base, as hanging from its apex; as a mountain, as a wedge, as an arrow or pointer, as an overturned object which is meant to stand on the shorter side of the right angle, as a half parallelogram, and as various other things. . . .
>
> "You can think now of *this* now of *this* as you look at it, can regard it now as *this* now as *this*, and then you will see it now *this* way, now *this*."[15]

Similarly, Rover team members describe images as concealing different kinds of information that talented image processors must work to reveal by applying different visual conventions. As one explained it, "There's all kinds of information in there [in the image]. These blueberries—it's not so evident that they're made of such different material as the rocks they're sitting on. . . . Ross and Gwen [two mission scientists] really find some hidden mineralogy."[16]

In this account, "information" is "in" the image. A cursory glance or even a single-filter image is not enough to make distinctions in material composition "evident." It is the skilled techniques of image processors like Ross and Gwen that identify compositional distinctions by making them visible and observable. Clicking through decorrelation stretches on the Pancam image processor, this same team member described one image as "almost like seeing through the dust," while another "would not reveal . . . that we'd gotten into something different there." One decorrelation stretch was deemed more useful than the other because "[you shouldn't] waste your time on dust when what you wanted [to see] is the rock."[17] Which filtered images are combined and how they are displayed vary based on the image processors' intent: what they want to show.[18] Purposeful image construal, then, relies on mastering visual techniques that reveal certain aspects and conceal others.

Like lab work or fieldwork, it takes skilled membership to produce these observations. Ben analyzes Cercedilla using the masterful application of techniques that enable him to see the kinds of things geologists prefer to examine—mineralogical composition, texture, morphology, and so forth—and to display them in locally sensible ways. This kind of work is a primary component of scientific work on the Rover team. Most of the mission's scientists are trained geologists, geochemists, or atmospheric scientists, professions with a strong emphasis on fieldwork and lab work alongside computational analysis of datasets. But given their considerable distance from their field site, scientists frequently rely on imagery and image-processing software tools to produce knowledge about Mars. Digital image processing, to a large extent, constitutes the essence of "doing science" on another planet. Ben's colleague, Julie, concurred, telling me, "We [planetary scientists] have all become what they call 'pixel pushers' instead of field geologists."[19]

Such work has even colored, so to speak, how the scientists approach their fieldwork more generally. As Ben explained to me, gesturing to the bright hues of Cercedilla, "This is my fieldwork these days, and I sort of get used to the fact that this is the data you have to work with. I would almost feel frustrated being in the field and not having Pancam!"[20] Ben's eyes are fine-tuned instruments for fieldwork on Earth, thanks to his training in geology. Now he considers them deficient compared with rover vision. Other scientists across the mission frequently emphasized to me that the rover had the advantage of being able to see in different wavelengths than the human eye. Jude, a Pancam operator, described this as a feature of robotic space exploration more generally. As she put it, "We would not expect to see this [feature] without our instruments. That's one of the advantages robots have over humans."[21] But it is not only the robots or the instruments themselves that enable this kind of vision. A human with Pancam eyes would be limited to seeing through one filter at a time. Equipped with computational image-processing tools, the possibilities for seeing expand. It is not just the ability to "see in the infrared" that makes digital image work advantageous; it is the many visual combinations of a variety of filtered images, each presenting new aspects of Mars to human view.

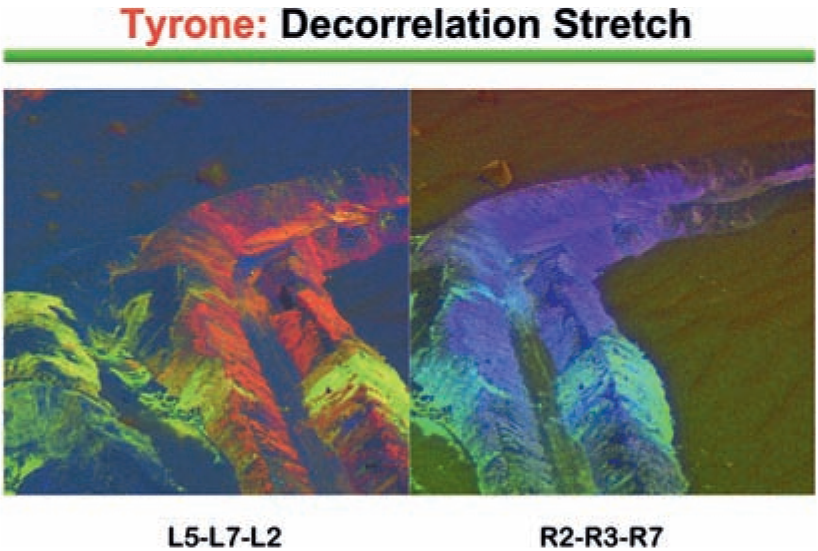


Figure 3.8. Tyrone, decorrelation stretch, from Susan's presentation. Used with permission.

