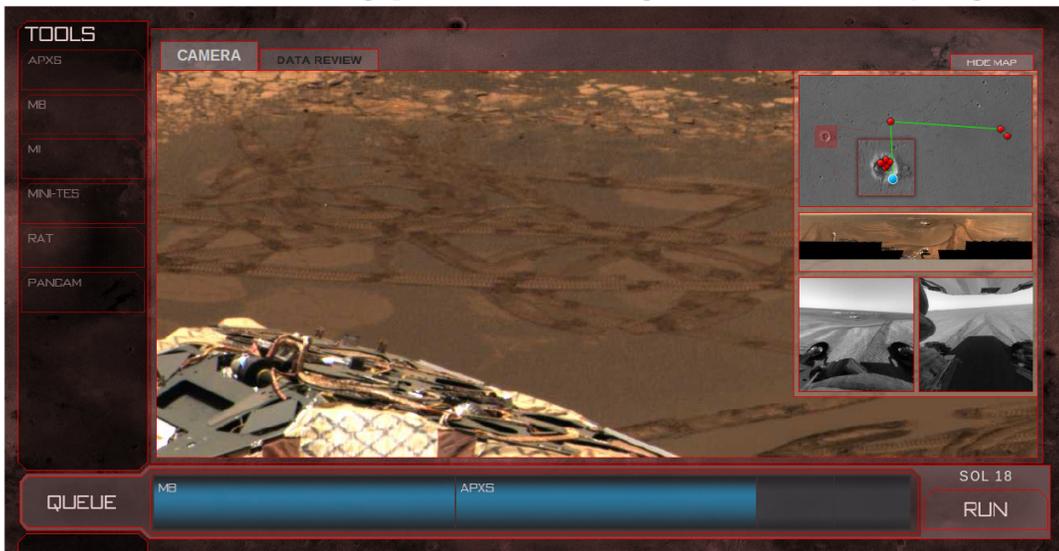


The Extraterrestrial Virtual Field Experience

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Extraterrestrial Virtual Field Experience: Mars Exploration Rover *Opportunity* at Meridiani Planum

1.0 How to Use This Module

This is a computer-based laboratory module for high-school students. The module uses actual NASA data returned by one of the Mars rovers, and puts students in the scientific decision-making “driver’s seat” to see if they can make some of the important discoveries about Mars that the rover science team did using the same data. While this might sound ambitious, the software simplifies mission operations and science concepts to make them accessible to the students. In addition, students get help from the “Mission Manager” embedded in the software that helps explain the latest data, and sometimes poses questions to guide student inquiries toward the ultimate scientific goals. The students also will get assistance from you, their teacher, and that’s where this Teacher’s Guide comes in, and the associated Teacher’s Introduction Slides that can be presented to the students at the beginning of the exercise. Skills emphasized in this module include: (1) making an observation, interpreting an observation, and the difference between these; (2) note-taking beyond record-keeping, as an aid for distilling information toward an overall learning objective; (3) prioritization of inquiry for efficiency of inquiry. Along the way, the students will exercise several earth science concepts they should already be familiar with (the power of erosion to change landscapes, the principle of superposition, the differences between rock, mineral, and element, etc.), and be introduced to new information specific to exploration of the unknown, particularly how the Mars Exploration Rover mission was conducted.

The module is intended for two or more sessions of an Earth Science class as syllabus enrichment, or as an after-school enrichment activity for a science-oriented student group. In either case, teacher preparation and practice ahead of time is essential to reduce the “coming up to speed” portion of the exercise. Students must first become familiar enough with the software and the Mars rover itself in order to carry out the exercise, but time spent on this initial phase ideally should be as brief as possible. To help with this, the software is designed to be simple and fairly intuitive to use. The rest of this Teacher’s Guide explains some of the science the students will be involved with, a brief Mars Rover “owner’s manual,” and some guidance for rubrics to monitor and evaluate student learning and performance.

2.0 Science at the Mars Exploration Rover *Opportunity*’s Landing Site

The planet Mars is about half the diameter of Earth and has 10% of Earth’s mass. However, the surface area of Mars is approximately the same as Earth’s land exposed above sea level. Consider how vast and diverse all the different landscapes of Earth are: various individual mountain ranges, valleys, and plains, and the unique settings among all of these across the world. Consider also how long it has taken humans to explore these landscapes and to start understanding them. A similar amount of landscape exists on Mars for exploring and discovering.

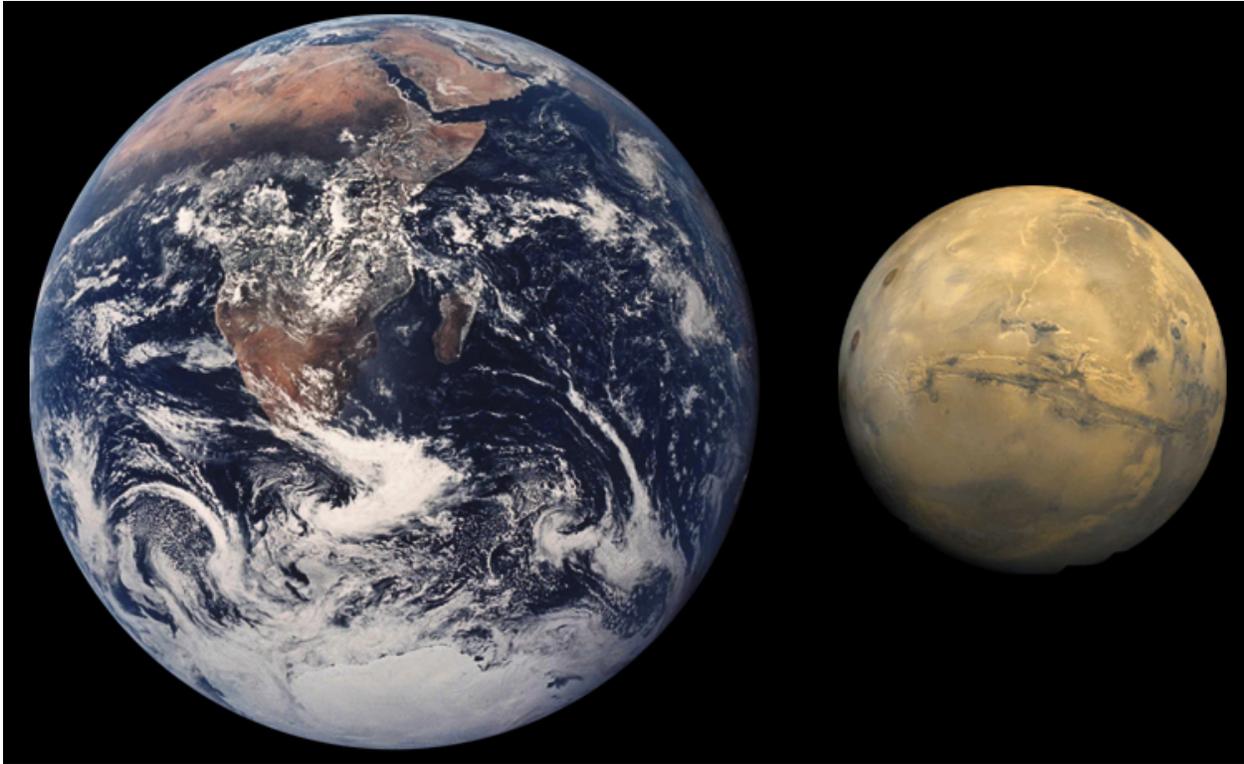


Figure 1. Earth and Mars compared, at the same scale. Mars has 10% of Earth's mass, but about the same amount of dry land area to explore.

However, Mars is hard to get to, much harder to get to than even the most remote parts of Earth. Each Mars mission requires years of preparation, followed by months of travel time to Mars. After landing, actual exploration on the surface must be carried out as quickly and as efficiently as possible before spacecraft hardware wears out or breaks from the harsh environment. Because of all these challenges, astronauts are not likely to visit Mars for many years. In the meantime, we use robots—stationary landers and wheeled rovers. Even the most capable rovers have driving ranges of only a few dozen kilometers, covering a tiny fraction of all there is to explore and discover. Thoroughly exploring the surface of Mars would take hundreds of rovers crisscrossing the planet's vast surface for many, many years.

Exploration of Mars on this scale currently is not practical. Landing a rover on Mars is a very risky, expensive venture that has been accomplished only four times in human history. This module concerns one of these missions: the Mars Exploration Rover (MER) *Opportunity*. With so few rover missions, and such a large planet to explore, each rover landing site is chosen very carefully to tell us as much as possible. After much consideration, a landing site for *Opportunity* was chosen on a level plain called Meridiani Planum. This is one of the few places on Mars where signs of the mineral hematite have been detected from orbit. Hematite on Mars was an exciting discovery! Hematite is an iron mineral that on Earth usually forms in the presence of abundant water. Mars is a cold, dry place now, but the presence of hematite on the ancient landscape of Meridiani Planum indicates that long ago, water probably was abundant there. Water is a requirement for life as we know it. So Meridiani Planum seems like a very promising place to find out more about the role of water in the ancient history of Mars. Perhaps conditions in the past, including enough water, might have allowed life to form.

In this module, the goals of the students are very similar to the original goals of the MER *Opportunity* mission: **Explore the surface of Meridiani Planum. Find the hematite. Figure out how the hematite got there. Determine what the surface of Mars was like back when the hematite formed.**

3.0 Concepts Students Should Have Some Familiarity With

Students should have some familiarity with the following three concepts (these will be *reintroduced* during interaction with the software, but not specifically taught from scratch). These concepts might be covered earlier in a class syllabus, or introduced briefly, early in the first day of the module:

- (1) *Erosion*, the wearing away of rock, transports material downhill. In time, erosion makes landscapes more level by
 - a. *reducing high areas*, and
 - b. *filling in low areas*

So a level plain usually means a lot of erosion has occurred. What you see there is not what the landscape used to look like; the landscape of the past must be “reconstructed” in our imaginations, guided by whatever evidence that has been left behind. It might bother some students that the evidence is incomplete, but this is realistic.

