Student questions: Ken Edgett colloquium on "A more vast and accessible Martian sedimentary rock record"

2/15/17

Ken Edgett responses in blue. Thank you, SESE students, for these great questions; many of them would be good starting points for research papers, a thesis, even a dissertation.

Question 1: What if I took a sample from mars and brought it to the earth for example the sandstone on mars is any different than the ones on earth?

From a sediment texture and structure point of view, Mars sandstones should be exactly like Earth sandstones… i.e., composed largely of sand-sized grains. Where Mars sandstones will generally differ is in composition. A combination of the relative abundance of silicic crustal rocks ("continental crust") on Earth relative to Mars, and the more vigorous chemical weathering of rocks and constituent minerals on Earth, means that typical Earth sandstones are much more quartz-rich. Martian sandstones are typically derived from mafic (plus or minus) parent rocks and the consituent plagioclases, pyroxenes, and (sometimes) olivines, are better-preserved under Martian conditions. Mafic sandstones are relatively rare on Earth.

Question 2: Is there any spots on Mars that has a buried bedrock? That could have maybe some new rock units for us? And are there any plans in the future for making a lab on mars that could do an actual experiments instead of the rovers?

There is certainly bedrock on Mars that is not exposed at the present-day surface. It is certainly likely that some of the buried rock units are of an unknown nature, because we haven't been able to detect them, yet. These could easily include igneous, impact melt, and sedimentary rocks as well as, perhaps, some forms of metamorphic rock (at least contact metamorphic).

The rovers on Mars *are* miniature laboratories, to some extent. The Curiosity rover, in particular, carries an x-ray diffraction capability, for mineralogy (http://dx.doi.org/10.1007/s11214-012-9905-1), and, for geochemistry, an onboard lab containing a gas chromatograph, tunable laser spectrometer, and quadrupole mass spectrometer (http://dx.doi.org/10.1007/s11214-012-9879-z). Those are in addition to the various remote sensing and contact instruments onboard (see summary in http://dx.doi.org/10.1007/s11214-012-9892-2).

If the question about laboratories on Mars refers to the idea of building a human-occupied base on Mars, complete with laboratories for on-site study (as opposed to taking samples to Earth for study in laboratories here), the answer is that there are certainly hopes and desires that someday this sort of thing will occur, but, at the moment, there are no plans "on the books" – i.e., funded by government or non-government agencies or persons, to land humans on Mars and have them set up and operate a laboratory. The US space agency, NASA, has had a policy for several years, now, of working toward developing the capability to send humans to Mars as early as the 2030s, but whether this actually happens is subject to a lot of decisions that haven't yet been made and funding that has not yet been approved.

Question 1: You would expect the older rocks to have more craters , but that's not the case on Mars. Why is that?
One of the most basic tenets in planetary geoscience is the notion that the most heavily cratered surfaces (cratered by impactors such as comets and asteroids, many kilometers down to small dust grains in size), with crater diameters measured as a function of surface area on given geologic or geomorphic units, is the oldest surface. For example, the heavily cratered terrains of Earth's moon are the oldest rock exposures; the less-cratered surfaces, the lunar maria, are younger. On Mars, at the scale of very large craters (larger than a few kilometers in diameter), this is also true… the heavily cratered terrains of Mars, taken as a whole, consist of bedrock older than the less-cratered plains, volcanoes, and polar cap deposits.

Of course, for a planet where erosion occurs, such as Mars, the issue of relatating crater populations (size-frequency distribution as a function of unit area) is complicated by questions of burial and exhumation… how long was a surface exposed to the sky such that the rock unit could receive incoming impactors and become cratered, combined with how long was that surface subsequently buried such that no impactors damaged it, combined with how long (and how many times) was that rock unit re-exposed to the sky to receive new impactors… this brings about the concept of "crater retention age," which is some function of these things (http://dx.doi.org/10.1016/j.icarus.2004.11.023).