From *Drawing As* to *Seeing As*: The Case of Tyrone

The true power of *drawing as* lies beyond the desktop: it is in interactions with other scientists that we witness an iterative relationship between these local representational practices and collective or shared seeing experiences. For an example, I return to this book's opening vignette: Susan and the case of Tyrone.[22]

A staff scientist at a midwestern research university associated with the Rover mission, Susan was a geophysicist by training when she joined the mission, but later she chose to complement her work on the rover's spectrometers with the Pancam's imaging capabilities. As she put it in our interview, "You shouldn't limit yourself to one [rover] instrument: it's the most foolish thing you can do!" During the Martian winter in which *Spirit* remained stationary, without enough solar power to drive, Susan traveled to a different university to spend time with the Pancam operators there, to train for the role of Pancam Downlink Lead, which requires reporting daily on the status of the remote instrument, and to learn to use the Pancam image-processing tools. While training, she practiced these techniques with recently acquired images, including the pictures of the patch of roughed-up soil at Tyrone (fig. I.2). As Susan recalls, it was while she was making false color composites that she first noticed that what looked like just a patch of white soil in a single-filter image produced different colors when composed into a decorrelation stretch (fig. 3.8).

Figure 3.9. A histogram of Tyrone pixel values (right), as seen on Susan's screen as part of her image-processing practices. Author's photo.

Intrigued by how something that looked like a single feature could perhaps be made of different types of material, Susan first turned to the numerical side of the image in order to characterize what she saw in the false color image. This would help her isolate the spectral properties of the two kinds of soils and possibly determine their composition. As she explained, "I'm not looking at a pretty image. I use [a] histogram . . . if my purpose [is] to see if [it is] two different types [of] material." Instead of asking the computer to generate a graph for a particular region of the image as Ben did, Susan asked the computer to display all the pixel values at once on a graph (fig. 3.9). That is, she *drew* Tyrone *as* a histogram: a graph in which individual pixel values are plotted together. Construed in this way, the image data showed two distinct clusters of pixel values. Susan interpreted these two branches of the histogram as different types of material, whose properties of light absorption were so different that they produced radically different pixel values in the image at hand.

Figure 3.10. Coloring in one branch of the histogram on the right screen in yellow and another in green reveals two distinct types of soil at different depths in the image on the left screen. Author's photo.

The Tyrone histogram showed that two kinds of material were present in the image data, but it did not show where that material was located or why it was changing. Susan therefore used another Pancam tool to "separate them [the two materials] spatially." When she colored in one branch of the histogram in green, all the pixels plotted on that branch lit up in green on the picture version of the same file. She could then see where that material was scattered. She proceeded to color the other branch of the histogram in yellow, lighting up a different patch of white soil (fig. 3.10). Thus two kinds of soil with different spectral characteristics were confirmed. And because of where those different patches of soil lit up in the image in green and yellow—what Susan called "spatial correlation"—she could tell that the yellow material was buried deeper in the wheel track than the green. Applying the same techniques to a series of images of Tyrone taken over several days, Susan noted that the histogram changed; that the yellow branch started to conflate with the green one (fig. 3.11). This suggested to her that the