- (2) *Different materials* can erode *at different rates* (even under the same conditions). Materials more resistant to erosion erode more slowly and last longer before disappearing.
- (3) *Sedimentary rocks* are the only rocks that record clues about what the *surface environment* was like—back when sediments were deposited. (Igneous and metamorphic rocks are less informative.) As a consequence, the interpretation of sedimentary rocks can be complicated! Nonetheless, sedimentary rocks are uniquely valuable for finding out what places were like in the past. Want to find out what past environments were like on Mars? Find the sedimentary rocks and focus on them.

4.0 Concepts that Probably Are New to Students

Some principles probably will be new to students. These will need to be introduced briefly before user interaction with the software. In most cases “Mission Manager” reports in the software will also help explain these concepts.

- (1) Hematite is an important iron mineral that on Earth is associated with abundant water. Hematite combines iron (Fe for Latin “ferrum”) and oxygen (O) in a molecular ratio of 2:3 or Fe_2O_3 . On Earth hematite is mined for its iron content and used in steel for cars, bridges, buildings, and many other essential applications. Hematite generally forms by precipitating out of solution in water, or through alteration of other rocks by water to produce hematite as a byproduct.
- (2) Minerals, when scraped across a hard surface, leave a narrow powder trail (like writing on the sidewalk with a stone). The color of this powder can sometimes help identify the presence of certain minerals. Formally, this is done by scraping a mineral sample against

a porcelain plate to produce its “streak.” Most mineral streaks are white or clear, but hematite’s streak is a diagnostic dark red. The Rock Abrasion Tool (or RAT—see below) grinds into rock surfaces on Mars, creating powder. If the rock has some hematite in it, the powder might be reddish.

- (3) The surface of Mars is, on average, much more ancient than most Earth landscapes. Earth has plate tectonics, responsible for continental drift, sea floor spreading, and creation of new mountain ranges. Plate tectonics renews the surface of the Earth slowly, but continually, creating new relief. Weathering within Earth’s atmosphere and hydrosphere acts to reduce this relief, altering landscapes on relatively short geological timescales. But on Mars there is no plate tectonics to constantly create new relief, and erosional processes are less efficient (due directly and indirectly to the thinner atmosphere), so martian landscapes generally are ancient as well as partly eroded.
- (4) Water interacting with sediments before they harden into rock can leave telltale traces of the solution and dissolution of minerals. These include concretions, and formation of salt-related crystals in sediments that become saturated with water. Long after the water that caused these reactions has vanished, concretions and salts remain in the rock for us to recognize and interpret.

5.0 Introduction to the Rover *Opportunity* and its Science Instruments

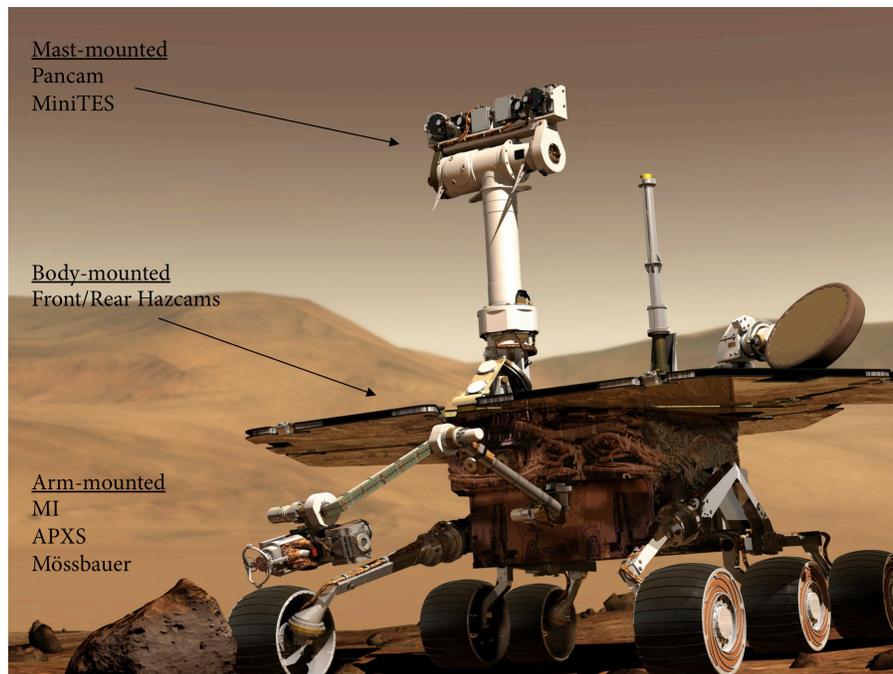


Figure 2. Instruments on MER Opportunity are mounted on the head-high mast, on the end of the arm, or bolted down low to the rover body. Six wheels drive the rover.

The teacher and students should get to know a little about the rover before “using” it, but familiarity also will come as the mission unfolds and experience is gained—the same thing

happened with the real rover on Mars and its science team. Students can think of the rover as a surrogate for a human being—themselves(!)—walking around the surface of Mars, pausing at times to bend over for a closer look at things. The rover has two color “eyes” about the same height off the ground as a standing human. The rover has an arm (with shoulder, elbow, and wrist joints) that at its end has a magnifying glass (the Microscopic Imager) and other instruments to (scientifically) “scratch and sniff” rocks and soil to find out more about them. The rover can move, of course, although a little more slowly than a human would, similar to the creeping pace of a person who would walk by placing the heel of one foot slowly and carefully against the toe of the other. Here is more information about the rover and its payload:

- **Navcam** is a mast-mounted “black and white” (actually gray-scale) camera for navigating to new drive locations, for general reconnaissance, and for targeting the other science instruments. It doesn’t show things at the highest resolution, but it is very efficient.
- **Pancam** is the high-resolution color camera, mounted about eye-level for a person standing on Mars. In addition to color, Pancam has higher resolution than Navcam, above. But this makes Pancam more expensive to use so it is practical for carefully selected targets only. Pancam images in this module are stretched and processed to enhance subtle color differences. While this makes the images more immediately useful, students should keep in mind that the true colors of the martian surface generally are various shades of reddish gray.
- **MiniTES** (officially the Miniature Thermal Emission Spectrometer) is a mast-mounted instrument that uses infrared light (which our eyes cannot see) to look for mineral signatures. The wavelengths of light it sees do not permit true “camera”-like images. Instead, it produces relatively low-resolution “maps” of individual spot measurements. The very low ground resolution is made up for by its ability to identify the presence of minerals like hematite from distances of several meters away. MiniTES data were acquired many times during *Opportunity’s* mission, but for simplification purposes here, only the initial reconnaissance mosaic from this instrument is included for use at the very start of the module.
- **Front Hazcam** is mounted low on the front of the rover and shows a “dog’s eye” view, close to the ground. The Front Hazcam is necessary for using the arm. If an area you are interested in using the arm-mounted instruments doesn’t show up clearly as a target in the Front Hazcam view, you can’t safely use the arm on it.
- **MI** is the hand lens, mounted on the end of the arm to enable close-up views, *nearly touching* the target. (MI stands for Microscopic Imager.) The MI can be used only on targets identified in Front Hazcam views as safe for the arm to approach.
- **APXS** is also on the arm and *touches* targets to tell you which elements are present. Hematite hunters should pay attention to how much *iron* is present in APXS results. (The formal name for the APXS is Alpha Particle X-ray Spectrometer—kind of a mouthful for students so we use just “APXS” instead.)
- **Mössbauer**, like APXS, is on the arm and *touches* targets to tell you about different minerals

containing iron. This might seem like a narrow job description, but much Mars mineralogy involves iron, so it's a pretty useful instrument! In particular, Mössbauer can tell you how much of the iron in an APXS-ed target spot is in the form of hematite. It's important to realize that you need both APXS *and* Mössbauer (generally in that order—see below) to determine the amount of hematite in an arm-sampled target spot. You can't use both instruments at the same time on the same spot; one measurement must come after the other.

A good strategy for efficient hematite hunters:

Navcam to look around, and for targeting higher resolution Pancam

Pancam for looking at high-priority targets, including those that might be worthy of arm work

Front Hazcam for selecting and targeting arm work

For arm work (which takes lots of time, so decide carefully):

Do MI first and decide if further arm work is justified. If so,

Do APXS next and see if there is lots of iron ("FeO" or iron oxide) in the APXS results.

If the APXS results are iron-rich, do Mössbauer to find out how much of the iron is hematite.

If the APXS results don't show much iron, there can't be much hematite, overall. Skip the Mössbauer to *save time*, and move on!

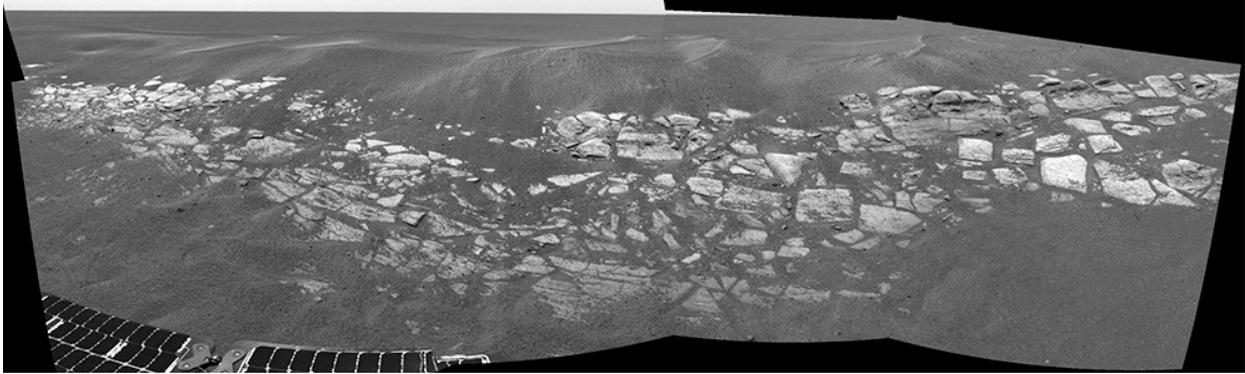
- **RAT** (Rock Abrasion Tool) can grind into the surface of a rock target to remove surface weathering products and get cleaner insights into the interior of high-priority targets. After RAting a rock, follow-up MI is required, possibly APXS and, if warranted, Mössbauer.
- **Rear Hazcam** images are included mostly for completeness. They can offer a useful perspective to help orient the rover position relative to geological features nearby.