However, there is another wrinkle in the topic of crater retention and the relative and absolute age of a rock unit exposed at the Martian surface, and it has to do with how well that rock resists erosion. This applies mainly to the smallest impact craters, generally less than a kilometer in diameter. For most of the 2000s decade, it was looking like the surfaces that retain small craters best were lava plains, lava flows, volcanic edifices… i.e., generally hard rocks like basalt (http://www.msss.com/biographies/edgett/abs/2005_2009/DPS_2009_Edgett.pdf). However, as I was showing in my Colloquium presentation, the Curiosity rover site has shown us that this view is in need of revision… that there are also sedimentary rock surfaces that retain small craters as well as do lava flows (https://gsa.confex.com/gsa/2014AM/finalprogram/abstract_244787.htm); an example given in the talk was the cratered surface that the Curiosity heat shield impacted during the landing events on 6 August 2012… it turned out to be a sandstone. That there are relatively heavily-cratered sedimentary rock units on Mars (heavily cratered by craters smaller than 1 kilometer diameter, that is) is a departure from the "conventional wisdom" built up over the first decade of examining sedimentary rock occurrences on Mars, as summarized by Grotzinger and Milliken (2012; http://dx.doi.org/10.2110/pec.12.102.0001).

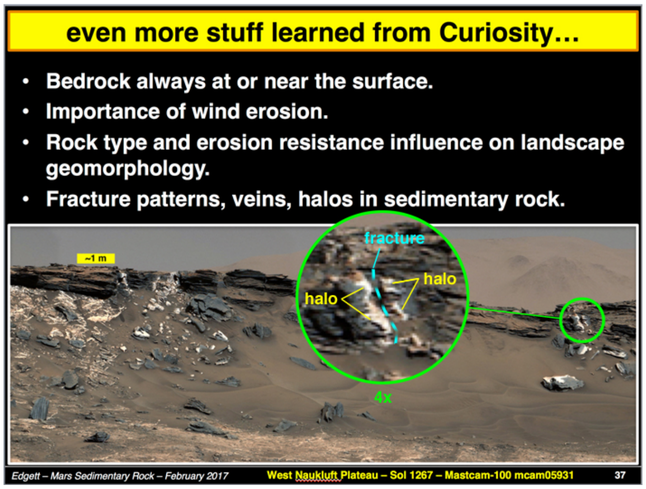
Question 2: Is it possible that Martian sedimentary rocks formed without the presence of water?
Interesting question because there are sedimentary rocks on Earth's moon… they are breccias cemented during impact events which can sinter and bind regolith grains together (e.g., see sumary/overview in http://dx.doi.org/10.1007/978-94-010-0800-6_3). Similar breccias can occur on asteroids and other planets, icnluding Mars, and some of these are found as meteorites on Earth. That said, the sedimentary rocks at the Opportunity and Curiosity rover sites certainly involved water in their diagenesis (the changes that occurred in the sediment, after deposition). A

challenge is to decipher the relative roles of water over time in any given rock unit, relative to the tools and observations we are able to make, on Mars, under present and future circumstances.

Question 1: Approximately what percent of Martian sedimentary rocks are comprised of Terran sedimentary rocks (sandstone, mudstone, limestone), or do we know within any degree of accuracy?
I am not certain that I understand the question, as written… i.e., "Terran". Martian sedimentary rocks would be composed of pieces of older Martian rocks, not pieces of Terran (Earth) rocks. That said, another way of looking at the question is the extent to which Mars sedimentary rocks are similar to Earth sedimentary rocks. This, then, gets into questions that touch upon both the physical properties of the sediments (and the rocks which formed from them) versus composition. The sedimentary rocks thus far identified on Mars include conglomerates, sandstones, and "mudstones" (in which "mud" refers to any rock of silt- and clay-sized particles in unknown proportions… mud is not meant to refer to having been wet… I know, I don't like this term, "mud," but this is what is presently being used, per logic described by Grotzinger et al. (2014; http://dx.doi.org/10.1126/science.1242777)). Some rocks interpreted to be sedimentary contain sulfate minerals; some contain clay minerals; some observations from the THEMIS and TES instruments (operated by ASE SESE Professor Christensen's research group) suggest Mars has chloride minerals (e.g., halite), as well (http://dx.doi.org/10.1126/science.1150690). Carbonates also exist on Mars but whether these are sedimentary rocks, or not, remains uncertain in some cases; typically these are not limestone or dolomite and not thought to be connected with bigenicity. Mars also has impact breccias and a few of them have come to Earth as meteorites and are undergoing intense study (e.g., http://dx.doi.org/10.1126/science.1228858).