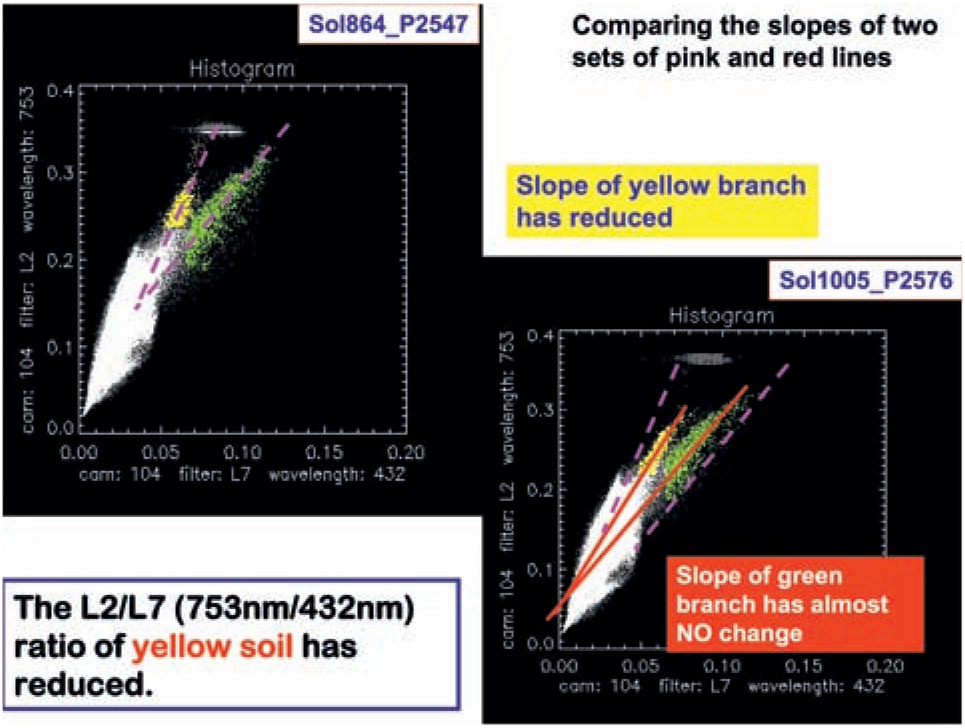


Figure 3.11. The slopes of the histogram change over time. From Susan's October presentation. Used with permission.

yellow material was changing in some way to become more like the green, perhaps owing to its recent and unexpected exposure to the Martian atmosphere.

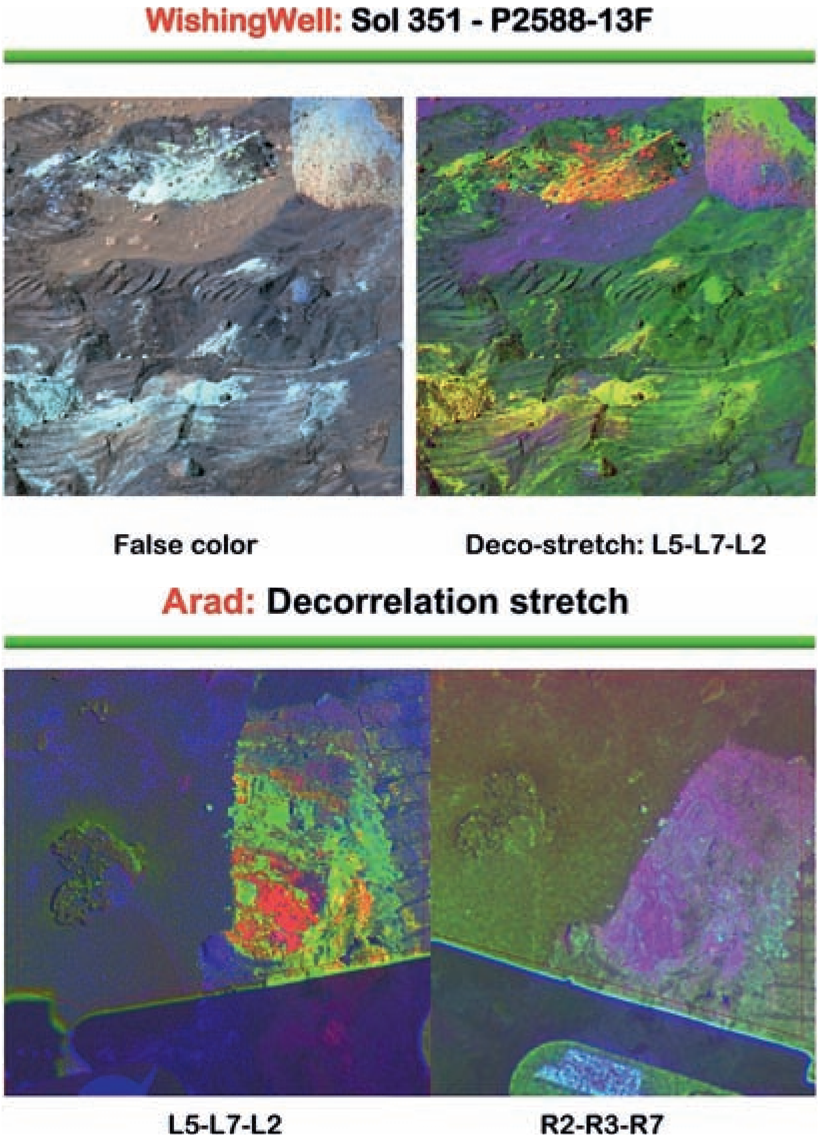
So far this story is not unlike Ben's. As Susan *draws* Tyrone *as* a histogram, then *as* composed of two kinds of soil, her processing techniques reveal an aspect of organizing visual experience; and bringing several of these aspects together in concert, she makes a claim about a particular region of Mars. Each of these transformations also allows her to make an interpretative claim not just about evidence for two-toned material, but about its location and other characteristics. Where the story takes a novel turn, however, is when Susan left her screen to present this work to her fellow Mars Rover scientists.