Color and high resolution can reveal subtle, important details. Students might wonder: why not use Pancam all the time, instead of the lower-resolution "black and white" Navcam? The extra information in color, high-resolution Pancam images comes at a steep cost: Pancam needs approximately 27 times longer to capture the same scene in color as can be viewed in less detail in a single Navcam "black-and-white" picture. And for that same scene, Pancam creates typically 27 times more data, requiring more time to transmit from Mars back to Earth. If we only used Pancam, the rover would spend a lot of time waiting around, and wouldn't be able to drive to and investigate as many different places before it's mission ended.

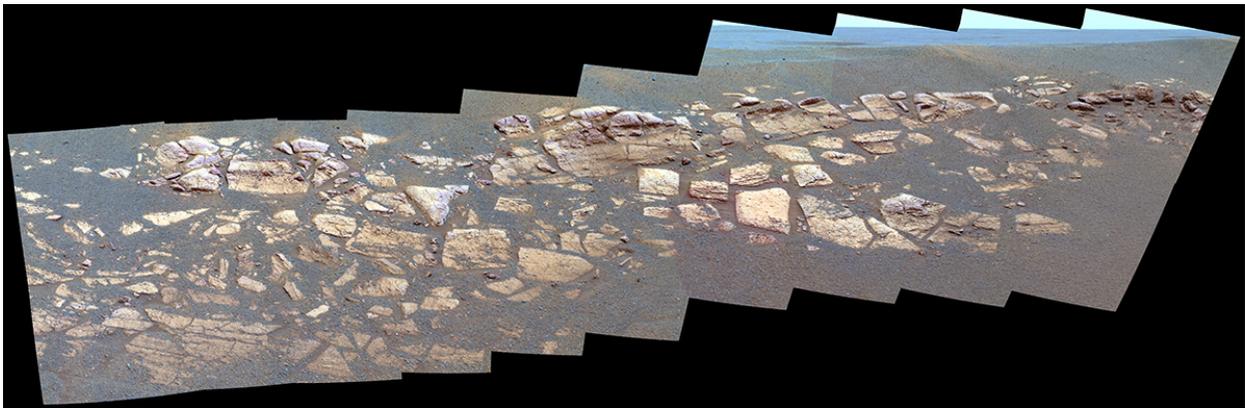
Instead, it's more practical and much more efficient to use a balance between all of the cameras on board. For getting a quick, immediate sense of the new ground near the rover at the end of a drive, we use Navcam, which is good enough also to plan or target more detailed observations—and to decide where to drive to next. Pancam typically is used only to cover special areas where the most important science clues could be. Large, 360° color panoramas using Pancam can be obtained only very rarely.

6.0 Example Data Products

This section shows example data products, in some instances looking at the same terrain with different instruments to illustrate different resolutions and capabilities.



*Figure 3. **Navcam** images are not color, nor high resolution, but cover a lot of area so they are efficient choices for navigation and for surveys to choose targets for other instruments. In this Navcam 5x1 mosaic the rover has moved close to the rim of Eagle crater to scout the outcrop there for potential arm work and/or close-range Pancam observations. Flat plains outside the crater are visible at the top of the mosaic (note straight horizon at upper left).*



*Figure 4. **Pancam** is MER's high-resolution color camera, which makes it a great scientific tool. However, this comes at the cost of requiring much more time to acquire and return coverage of the same area that could be covered much more quickly with lower resolution, gray-scale Navcam images. This example Pancam 10x3 color mosaic covers some of the same outcrop shown in the previous figure. The actual Pancam data product in the module software allows zooming to full resolution, revealing details not discernible in this figure.*

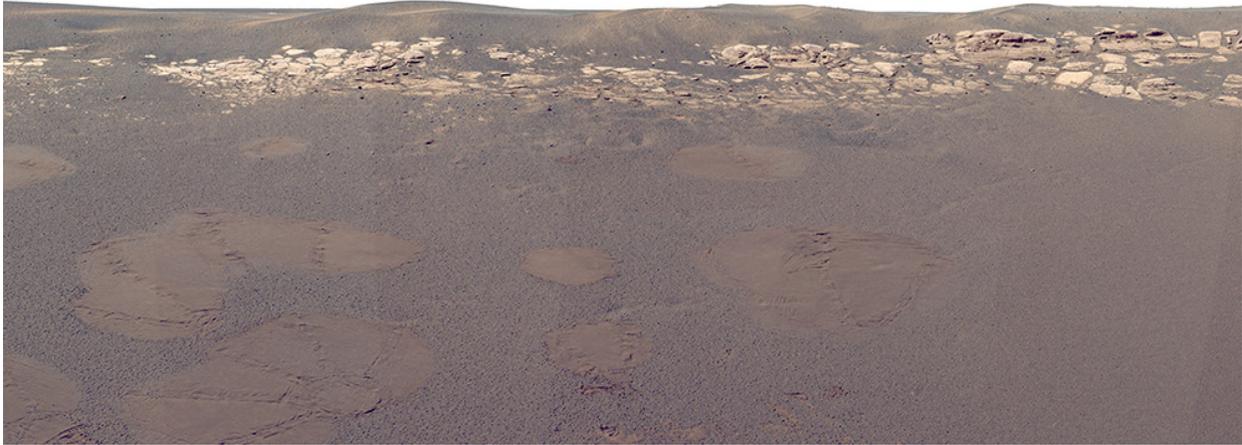


Figure 5. This **Pancam** view is from the initial panorama obtained from the center of Eagle crater looking outward at light-toned outcrop near the crater rim. This is the same terrain seen later in the mission from much closer range in the previous two figures, and is the same terrain combined with MiniTES hematite data in the next figure.

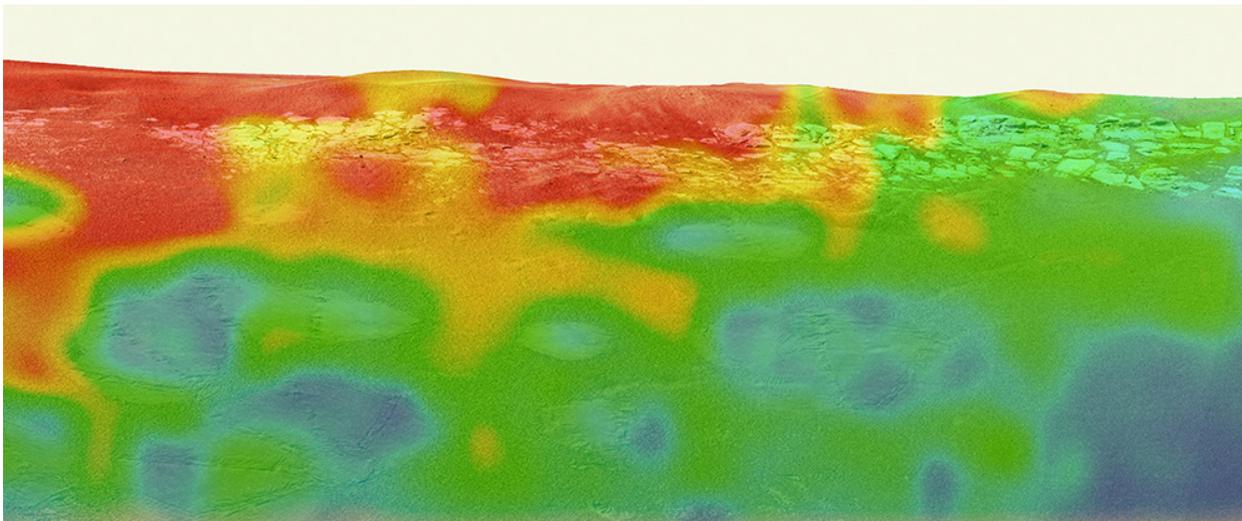


Figure 6. **MiniTES** infrared data are too low-resolution to interpret easily on their own (without guidance from camera images of some type). Here, the blob-like low-resolution MiniTES data (reddish areas have more hematite than bluish areas) are projected on to the first Pancam mosaic, to allow correlations between hematite abundance and surface features. See text for discussion. This is the only MiniTES data product in the module.