Question 2: Are there "unique" sedimentary rocks or features found on Mars but not on Earth?
From a sedimentary rock perspective, it is perhaps more the other way around… that it seems likely Mars lacks the types of biogenic sedimentary rocks (e.g. coquina) and rock textures and structures (e.g., macrofossils, bioturbation) familiar to us on Earth. Mars also seems to lack limestone and dolomite. Rock units formed from chemical precipitation, for example in an evaporative setting such as a playa, are thus far still speculative for Mars. There is still much to learn and explore on Mars, of course; while, as I showed in the Colloquium talk, we have covered 99.1% of Mars at 6 meters per pixel, and some percent at even higher resolution from orbit; plus the lander and rover views obtained thus far, there is so much more to explore at the scale achievable by rover and lander cameras.

Question 1: What is meant that halos are seen in these sedimentary rocks seen on Mars?
The term, halo, refers to something I showed briefly on "slide" 37… below is that same "slide" but I have added some elaboration, inside the circled areas, showing what I mean by "halo". In this case, the host rock has been fractured and the rock on either side of the fracture – the "halo" – has been altered… in this case, the alteration made dark gray rock appear very light gray or white.



even more stuff learned from Curiosity…

- Bedrock always at or near the surface.
- Importance of wind erosion.
- Rock type and erosion resistance influence on landscape geomorphology.
- Fracture patterns, veins, halos in sedimentary rock.

Edgett – Mars Sedimentary Rock – February 2017 West Naukluft Plateau – Sol 1267 – Mastcam-100 mcam05931 37

Halos like this were observed by the Curiosity rover team; the halo and host rock were drilled and studied in terms of chemistry and mineralogy and the conclusion was that fluids had moved through the fractures and permeated the adjacent rock, causing the grains and cements (these are sandstones) to become altered. An example of this story was in a Fall AGU abstract by Ming et al. (2016; https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/160060); some observations from the images were described at the same conference by Edgett et al. (2016; https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/152017). Fracture-associated halos have also been seen in sedimentary rocks viewed by high resolution orbiting cameras (http://dx.doi.org/10.1126/science.1136855).

Question 2: What time frames are we looking at for the sedimentary processes creating the lithification that is seen occurring on the surface of Mars?
This is a tough question to be certain of the answers because absolute dates for Mars rocks are hard to come by. With a few exceptions (the meteorites from Mars and the absolute age of the bulk sediment in a mudstone studied by the Curiosity rover team… for the latter see Farley et al. (2014; http://dx.doi.org/10.1126/science.1247166), the best that can be done is to base absolute ages on impact crater counts (size-frequency of diameters as a function of rock surface unit). For Gale crater, where Curiosity landed, the best one can do (Thompson et al 2011, http://dx.doi.org/10.1016/j.icarus.2011.05.002 and Le Deit et al. 2013, http://dx.doi.org/10.1002/2012JE004322), the best estimate is that all of the sediment which filled or partly filled Gale, and its lithification, and the bulk of its exhumation, all occurred within a few hundred million year period, perhaps before 3.0 billion years ago, with the crater having formed roughly 3.6 billion years ago. The Farley et al. (2014; http://dx.doi.org/10.1126/science.1247166) age for the bulk parent rock sediment in a sampled mudstone was roughly 4.0 billion years, consistent with the idea that the rock into which Gale crater formed was older than the crater itself (logical, of course). So, I guess the short answer to the question is that most of the action probably happened on "early Mars," with some rocks forming when the planet was very young (4.5 to 4.0 billion years ago) and most of the rest of the action, for sedimentary rocks, perhaps occuring before 3.0 billion years ago. But, this question is far from answered; we don't know enough, yet, about Mars.

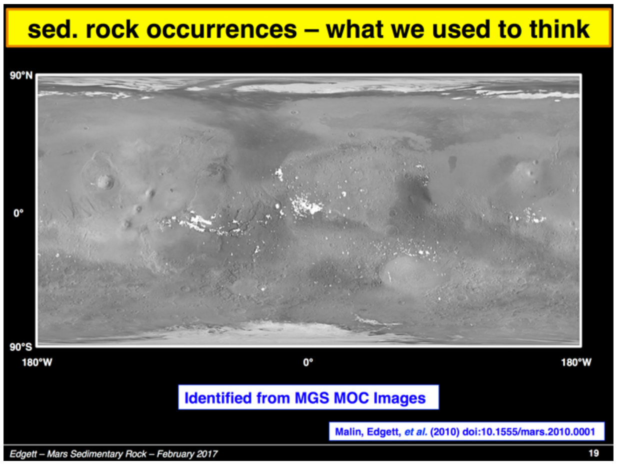
Question 1: Does the sedimentary rock that has been analyzed seem more or less resistant to the sediments on Earth, or are they a close analogy?