Susan began by presenting these results to her colleagues at the End of Sol meeting in October 2006, the teleconferenced weekly meeting geared toward the presentation of ongoing, preliminary science results. She then requested further images of the Tyrone region over the Martian winter, while *Spirit* was stationary, and her fellow team members were suitably convinced from her presentation that they should include her "Christmas wishing list [*sic*]" of follow-up observations in *Spirit*'s plan over the following week. A few months later she presented the results of these wished-for images at the face-to-face team meeting in February 2007, at Caltech in Pasadena, California. She began her presentation by showing the decorrelation stretch of Tyrone that she had first displayed a few months before. "You're all familiar with this beautiful Pancam image," she said. Then she applied the same stretch to eight pictures of rover tracks taken from across the region (fig. 3.12), narrating as follows:

> A similar situation happened in the Arad area, where we see the . . . color difference. This yellowish area shows this kind of spectra, and you have the slope at this kind of peak. . . . And when we do the decorrelation stretch we see the yellowish soil shows in the orangish in this area . . . also the purplish in the right eye is in the decorrelation stretch. . . . And at Paso Robles, we also see this area is the yellowish and the whitish [soil, in true color]. . . . At Wishing Well we also exposed some kind of lateral material. . . . we see there are also color differences.[23]

Applying the same visual convention from Tyrone to images taken across the region was a powerful representational technique. At this moment, the team came to see the two-toned soil, and see it everywhere.

But what could this observation mean? Susan next applied the same decorrelation stretch to Pancam images of Tyrone taken at different times in the mission. She showed that the histogram was changing slope, indicating a change in the properties of the white material. She cautioned, "We need to be sure this change is real, so I checked several factors." She next reviewed and dismissed the effects of a "diffuse sky" on how "the spectra behave," and any possible relation to optical effects of the camera using calibration data. Certain now of "the basic phenomenon of this observation," Susan suggested a change caused by atmospheric exposure and the subsequent dehydration of the salt properties of the soil. She corroborated this hypothesis with an experiment in her laboratory on Earth, showing that ferric sulfates decreased in acidity and could have affected the detected histogram slope.[24] Then Susan presented a topographical map of the area around Tyrone, highlighting the geographical locations of the observed light-toned soil. Considering that the soil was consistently visible in local lowlands, she put forward the potential hypothesis that this ferric sulfate deposit could have been distributed evenly throughout the region by something like flowing water.



Figures 3.12A, B. Susan applies the same decorrelation stretch that she performed on Tyrone to other regions in her February presentation. Used with permission.

Susan's presentation was catalytic. The entire Rover science team began excitedly exchanging ideas and hypotheses about the light-toned soil. One scientist stated that "these observations make a compelling case" for some form of liquid water transport system in the deposit of the soils; another asked whether wind, instead of water, could have achieved the same distribution. Another scientist wondered whether volcanic processes could be responsible for laying down the salty deposits because of their high sulfur content, while another put up a slide showing an image of an environment in Iceland that she suggested "might be more consistent with what we're seeing" at *Spirit*'s site on Mars. Several other scientists took up the discussion of how old the salty deposits might be, with estimates ranging from millions to billions of years. The Principal Investigator extended the discussion past the projected end of the meeting to accommodate further conversation as scientists exchanged potential formation scenarios and raised challenges to each other's explanations.

All present treated the existence of the two-toned soil and its distribution as fact. The question up for discussion was not whether "the basic phenomenon of this observation" (as Susan put it) existed or how best to see it, but why it was there and how it got there. Discussion thus centered on different hypotheses about its origin and depositional mechanisms and generated proposed observations with the rover's suite of instruments to determine which of these hypotheses might be ruled out and which might be feasible or worth pursuing. When the discussion was summarized at a subsequent meeting, it was dubbed "the Light Soil Campaign" and encompassed a variety of observations aimed at better characterizing the two-toned soil at Tyrone and elsewhere. These observations formed the basis of rover operations for the following two weeks, and follow-up investigations on light-toned nodules that were also requested as part of the campaign formed the crux of *Spirit*'s investigations on the western edge of Home Plate.

Susan was adamant that the use of yellow and green colors revealed a distinction in the soil instead of adding or coloring in an interpretation. "The change was real," she said. But her use of color was important for "showing" this distinction both to herself and to others. Her initial interest in the light and dark rocks on the mission made clear the importance of conscripting other scientists to her point of view. With respect to Tyrone, as she put it to me when I visited her laboratory: "You decide the color you want to show, the color you want to use, but the data is there, it's not the color. . . . Because the existing data [images] contain this kind of information, you decide how you want to show [the data]."