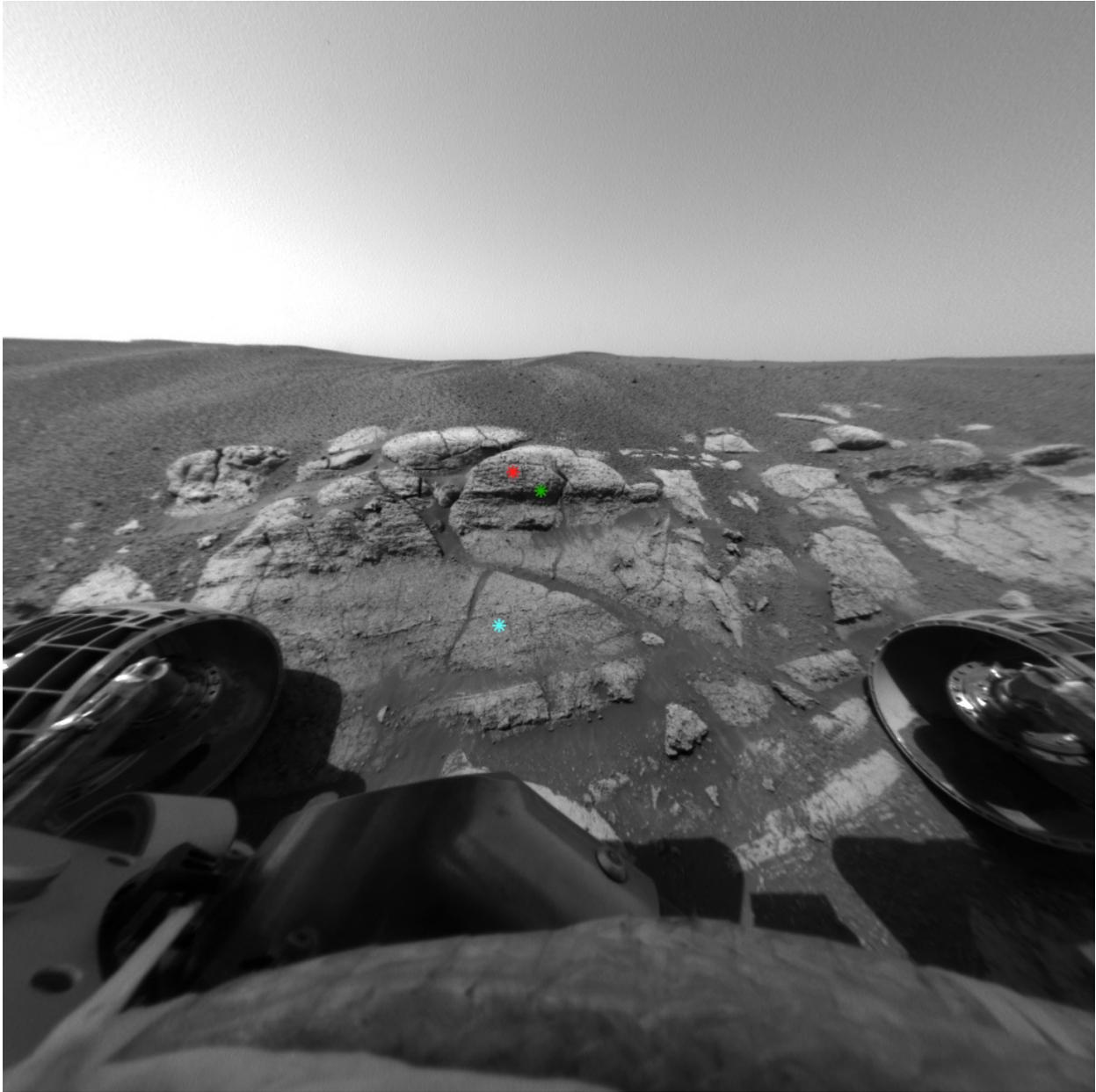


Figure 7. **Front Hazcam** is a very wide-angle camera that is mounted on the front of the rover down low, partly so that it can allow planning of arm activities. It is gray-scale only, no color. In this view, three possible arm targets are marked with colored asterisks showing where it is safe for the arm to work if the user feels the investment in time would be worth the scientific benefit. (This area happens to be visible also in the upper right of the Navcam, Pancam, and MiniTES data of Figures 3-6.)

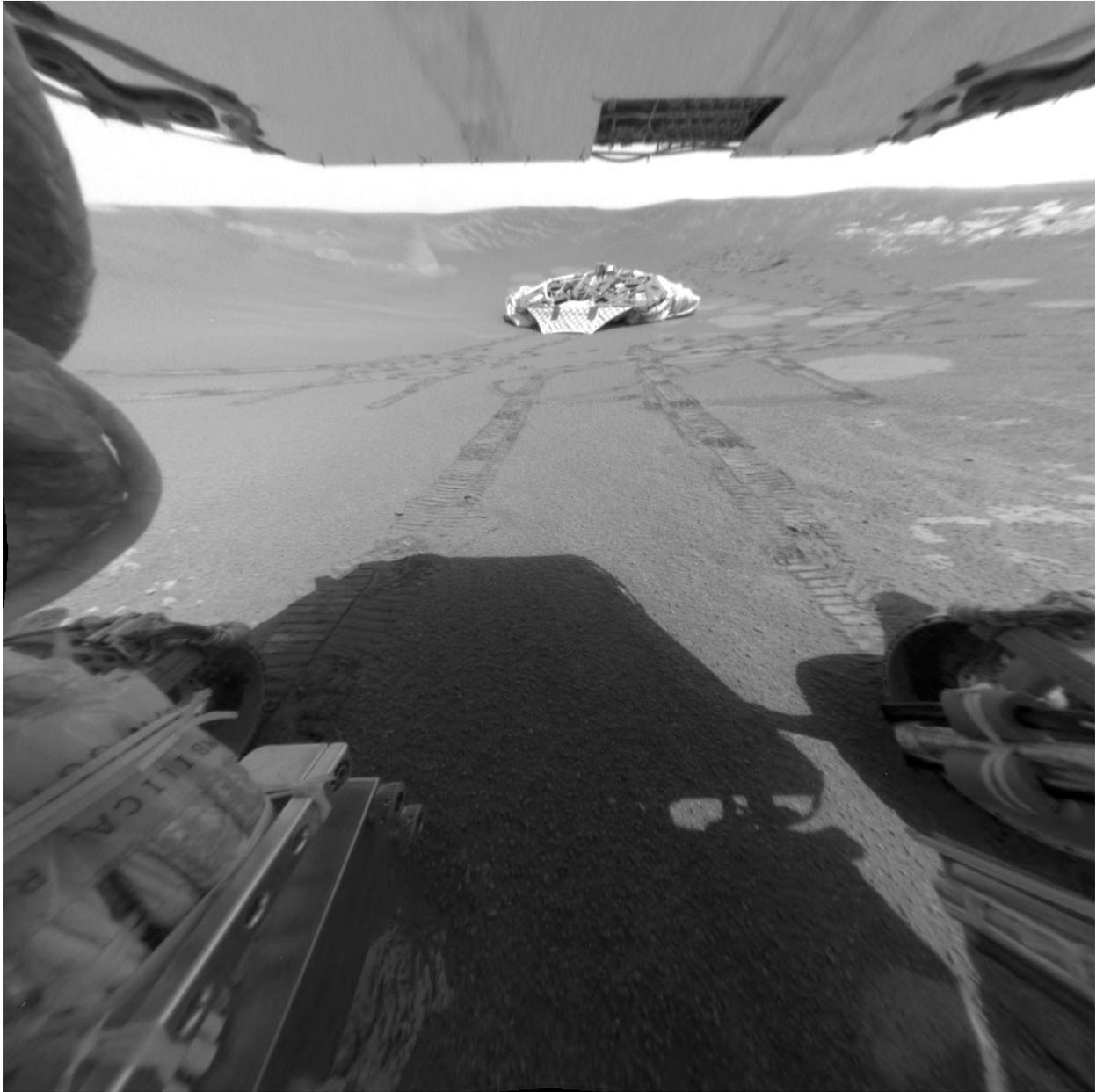


Figure 8. **Rear Hazcam** is identical to the Front Hazcam: a wide-angle and grayscale-only camera. The gray material across the top of this image is overhanging solar panel. The rear wheels are partly obscured by other rover hardware much closer to the cameras. This view was taken at the same rover position as the previous figure.

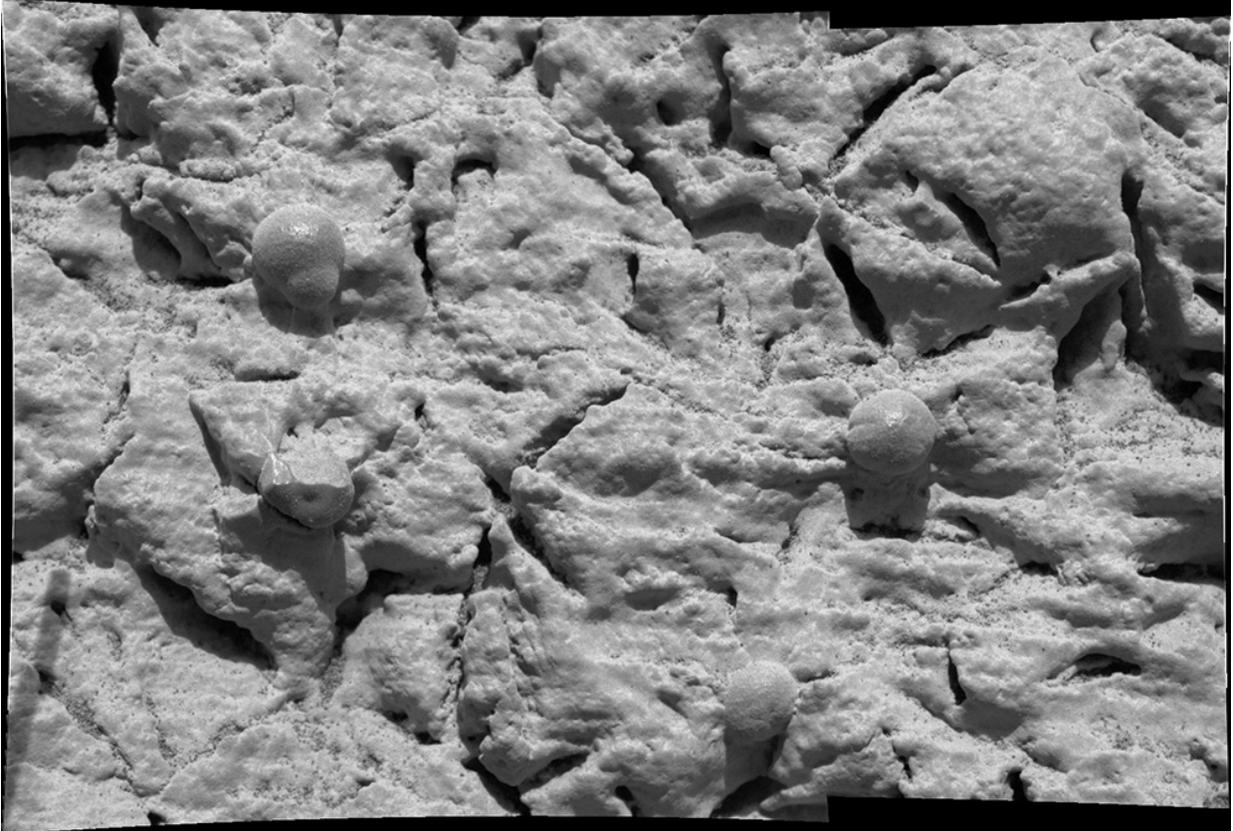


Figure 9. The MI is a gray-scale camera, and most products are single images showing 31 mm x 31 mm of the target at very close range. This is an unusual 2x1 MI mosaic, about 31 mm high and 45 mm across, covering outcrop. MI views such as this are required before the other arm instruments—APXS and Mössbauer—can be used on the same target.