This is a good question and I am not entirely certain how to answer. On the one hand, resistance to weathering and erosion is a function of rock properties and climate (or, if you think about limestone caves and karst, for example, there is also a subsurface environment to consider when it comes to weathering and erosion). Mars is considerably more dry, today, than the driest environments on Earth, so that is one aspect of climate (wind erosion presently dominates over water erosion, for example). Another aspect on Mars relative to Earth climate is temperature, particularly diurnal and seasonal temperature range (how much the temperature changes over the course of a day as well as seasonally). Temperatures at the surface can swing more than 100°C in a single Mars day at the equator… so there will be some thermal stresses on rock, for example.

Another approach to answering this question might come from how difficult or easy it is to abrade or drill a rock on Mars, relative to Earth, or how easy it is to scratch the rock (on Curiosity, we can scratch "soft" rocks, like mudstone, with Curiosity's wire brush, the Dust Removal Tool (DRT), but we usually don't scratch the sandstones). Quantitative analysis of the relative properties of rocks we have drilled, abraded, or scratched on Mars versus counterparts on Earth are somewhat hard to come by, though, because the information would be in engineering data that haven't necessarily been fully calibrated and tested for this particular purpose, which is a purpose above and beyond the reason why these tools were designed. That said, I think there might be some preliminary studies, along these lines, in the scientific literature, but I would have to spend about an hour searching (I apologize).

Question 2: What are some possible reasons for the prominent outcrops that seems to cluster near the equators.

This is a good question which I think stems from "slide" 19 in my Colloquium talk (see below), in which many of the white dots, indicators of the types of sedimentary rocks recognized during the first decade (2000s) after they were first known to occur on Mars, are found at equatorial latitudes.


sed. rock occurrences – what we used to think

Identified from MGS MOC Images

Malin, Edgett, *et al.* (2010) doi:10.1555/mars.2010.0001

Edgett – Mars Sedimentary Rock – February 2017

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One thing to keep in mind is that these (slide 19, above) are places where light-toned, layered, not-much-cratered) examples of sedimentary rock are found. My present view (the main thrust of the Colloquium talk) is that sedimentary rocks are much more common and occur, at a minimum, throughout the heavily cratered terrains of Mars, some of which are under the south polar layered materials. That said, there are a few good reasons why those particular exposures occur in the equatorial regions: (a) it has long been known since the Mariner 9 mission in 1972 that middle and high latitude terrains are "mantled" with materials that obscure bedrock from direct exposure, direct view (e.g., http://dx.doi.org/10.1029/JB078i020p04117); (b) the equatorial latitudes include the deep canyon system known as the Valles Marineris, which is where a lot of these light-toned, lightly-cratered, layered materials occur; and (c) some portions of Mars, even at equatorial latitudes, are obscured by mantles of fine dust (e.g., http://dx.doi.org/10.1029/JB091iB03p03533). In addition, of course, some colleagues have proposed that there might be a relation between volcanism, wind distribution of tephra from the volcanoes, and the equatorial occurrences of these layered rocks (e.g., http://dx.doi.org/10.1029/2003JE002062), but I don't think it is necessary to invoke this hypothesis; these light-toned rock units are not likely to *all* be primary tephra deposits and we have reasons a, b, c, noted above, as to why they *seem* to occur mostly at equatorial latitudes.