Green and yellow thus became convenient ways of reconfiguring the pictorial representation of the image so that this feature of the soil "lit up" (or "popped out"). The colors also depict "information" that is "contain[ed]" *in* the image, not glossed onto it in interpretative annotations. This is important to team members, who distinguish between annotations as interpretations (discussed in the next two chapters) versus image-processing work that presents existing distinctions in the data. But while the image "contains this kind of information" (the spectral properties of the soil), it is at Susan's discretion to "decide how to show" the data. That is, *drawing as* practices allowed her both to see a distinction in the soil and to show her colleagues what to see in the soil too. Reconfiguring the soil in this way means that every time scientists look at the image of Tyrone, they see the two-toned white soil. Once the distinction has been made in one aspect, it cannot be unseen.

This is not limited to Susan's transformations of Tyrone, or to Pancam imagery alone. Across the mission, team members articulate the Wittgensteinian dawning of aspect when presented with a digital image that has been drawn so as to present particular properties. Expressions such as "now I see!" can be heard in SOWG, End of Sol, and science team meetings as well as at scientists' desks as they go through different image-processing routines or present these interpreted image products to their colleagues. As one scientist examined an image produced in his lab, he noted, "It's efficient to have something like that [image] to communicate what you're showing, what your interpretation [is]." Even in operating the MiniTES thermal spectrometer, a team member explained that he had to "show other spectra to teach [the team] what to see," or that he took the approach of "I'm only gonna show you the part I want you to pay attention to." This is not hiding data that might be essential to interpretation, but rather limiting data to the relevant part: an attempt to *draw as*, to delimit aspect in order to produce and reproduce a *seeing as* experience across the team. As I will show in the following chapters, this use of purposeful image construal to direct a viewer's attention in turn presents implications for the kinds of science and operations that are eventually planned as a result of collective visual interpretation. As a MiniTES operator explained to me, "the science questions come out of the imagery."

Drawing As, *Seeing As*, and Social Formation

Drawing as, then, is not only a question of making epistemic distinctions and visualizing an object, it is also a question of drawing distinctions and unifications among subjects, of drawing actors together into different social configurations. Even while *seeing as* experiences are produced by *drawing as* practices at Susan's

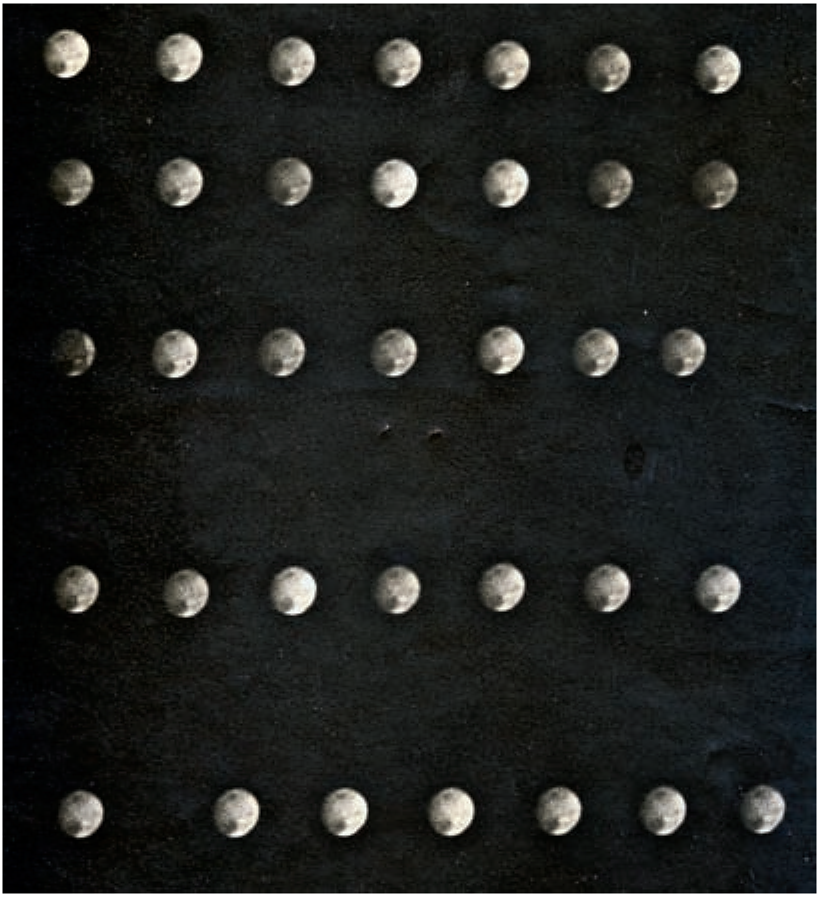


Figure 3.13. Percival Lowell's photographs of Mars. Lowell Observatory Archives.

or Ben's desk, this seeing is social, intertwining both visual practices and social commitment.