Figure 10. This color-enhanced Pancam view shows where the **RAT** ground into outcrop near the rim of Endurance crater. The rock powder produced during the RAT grinding is reddish, suggesting the presence of at least some hematite in the rock from the mineral hematite's diagnostic reddish "streak." See text for details. This area also happens to appear (in pre-RAT condition) in Figures 3-7 and 9. As a hint, the MI view in Figure 9 is centered on what would become the RAT target, shown here after the RAT has done its work. There is a slight tilt difference between this and the previous figure, but the pattern of three blueberries in the RAT hole here can be matched with those in the MI view in the previous figure.

APXS results for Fred_Ripple

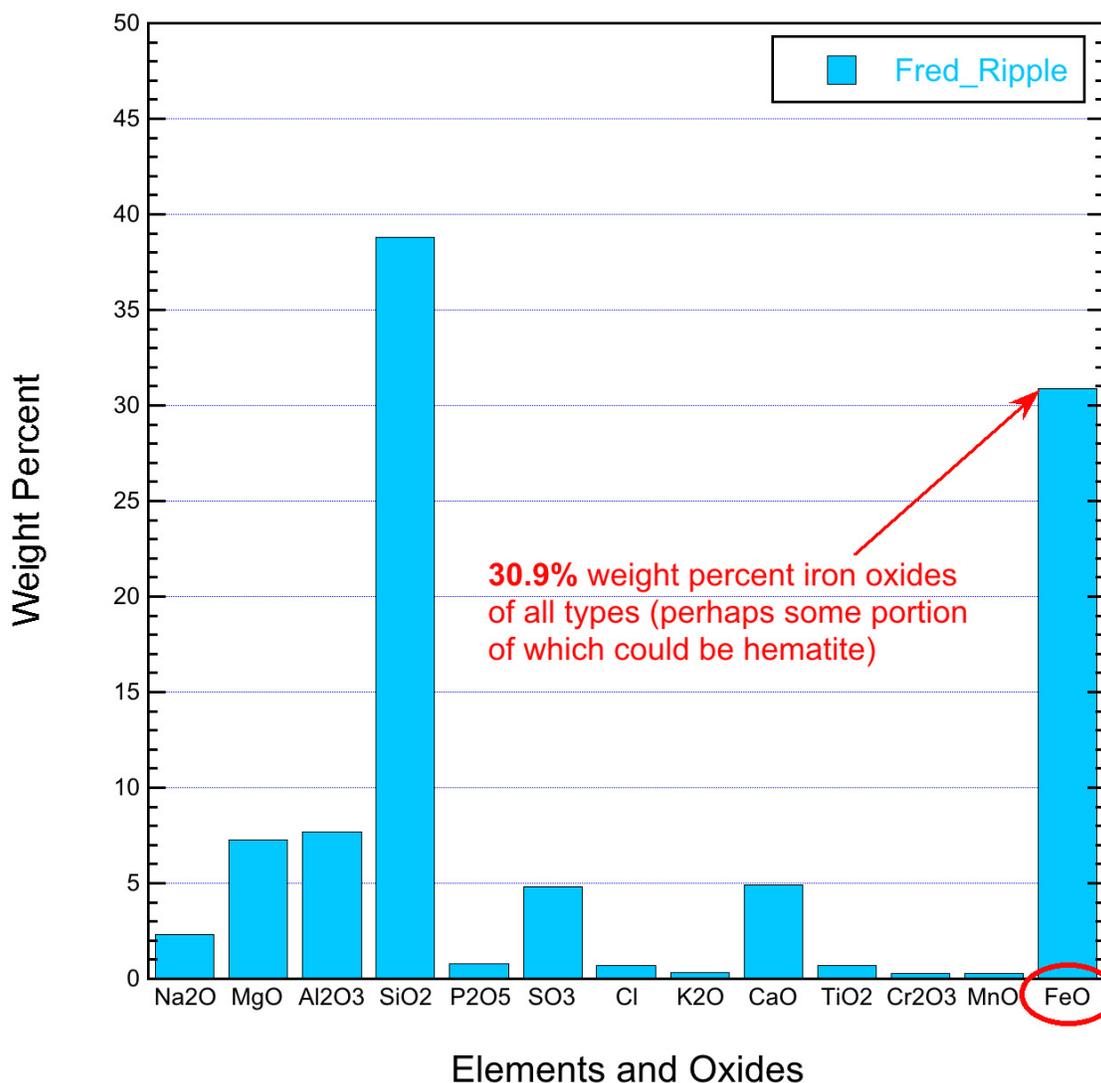


Figure 11. APXS data are gathered by pressing the arm-mounted APXS instrument against a rock or soil target. APXS results are presented as bar graphs like the figure above, showing oxides of thirteen elements. The important one for our purposes is FeO, iron oxide, because hematite is a form of iron oxide. APXS measures how much of the material is iron oxide, but it cannot tell how much of the iron oxide is in the form of hematite. In this case, the material is 30.9% iron oxide of all types. That's a relatively high value (as students will start to realize after trying APXS on several types of targets), therefore the extra time required for a follow-up Mössbauer measurement at this target seems justified (see next figure).

Mössbauer results for Fred_Ripple

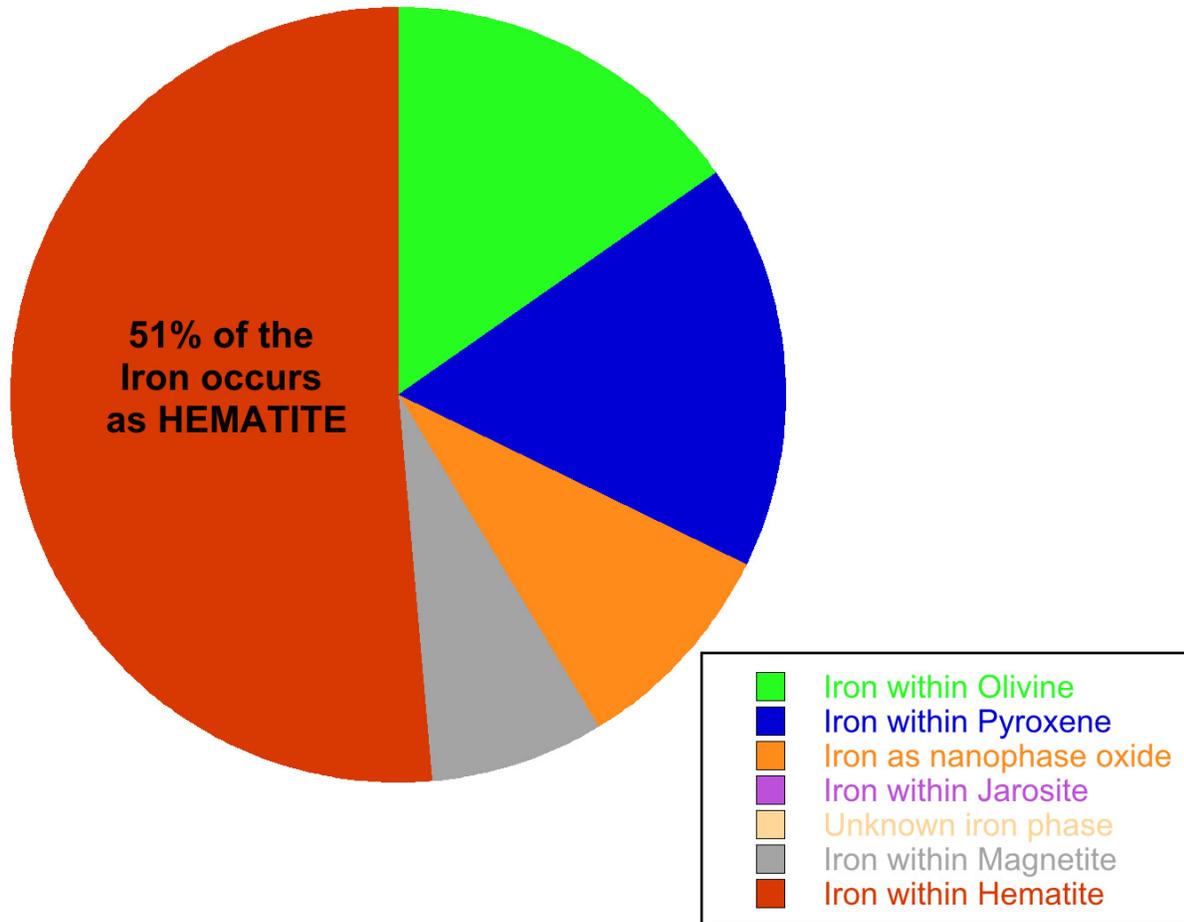


Figure 12. **Mössbauer** data are obtained by pressing the arm-mounted Mössbauer instrument against rock or soil. The results are presented as a pie chart like the figure above showing the different forms of iron oxide. The amount of hematite (shown in red) matters most for our purposes. This particular example has a rather high fraction of its iron oxide as hematite. This, combined with the APXS results on the same target (see previous figure), indicate a relatively high proportion of hematite in the material overall: 30.9% of the material is iron oxide, of which 51% is in the form of hematite, so overall the target material hematite is 0.309×0.51 or about 16%. The Mission Manager report spells this out for the student, stating: “The Mössbauer team reports that of the 30.9% of the soil that is iron oxide (APXS results), about 51% of that is in the form of hematite. Overall, the ripple surface is about 16% hematite.” That’s a lot! By the time students reach this particular target in the exercise, they should be realizing that the coarse soil of the large ripples covering the plains outside Eagle crater must be one of the main “carriers” of the hematite signature originally detected from orbit. Other “carriers” are even larger concretions—the “blueberries”—scattered on the soil that have weathered out of the light-toned bedrock (and are still weathering out, as seen in the outcrops inside the rim of Eagle crater).