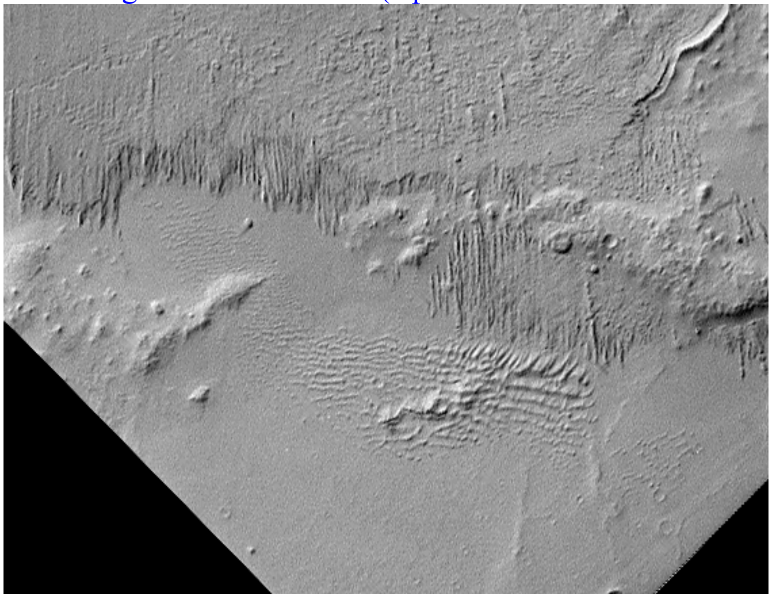
Question 1: Have unconformities been discovered in the sedimentary record and do they suggest an earth like tectonic activity?
Yes, unconformities are indeed observed. Generally they seem to be erosional unconformities, we don't see the classic Earth-like angular unconformities connected with tectonism. That said, Mars certainly has had some tectonic activity, but it differs from Earth (no plate tectonism; mountain-building, etc.). An erosional unconformity in the rock record in Gale crater was recognized in the first paper to describe Martian sedimentary rocks (http://dx.doi.org/10.1126/science.290.5498.1927). Another example in Gale crater was more recently recognized by a combination of rover and orbiter images by Watkins et al. (2016; http://www.hou.usra.edu/meetings/lpsc2016/pdf/2939.pdf). Unconformities also occur where impact craters and/or their ejecta deposits are buried… they are indicators of a past erosional surface, exposed to impactors, that was later buried and became part of the rock record.

Question 2: Are there any iron banded formations of the sedimentary rock that suggest sea environments like here on Earth?
We have not observed Earth-like banded iron formations on Mars. Then again, we have only seen sedimentary bedrock, at ground leval, at two sites thus far… the Opportunity and Curiosity rover sites.

Question 1: Though sedimentary rocks, what types of source rocks would you hypothesize to be the most prominent on Mars?
The source or parent rocks for the sediment grains that compose the sedimentary rocks on Mars are probably mostly igneous (mostly mafic), though the relative proportions of extrusive and intrusive igenous rocks, and the relative contribution from impact melt rocks, are not entirely known. Also, I would have to do some digging into the literature to understand what are the present models and thinking on the nature of the earliest Martian crust, differentiation of Mars,

etc. One recent paper that *might* help is a review/overview by Sautter et al. (2016; http://dx.doi.org/10.1016/j.lithos.2016.02.023).

Question 2: I'm studying geology and you showed a picture where people thought the image was possibly sand dunes but they weren't. As a geology student, I would have actually first guessed the image was more solid rock with steeper cliffs due to erosion and collapse that favored a certain direction do to common wind and water paths. This led me to wonder if this sand dune hypothesis may be because various defining characteristics of sand dunes on Mars differ than on Earth due to gravity and atmosphere differences; is this possible or do sand dunes follow many of the same general rules as they do on Earth?
I think you are referring to the series of images I showed on "slides" 16–18. The feature was also seen in Viking 1 orbiter images such as 436S03 (a portion of which is shown here).



What was different from typical dunes of this scale and morphology on Mars, as could be determined from these old Viking images, was that this dune field did not have a low albedo; its albedo was the same as the surrounding terrain. This suggested that maybe it was mantled with dust (and therefore inactive) or that it consisted of lighter-toned sand grains than most other Mars eolian dunes. The Mars Global Surveyor Mars Orbiter Camera showed, with its new high resolution images in 1999, that the landforms resemble a dune field (before then, Edgett and Blumberg 1994, http://dx.doi.org/10.1006/icar.1994.1197 had, just by brief mention, compared the morphology to the Dumont dunes in California) but they are fairly heavily cratered and must therefore be lithified (http://dx.doi.org/10.1029/1999JE001152). Subsequent higher-resolution imaging from the Mars Reconnaissance Orbiter High Resolution Imaging Experiment (HiRISE) showed the material is not only lithified but eroded; the slip-faces no longer at angle of repose but are steeper and shed boulders (interpreted to be sandstone). So, yes, I agree, the morphology isn't exactly like that of modern Martian dunes because these were buried, lithified, exhumed, and subjected to erosion (wind, gravity, etc.).