Planetary images have long been complicit in this tight combination of *drawing as*, *seeing as*, and community formation. The astronomer Percival Lowell, well known for his insistence on Mars's canal network, battled the same issues of visual salience, expertise, and communication of categories. When in 1909 Lowell was invited to submit his photographs of the planet, taken through his famous telescope at his observatory in Flagstaff, Arizona (fig. 3.13), to the Dresden Photographic Exhibition in Germany, he initiated a long exchange with his colleagues Vesto Slipher and Carl Lampland about how to visually communicate what they could see.[25] Newly introduced to astronomy, photographs offered an unparalleled appeal to the public to see the Martian canals for themselves. But the scientists were aware that the photograph was itself ambiguous. Shades of light and dark played over the planet's surface, mechanically and passively inscribed, perhaps, but demonstrating precious little. Just presenting row on row of tiny photographs was not enough; the public had to be taught how to see them. Slipher therefore wrote to Lowell and Lampland: "What do you think should be placed along with the Mars Photographs in the way of drawings? To those who are not familiar with the difficulties in the way of success in such work (and they are 99.99%) the photographs might not come up to expectation if shown along-side drawings. . . . Now on the other hand, there must be something with the photographs to point out what to expect and look for in the photographs."[26]

To disambiguate the photograph and train the viewer in what to see, Slipher needed to *draw* Mars *as* a canal-crossed planet. One possible solution was to annotate the images by placing drawings next to the photographs, directing observers' attention to relevant features, parsing the photograph so that others could see.[27]

Nor is this phenomenon limited to photography. In 1609, Galileo Galilei famously turned his telescope toward the moon and produced one of the most famous images in the history of astronomy: a cratered, pockmarked moon (fig. 3.14). Historians of science hesitate to say that this drawing represents exactly what Galileo saw: we cannot know what image actually hit his retinal wall. But his drawing presents no ambiguity about what he presumes the dark patches on the moon to be. Using the then-novel technique of chiaroscuro (shape from shading), Galileo *drew* the moon *as* a topographical body, with craters and pockmarks.[28]

Note first of all that *drawing* the moon *as* a topographical body reveals where Galileo's theoretical commitments lie.[29] *Drawing* the moon *as* a topographical body makes a Copernican statement about what the moon is and how we should best understand it. The drawing need not be a perfect record of what Galileo saw, but the drawing is where the discovery emerges. The images in *Siderius Nuncius* present an excellent comparative example of how visual and theoretical insight is produced in and through the purposeful use of representational techniques and selectivity.[30]

But the case of Galileo is also important because it demonstrates the reciprocal relation between drawing and seeing. After a tour to the New World, where he had mapped the territory of Virginia, Queen Elizabeth I's geometer Thomas Harriot also turned his telescope toward the moon in 1609 and, presumably, drew what he saw: a crescent, some shading, and a dark patch near the center

Figure 3.14. Galileo's image of the moon, *Siderius Nuncius*, 10 C2R. By kind permission of the Institute for Advanced Study, Princeton, NJ.

(fig. 3.15). The image betrays little sense of what the moon is or how to organize this visual experience. Only a year later, in 1610, Harriot produced a radically different set of drawings of the moon, clearly emulating the recently published Galilean view: a pockmarked moon, divided perpendicularly into light and shade, with a giant crater in the center (fig. 3.16). Galileo's way of drawing the moon was a powerful way to communicate and reproduce his particular way of seeing—his skilled vision, his discrimination of categories, and his theoretical commitments too—even at a great distance.[31]

These historical examples make it clear that *drawing as* practices do not construct (only) the world on Mars or on the moon. They also construct communities on Earth. The case study of Susan and Tyrone is especially illuminating for how her *drawing as* practices translated into a *seeing as* experience that was taken up across the mission and that directed further rover operations. Similarly, the discussion of Galileo and Harriot shows how a depiction of the moon as a sublunary object both required and strengthened a community of astronomers who

Figure 3.15. Harriot's image of the moon, July 26, 1609. Copyright Lord Egremont. Used with permission.