7.0 Using the Software—A Tutorial

The prototype Extraterrestrial Virtual Field Experience is designed to run in an internet browser on a desktop or laptop computer. It should work with all of the major operating system and browser combinations, but we recommend Chrome or Firefox. Your experience will be better on larger format screens (>13 inches). The EVFE will not, at present, work on tablets or other mobile devices. You can navigate to the activity directly by the following link.

<http://spif.astro.cornell.edu/EVFE/default.htm>

Upon loading, you should see a screen like the following. Feel free to click around to familiarize yourself with the interface.

Interface Basics



Figure 13. The main Camera view, highlighting major points of functionality.

The regions of functionality are defined as follows:

1. **The Camera view, or main window.** This is where primary Pancam and Navcam panoramas or Front/Rear Hazcam images will be displayed and from which targets for the other instruments can be selected. Browse this region by clicking and dragging.
2. **The Tools bar.** This column contains icons corresponding to each of the major science instruments on the Mars Exploration Rovers. When a target is selected, icons in

the tools bar corresponding to instruments that can be used will light up and can be selected here.

3. **The Planning/Data Review toggle.** These tabs allow you to switch between the Planning view, which shows you information corresponding to the sol being planned, and the Data Review panel, which shows you information in the form of Mission Manager Reports from past sols' activity.

4. **The Minimap.** This shows small views of the current position of the rover as viewed from orbit as well as of the current Pancam or Navcam panorama and Hazcam images. You navigate between the Map and Pan/Nav/Hazcam by clicking on their corresponding regions here, or you can click and drag the current view footprint to navigate the main window. Clicking the overhead/orbital map permits driving between sites. The Minimap can also be hidden from view with the "Hide Map" toggle.

5. **Image Zoom.** To zoom images in for a more detailed look or out to get the big picture.

6. **The Queue bar.** Observations that are to be performed by the rover on the following sol will appear here. The queue has ten slots corresponding to total resources available in any single sol, and an observation can require one or more slots.

7. **The Uplink button (and sol counter).** Press this button to uplink the current queue to the rover and receive the science data in return.

8. **Observation footprint.** Signals that an observation can be made at this location. Hover over or click on it to learn more.

9. **The Menu Button.** Through which games can be saved, restored, or reset, and a complete Mission Manager log can be downloaded.

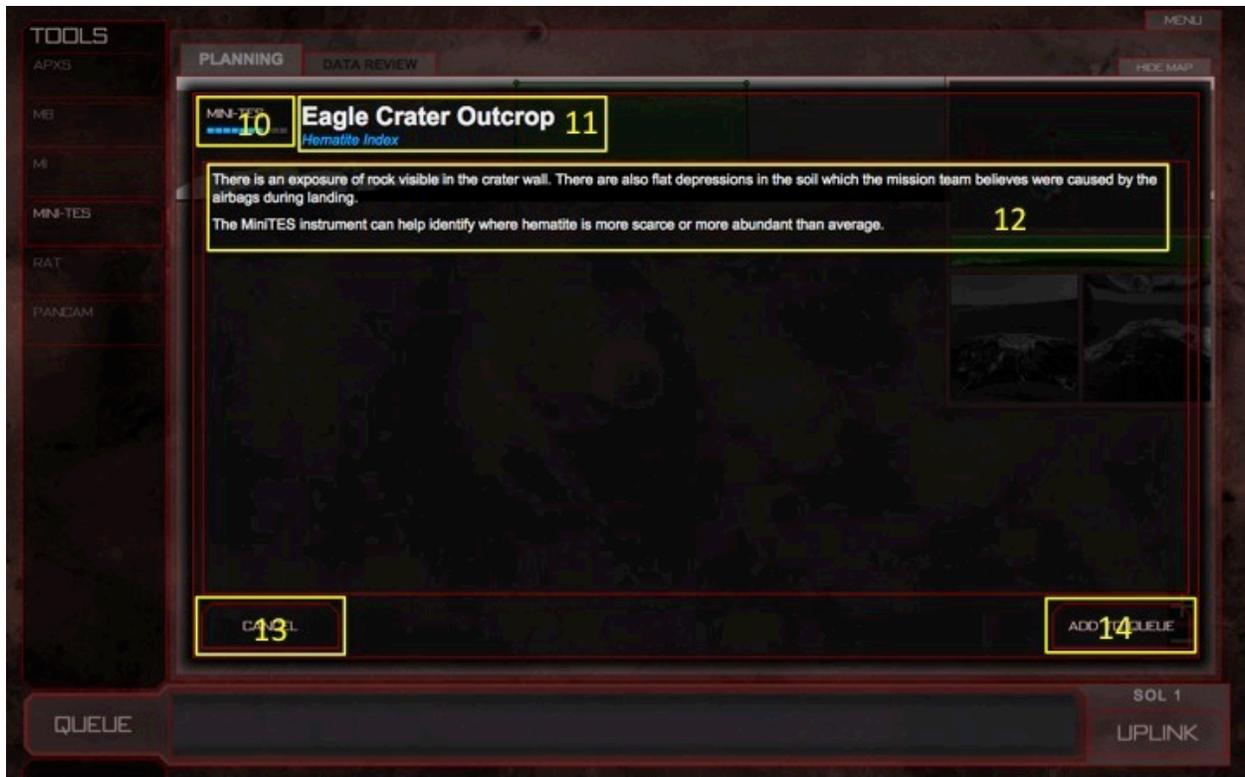


Figure 14. The observation summary dialog.

10. **Resource usage preview.** Indicates the instrument and the fraction of total available time that would be consumed by this observation.
11. **Site and observation names.** The name of the specific site and target or observation. These are mnemonic names that make it easier to refer to specific observations. They are sometimes also descriptive.
12. **Site and observation description.** Provides some insight into what kind of information might be obtained by making this observation.
13. **Cancel.** This exits the dialog without queueing the observation. The observation will still be available, however.
14. **Add to Queue.** Enqueues the observation for execution by the rover.

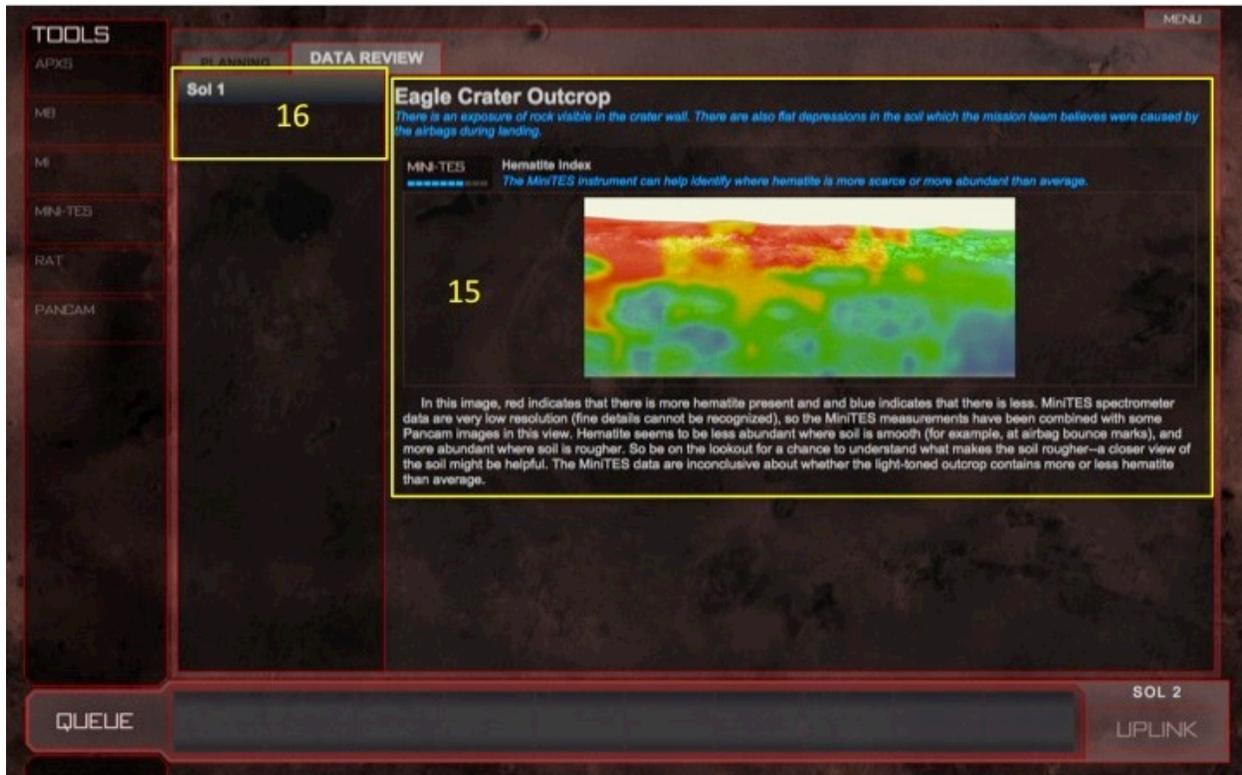


Figure 15. The Mission Manager Report in the Data Review panel.