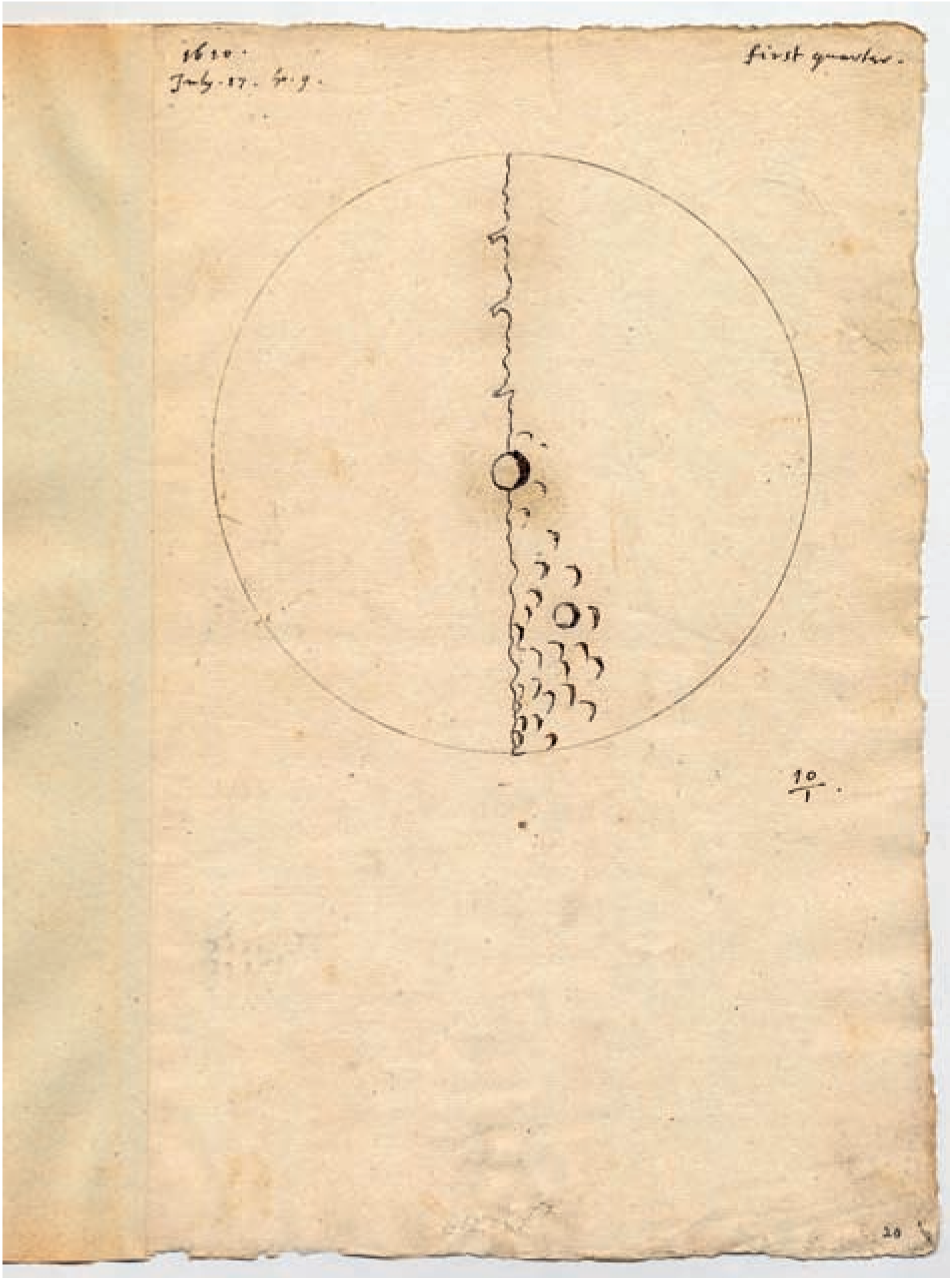


Figure 3.16. Harriot's image of the moon, July 17, 1610. Copyright Lord Egremont. Used with permission.

believed in the Copernican worldview and its practices, who took up Galileo's way of seeing and representing as their own. If seeing is social and *drawing as* practices produce and reproduce these modes of seeing, then how we represent Mars is not just a question of what *Mars* is like, or even of what we *think* Mars is like—it is about what *we* think Mars is like.

This is especially visible in the disciplinary heritage of *drawing as* practices. Scientists like Ben or Susan deploy representational practices shaped by their disciplinary training, but they may also appeal to those same disciplinary divides to ground their visual transformations or support their requests for particular images. Sam frequently explains his predilection for maintaining high resolution despite observation trimming as "I'm a geomorphologist, so I'll always take the higher-resolution image."[32] His colleague frequently prefaces his own graphs with "I'm gonna do a series of element to element diagrams—no surprise there, in that I'm a geochemist and all."[33] Even Susan, presenting her Pancam image results, joked to her peers, "I'm going to show a beautiful Pancam picture and pretend I'm a geologist."[34] These remarks establish a close relationship between disciplinary modes of inquiry and preferred visual forms.

Software packages, too, play a role in reifying these categories through practice, since they come preloaded with specific techniques for *drawing as*, presenting a ready-made *seeing as* experience to viewers consistent with disciplinary interest. Scientists use particular software packages specific to their disciplinary and institutional heritages: geographers prefer ARC-GIS or ENVI, the USGS developed ISIS for planetary studies, and astronomers use IDL. These different software packages implement differences in ways of seeing that can produce different aspects even when producing the same kind of visualization. For example, when Ben's colleague Ross produced a decorrelation stretch of Cercedilla using different software, the two images looked quite different. One could also see details in Ross's images that one could not see in Ben's, and vice versa.

As another example, different types of maps betray different disciplinary approaches and software tools. Tom's Geographic Information Systems (GIS) laboratory at a large state university creates Rover transit maps, while Peter produces Rover transit maps at NASA's Jet Propulsion Laboratory's image-processing center and Joseph uses orbital images to produce geological maps. The three use very different techniques. Locating the rover using orbital GIS data, as Tom does, versus using the robot's odometry, as Peter does, presents unique advantages and disadvantages depending on the slip of rover wheels or the availability of orbital coordinates. Tom described these different maps as a question of different disciplinary perspectives and expertise, produced through software suites and visual transformations: "Joseph looks at the images and interprets the rocks very well; he is a geologist. I am not, I'm an engineer. He's good at the tactical, we should go here, we should go there. That [my software team] can't do. He doesn't have the tools we have, the software. Peter, he's a geologist . . . he doesn't have the math models and software we have."[35]

Tom explained that what he described as his "software engineering" perspective on Mars had the advantage of mathematical modeling but the disadvantage of little geological interpretation, unlike Joseph's and Peter's. Each perspective is encoded in and produced through the different images. Software suites and visual conventions make some possibilities available, but they limit others by leaving them out of the picture. Drawing attention to different scientists' disciplinary heritages, such as geography or geology, chemistry or geomorphology, can demonstrate why their visual production presents so many different aspects of the same images to view.[36]

This emphasis on multiplicity, however, demonstrates only one aspect of the relationship between *drawing as* and social formation. Different communities may present their own unique practices, but on the Rover mission those visualizations are treated as commensurate—resulting in different but reconcilable visions of Mars. They are brought into coordination with each other through methods consistent with the team's consensus-based organizational structure.[37] The Rover team accounts for this practice with its native philosophy of science; as one team member put it, "When you see it in all these different ways, then you get to know it." In the following chapters I will describe these practices in more detail, showing how *drawing as* techniques that present disciplined ways of seeing are coordinated to produce singular views of Mars. In this way, image processing and the practices of *drawing as* produce not only scientific sight and insight, but scientific community as well.

Conclusion

Spirit's activities at the western edge of Home Plate cannot be understood without careful attention to Susan's representational work. First *drawing* Tyrone *as* composed of two distinct kinds of salty soils distributed at different vertical layers, and then *drawing* Arad, Paso Robles, and Wishing Well *as* Tyrone, encouraged the rest of the team to see Tyrone as composed of those materials as Susan suggested, and then to see other examples as cases of the same phenomenon. Following this work of sorting out distinctions through drawing and seeing, a suite of rover operations enacted the light-toned soil and brought it to light in each encountered location. Soon thereafter, published papers bearing Susan's name along with those of her Athena Science Team colleagues began to appear in the planetary science section of the *Journal of Geophysical Research* and in the prestigious *Science* magazine.[38]

Such activity arose as a result of specific practices of image processing that purposefully composed images of the soil so that the team could see what Susan saw. The interpretation is drawn into, inscribed in, and produced through the very images that present the phenomenon, such that the phenomenon can be seen. And as this visual convention was applied across Gusev Crater, the scientists no longer *saw* the white soil *as* two-toned: they simply saw the two-toned soil, and saw it everywhere. These are the activities that constitute scientific work with digital images. Practical work with images disambiguates visual material, shuts down ways of seeing in order to focus on one aspect, one set of salient relationships. These techniques of *drawing as* reveal and present different aspects with every click of the button, enabling different *seeing as* practices at the point of the observer, as in Ben's situation with Cercedilla. But they also powerfully transmit a *seeing as* experience to subsequent viewers.

Visualization in science, then, is not a question of creating an ever truer or more singular image of an object. Rather, it is a practical activity of *drawing* a natural object *as* an analytical object, inscribing a value into the very composition of what that object is and what makes it interesting, so that subsequent viewers and image makers will see, draw, and interact with that same object in the same way. Team members' mastery of image-processing software provides them with one of their most important strategies for materially realizing objects in the visual field. These are the techniques and processes of *drawing as*: the practical activities by means of which a *seeing as* experience is produced. And if *drawing as* can transform the subsequent *seeing as* experience into just seeing, then we arrive at the special power of the scientific image: that the drawn features of an object are *seen as* phenomenal or even ontological properties by the actors in question. That is, *drawing as* makes epistemology look like ontology. It conflates our interpretative work in the world with the objects we encounter there and draws them accordingly.[39] Tracing the practical actions of scientists engaged in purposeful visual construal, then, presents an opportunity to literally trace actors' commitments at play through an examination of both practical activities (of drawing) and practical effects (further representations and interactions). The scientific image itself does not so much document the object out there as document the work of different communities of knowing subjects that enable, produce, and constrain knowledge of the world.