15. **Mission Manager Report.** Contains the name and context information for the target and observation as well as a description provided by the science team which may include scientific interpretations or suggestions about future work. If the activity has a graphical representation like an image, it is also available here.

16. **Sol Browser.** Permits retrieval and reference of the Mission Manager Reports from past sols' activities.

Technical Walkthrough

When you are ready to proceed with a walkthrough of the first few sols of activity, navigate to the Menu and hit “RESTART.” This will reset your session to the beginning point pictured in Figure 13.

The image seen in the Planning view is a Pancam panorama taken from atop the lander. You can click and drag on this image to look around. You can zoom in and out using the +/- buttons in the lower right corner. Or you can click on the Front and Rear Hazcam views in the Minimap to look at the views forward and backward off of the lander, respectively. In the middle of the Navcam view, you should see a large blue box; if not, zoom out or drag around until you do. Such boxes or “footprints” indicate that the region underneath is a target of interest

and observations can potentially be made at this location.¹ If you hover over the big blue box, the box will turn red and a small amount of text will appear describing the highlighted region. In this case, the box covers a patch of outcrop on the Eagle Crater rim and airbag bounce marks on the crater floor. Clicking on the box will turn it green and, simultaneously, one or more instruments will become available in the Tools bar. In this case, the Mini-TES instrument becomes available.

Now hover over the highlighted Mini-TES icon in the Tools bar. A small text box will appear describing what this instrument does and why making an observation with it might be useful at this location. If you click on the icon then a dialog will appear as in Figure 14 which contains the target and observation descriptions, target and observation names, and an icon indicating what fraction of a single sol's resources will be consumed by this observation. In this case, the Site name is "Eagle Crater Outcrop," the observation name is "Hematite Index," and this observation with Mini-TES will consume seven of the ten available resource slots for the sol. From this dialog you can choose to cancel the observation, in which case it will not be made (but will still be available), or you can add the observation to the queue by clicking on "Add to Queue."

When an observation is added to the Queue, it appears as blue in the Queue bar and will be labeled with the instrument name. The amount of space that an observation takes up in the Queue corresponds to the fraction of the total resources that it will use for that sol. You cannot queue more observations than you have resources, so you are limited in the total number of observations you can make per sol. The corpus of observations queued for a particular sol is sometimes referred to as "the plan" for that sol. If you click on an observation in the Queue, it will bring up a dialog that allows you to review the observation and, if desired, remove it from the queue.

When you are satisfied with your plan as it has been queued, you can choose to uplink it to the rover by clicking UPLINK. In the conceit of the activity, clicking "UPLINK" causes the plan to be sent to the rover, the rover executes the plan by making the requested observations, and returns the data.² As this Mini-TES observation is the only observation available right now, go ahead and click UPLINK.

You will immediately be presented with the Data Review panel as it appears in Figure 15. First note that the sol counter has incremented to indicate that time has passed. This panel provides a summary of the observations just made as well as scientific interpretation and guidance provided by the Mission Manager. If the observation resulted in graphical data such as

¹ Of course, the actual rover team has essentially free reign to make observations within the limits of mission safety, time, and resources. Because we are confining ourselves exclusively to real mission data in this activity, however--that is, we are not faking any imagery or results--you and your students will be limited in your options. It will only be possible to perform observations that the Opportunity Science Team performed in real life. In this way, you are really retracing their footsteps in some sense rather than exploring on your own. But we've done our best to design the activity to hide this fact, at least on the initial playthrough.

² The rover team often waits hours or days to get the results back from any particular observation. We decided to not simulate that particular bit of thumb twiddling.

an image, it is available here. In this case, it is a Mini-TES “abundance map” for hematite. You can click on this image to view it full screen. The left column of the Data Review panel indicates the sol on which data has been taken and, once you have more than one sol worth of data, you will be able to browse any previously collected data here based upon sol. Once you have read the Mission Manager report, return to the Planning view by clicking the Planning tab.

There are no additional observations available at this Site (on the lander). Once you have satisfied yourself of this fact by browsing the panorama and the Hazcams, it is time to move on to the next Site. Do so by bringing up the travel map by clicking on the orbital view. This displays the various Sites that are available for travel as red dots--the current Site is indicated by a blue dot--and the possible paths for traveling to them via the yellow line.³ The next site is labelled 02_24⁴ and is to the Northeast of the current location. Find this Site and click it.

Clicking a site in the overhead map brings up a dialog that asks you to confirm that you would like to travel. Travelling consumes some number of sols depending on terrain and distance. In this case, travel from the lander to Site 02_24 will consume 3 sols. Click TRAVEL to command the rover to move off of the lander to Site 02_24.

Again, the Data Review panel pops up describing the results of the drive. The drive completed on Sol 4, and so is filed under this date. The Sol Counter is at 5 because that is the sol being planned. Click on the Planning tab to see the context of the new location.

Site 02_24 is somewhat unusual in that a panorama is not available, only Front and Rear Hazcams. The Front Hazcam has a single footprint. Click on it to see that it makes a Pancam observation available at this location. Queue the Pancam observation and, in the process, learn that such observations serve as precursors to other operations with the robotic arm. Run the observation.

After reviewing the resulting Mission Manager Report, return to the Camera tab to find that the same footprint is still available in the Front Hazcam image. This time, clicking the footprint makes a Microscopic Imager observation available. Queue and uplink the MI observation.

Having reviewed the Mission Manager Report for the MI observation, return to the Camera tab to find, yet again, the same footprint in the Front Hazcam. This footprint now makes two separate instruments available: APXS and Mossbauer. You have enough resources to queue both observations on the same sol. Do so. Then uplink the plan.

In the Mission Manager Report, you’ll find that APXS and Mossbauer data are displayed as charts rather than images because these are spectrometers rather than cameras. The Sol Counter should now be at 8, and examination of the Front and Rear Hazcams will reveal that there are no additional targets available at this site. It is time to move on to the next Site (03_00).

³ In the current prototype module, only linear travel paths are permitted. That is, the Sites can only be traversed sequentially.

⁴ This site name was meaningful to the mission team. It refers to the 24th “position” at the 2nd site. While they are technically “historically accurate,” we may replace these numeric site names with easier to remember mnemonics in the future.

This concludes the tutorial. By this point, you have been exposed to all of the major concepts and points of functionality that will be required to operate the rover within the EVFE environment.

8.0 The Flow of Class Activity

Initially, the teacher might want to briefly review relevant concepts that students already are familiar with (e.g., section 3), and then introduce concepts that might be new (section 4), aided by information in this document and the Teacher’s Introduction Slides.

Early on, the teacher should explain the rubric that will be used to evaluate student performance. It is suggested that this involve: (1) the accuracy, effectiveness, and originality of material in student notebooks, which record observations, interpretations, hypotheses, noteworthy Mission Manager results, and other information; and (2) a Summary Sequence of Events written by each student that outlines the geologic history of the landing site. Summaries might be simple lists of events in time-order, or more elaborate short essays supported by observations, interpretations, and other information. Student summaries should include types of locations where the hematite was found, explanation(s) of how the hematite got there, and inferences about the ancient surface environment on Mars back when the hematite formed.

Underlying all of these activities is the essential goal of student *efficiency* in their explorations. The virtues of efficiency are obvious to students during near-frantic activities like timed tests, but can be more difficult to emphasize in day-to-day thinking in a general classroom setting. In this module, however, student success is greatly affected by their efficiency in observing, in writing (concisely), in distilling new information for what’s important, and in deciding what to do next. Real NASA rover missions are rarely undertaken, are enormously expensive, and have finite lifetimes (whatever eventually breaks or wears out on a rover can’t be repaired), so every working day on Mars is precious—and might turn out to be the last. The actual MER science team felt this pressure keenly as they went about daily rover operations, stuffing as much science into each day’s plan as possible, prioritizing all the things they wanted to do while trying to stay focused on the overall mission goals. It is intended that the realism of the module—involving the actual NASA images and data, and treading in the footsteps (wheel tracks) of the actual science team—will help imbue the students with a sense of efficiency and urgency in their activities. Reflecting this, there probably won’t be enough classroom time for the students to “press every button” on the software and collect every possible observation at every possible rover stop. The students should be informed from the beginning (and be reminded) that they will have limited time in the classroom to accomplish their mission goals, and not enough time to perform every possible observation at every possible rover stop (at least, not very thoughtfully). Students will have to prioritize as they go along, realistically evaluating their progress against the classroom clock. As in real life, meeting their mission objectives in the fewest number of sols (martian days) is the goal. Students should be asking themselves constantly, as they evaluate the latest data from the previous sol plan and contemplate what to do in the coming one:

“Based on what I’ve been finding here, what should be done *next* with the rover to learn the *most* about this landscape, as quickly as possible?”

The teacher should introduce the software by walking the class through the first few martian days or “sols.” This will show students how to operate the software and get them into the rhythms of recording essentials in their notebooks. Notebook format might be something left up to the individual students (for example, some might rely more heavily on quick sketches than others), or perhaps be recommended by the teacher. It might be very fruitful for the teacher to provide an example of notebook entries, distilling the collective class discussion from the demonstration of the first few sols, to serve as a guide for what is expected when the students are on their own for the balance of the exercise.

The landing site can be introduced at the same time by using the various camera views: Front Hazcam, Rear Hazcam, Navcam, and then Pancam. This is a good time to get the students to start thinking about what they are seeing, to practice making basic observations that they should strive to discuss concisely and clearly. This can be natural for some students, much more of a challenge to others. Our philosophy is that this can be learned, or at least improved with practice. The first Pancam mosaic might elicit a wide range of student reactions. Some will find it bland and empty—at least compared with scenes in their real lives at home or at school—and think “there’s nothing there.” Others might find the first Pancam mosaic overwhelmingly complex, with every pebble and outcrop exposure potentially different from the others and significant, to the point where they are almost paralyzed to know where to begin. We suggest beginning with something as simple as identifying two major types of “stuff” in the initial Pancam mosaic: (1) rocks and (2) soil—just two basic components, with details to be figured out later. (Is all the soil the same? Are all the rocks the same? It’s hard to tell, frankly, with these data. What do we need to do with the rover to answer these questions better?) To better engage the students, the class might be asked to speculate which of these units might be older and what their reasoning is for their answer. Have the students record these observations and a distilled version of the class discussion in their notebooks!

Next, introduce the brightly-colored MiniTES hematite abundance graphic (by scrolling around in the initial Pancam mosaic until finding the purple-shaded box, then selecting that box as a MiniTES observation and executing the sol plan). Redder color-coded areas have more hematite; bluer color-coded areas have less (see Figure 6). Ask the students (and get them to write down this question): What *correlations* might exist between hematite abundance (the reddish stuff in the MiniTES graphic), and other features of the landscape? Consider slope, surface roughness, inside vs. outside the crater, soil vs. outcrop, etc. in a brief class-wide discussion. The actual answers are that hematite abundance only correlates—loosely—with surface roughness, and also partly with materials near the rim of the crater. An important point: hematite abundance does not seem to correlate simply with either soil or with outcrop. Again, be sure the students are writing this discussion down. It might be emphasized that *non-correlations* are important clues, too, and should be recorded. A broad hint might be dropped that the hematite vs. soil roughness correlation might be useful later. It is probably worthwhile to briefly discuss with students the inconclusiveness of whether outcrop is hematite-rich or hematite-poor. The MiniTES data appear as fuzzy (but colorful, in this rendition) blobs on the surface—very low resolution compared with the details of rocks and soil in the images. This is realistic, and a characteristic limitation of this type of data. The teacher can point out that in science—in fact in all complex problems or issues that need discussing or solving—every data set or information source has inherent limitations and/or blind spots. Rarely, in the real world, is any information source perfectly accurate and perfectly comprehensive. Having not enough information to make all the conclusions is a common state a scientist (or any reasonable person) finds himself in

when facing a complex and/or new situation; this should be admitted—and it’s realistic! It’s okay!

The teacher should show the students how to “drive” the rover by driving to the next site (0224)—and be sure to point out the cost in sols of this activity. Driving is expensive, so retracing one’s steps to revisit a site is wastefully inefficient. After arrival at site0224, the teacher leads the class through activities there. This site allows use of the arm and the instruments on it, and is fairly representative of rover activities that students will be choosing and doing at other sites, including interpretation of APXS and Mössbauer results.

The teacher should discuss how to read the APXS and Mössbauer graphs (in that order), and how to focus on the important FeO and hematite values. Every APXS and Mössbauer graphic highlights these items in red, as a reminder. A little math is involved to relate these two graphs: APXS tells you how much iron (“FeO”) is in the sample. Then Mössbauer can tell you how much of that iron is in the form of hematite—what the mission goals ultimately care about. Use the site0224 APXS and Mössbauer graphs to show how the math works: In a simplified equation, $4\% \text{ of } 18.8\% = <1\% \text{ hematite}$. Or, $0.188 \times 0.04 < 0.01$. By the way, $<1\%$ hematite is not a lot; site0224 is not hematite-rich, so we’ll have to keep looking. Before the students discard this result, though, emphasize that where hematite *isn’t* helps narrow down where hematite might be, so a “negative” result like this shouldn’t be ignored or forgotten! Write it down! Emphasize that the students will be taking a lot of data from a lot of stops and there’s no way they’ll be able to remember it all and keep from getting results mixed up. They’ll have to take good notes, starting right from the beginning. The basic essentials that can be included in their notes as they go along can be: (1) summaries of the important essentials in the images, (2) some (not all) of the main points in the image results texts, including addressing the questions sometimes asked there, (3) APXS and Mössbauer results, (4) sol # and (5) site location. At the right times, sketches of ideas or hypotheses, and summaries of points made in discussion with “colleagues” sharing their computer are other, very important things to include in their notes. Good notes are also essential for making efficient use of the “Data Review” mode in the software because observations accumulate sol by sol (Data Review can be used for searching and finding).

Students, probably in small groups as computer facilities allow, might now take over their mission, with the teacher circulating among the groups, helping the students run the software, making sure that good note-keeping of results and hypotheses is established early-on, or at least improved as much as possible, and prompting students with stimulating questions about their data from time to time if they get stalled. The teacher can request that students turn in their notebooks for overnight review. Evaluating these, the teacher can make corrective suggestions directly in student notebooks and/or orally at the beginning of class the next day. (This might also discourage students from being tempted to “look up the answer” overnight on the internet by searching for summary accounts in archived news articles and NASA press conferences of what MER *Opportunity* actually discovered.)

9.0 Summary of Geologic Events at MER Opportunity’s Landing Site

The MER science team, in its interpretation of *Opportunity’s* landing site, has at its disposal many times the amount of data than included in this module, and much more time to sift through these data, analyze the data thoroughly, and publish their results. Their story can be found in extensive peer-reviewed scientific journal articles (some of which are still being written). Here in this module, students might be expected to derive only a fairly simple geological outline history based on the limited amount of data and time available to them.

Students might have time to visit only a subset of the potential rover stops in this module. In these cases, we suggest that any interpretation written by students that is plausible according to whatever data they were exposed to might be evaluated as reasonable, even if it differs from the geological outline offered below.

Version One: A Brief, Time-Ordered Listing

- (1) Long ago, light-toned bedrock forms, probably sedimentary of some kind. There used to be more of it (above) than what is left now.
- (2) Abundant groundwater invades the light-toned rock, enough to cause important changes. Hematite concretions form inside the light-toned rock.
- (3) Back up at the surface, strong winds drive dark sand grains from time to time, eroding away the light-toned rock. But the concretions inside the rock are much harder, so they get left behind as the light-toned stuff erodes away, and start to pile up on the sandy soil.
- (4) Today, there's not much light-toned rock left exposed for further erosion, but this still happens where exposures crop out, releasing concretions on to the soil surface. Mostly, the ground is covered with a residue of dark sandy soil, with loose hematite concretions that were "abandoned" by erosion of their weaker, light-toned host rocks. It's the concretions now lying on the soil surface that make the surface seem "hematite-rich" from orbit.

Version Two: A More Extended Narrative, for Teacher Reference

The light-toned rock seen in places around the inner rim of Eagle crater also underlies the soil-covered plains all around Eagle crater. It's just easier to see this bedrock in places like Eagle crater where the "third dimension" is available for inspection. If Eagle crater weren't half-filled with dark soil, even more of the light-toned bedrock would be visible at greater depths. Almost everywhere in our study area, the light-toned bedrock is covered by a veneer of dark soil less than a meter thick. The plains currently are very level, indicating lots of erosion has taken place (more on that later), so originally there must have been more of the light-toned rock, above current ground level. We don't know how much more above ground level this might have extended. Lineations in outcrop at Eagle crater indicate this material is sedimentary rock. (There are hints at what kind of sedimentary environment was present when the rock was laid down initially, but these clues are subtle and not emphasized in the module.)

Later, abundant groundwater passed through the light-toned rock, enough to cause chemical changes to the rock itself, including the formation of hematite concretions and, in places, crystals of some kind of salt. (There are hints in our study area that some of this groundwater reached the surface in places, too, but these clues are complicated to evaluate and are not emphasized in the module. Here, we stick to the pervasive influence of abundant groundwater.)

Still later, the light-toned rock, now with hematite concretions scattered inside it, was eroded down to its current level. The erosion process probably involved strong winds driving dark sand which sand-blasted exposed rock, creating a level plain. The light-toned rock is weak and not very resistant to erosion compared with the hematite concretions inside it. So as the light-toned rock material eroded away, the hematite concretions were released on to the surface, where they began to accumulate as more and more rock was eroded away, leaving more of the concretions behind.

Currently, there are so many hard hematite concretions covering the thin soil (which in turn covers the underlying light-toned bedrock) that only limited wind-related erosion is taking place. The hard hematite concretions essentially protect much of the dark, finer soil from being blown by the wind, and this limits the potential of wind-driven sand-blasting to remove additional light-toned rock. At the same time, there isn't much light-toned rock left sticking up where it could be vulnerable to sand-blasting erosion. Instead, stormy winds more recently have shaped the soil, including the smaller (1-2 mm) hematite concretions, into vast plains of wind ripples.

These vast plains of wind ripples, covered with hematite concretions left behind from eroding bedrock, are the main "carrier" of the hematite signature seen from orbit that first drew attention to this place on Mars as a landing site for *Opportunity* to explore.

Appendix A: Known issues and future work.

We want to receive feature requests and bug reports!⁵ But to avoid duplication in bug reports and feature requests, this is a list of known issues and planned features for future versions of the EVFE. Note that this list is specifically limited to *technical* bugs and features, items that relate directly to software and not content.⁶ Also note that this is not a complete list; this list will probably never be complete.

Known Issues

- The order of Mossbauer and APXS matters but is not enforced in the activity. Sometimes the Mission Manager refers to one of these observations as though it has been made when it has not.
- Data volume is quite high (because the images are so large).
- The graphic for post-RAT McKittrick Mossbauer results (site 04_54) is missing.
- The Berry Bowl MI footprints do not appear in the correct place (i.e. on the Berry Bowl).
- The “Berry Bowl Empty” MI image is missing.
- Site names might be a little confusing.

Planned Features

- In-app note taking
- Built in tutorial
- Play tracking (record and replay) for assessment
- Tablet and mobile support

⁵ Send them to Chase Million (chase.million@gmail.com).

⁶ Though we also welcome content feedback!