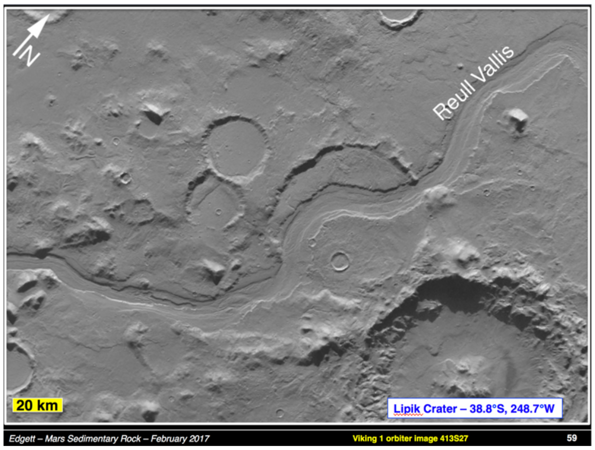
In general, though, Mars dunes exhibit morphologies and scales similar to Earth dunes and this has been known since the 1970s (e.g., http://dx.doi.org/10.1029/JB078i020p04139 and http://dx.doi.org/10.1029/JB084iB14p08183).

Question 1: Is it possible to determine if the older sedimentary rocks in the heavily crated areas have been altered by impacts or are still sedimentary?
I am not certain that I understand the question. On Earth, when impacts (meteors, asteroids, comets) occur in sedimentary rock, such as the Ries crater in Germany or the Chicxulub crater in Mexico, the target rock is still sedimentary; the impact doesn't change what the target rock was. Sure, it the impact event severely damages rock in the vicinity of the crater, and there may be impact-produced melt which cools to form rock, but the target rock is still what it was.

Question 2: Is there water or other processes in the subsurface that could be cementing sediment and creating sedimentary rocks currently, or were all the sedimentary rocks created a long time ago when Mars had water and other fluids cementing them?
The sedimentary rocks we have observed via our rovers on Mars, particularly Opportunity and Curiosity, appear to have formed long ago… on the order of 3–4 billion years ago, perhaps. Most of the action seems to have occurred long ago (see, for example, papers I noted by DOI link, above, about the age of rocks in Gale crater). Whether there are still processes acting upon sediments and sedimentary rocks in the Martian subsurface, today, is not really known. Certainly, there are rocks underground that are under pressure and experience temperature change on some time scale. One question is whether Mars has any liquid groundwater, today, or whether any water in the subsurface is frozen, and where this water or ice occurs. There are many papers published over the last two decades that poke at questions about subsurface water and ice on Mars and which observations from orbiter instruments might indicate one or the other. Water ice (not liquid) was certainly observed in the very shallow subsurface by the Phoenix lander team in 2008, and small impact craters at latitudes around 40° have shown there is shallow subsurface ice at middle latitudes (in some places), too. As for liquid water, I would consider the many papers about how mid-latitude gullies and mid-latitude as well as equatorial "recurring slope lineae" might have formed; some models involve groundwater, others do not. Finding subsurface liquid water, or even ice at low latitudes, is an open question and it is one that touches on issues of finding resources (water) for future human outposts on Mars.

Question 1: So from the data that was given, would one possible inference be there may have been intact craters well before some of the rivers flowed through?
Yes. And consider how difficult this might be, if the stream came from outside the crater and cut through it (going in one side and out the other) or at least cut into it (going in one side). If you drive to Meteor Crater in northern Arizona, as you are driving toward it, notice that it doesn't look like you are driving toward a crater, you are driving toward a plateau or hill or something... i.e, the raised crater rim, raised during the impact event. Now imagine, instead of driving toward it, you are a stream flowing toward Meteor Crater; what are you go going to do when the topography starts going up toward that raised rim? The stream is not going to flow up hill. For a stream to cut through a crater probably requires "superposition"… that is, the crater was filled and buried and the stream flowed across the buried crater without "knowing" that it was ever there (i.e., no response to the crater topography because there is no crater; it is buried). This kind of explanation is textbook Geology 101 of how the Susquehanna River in Pennsylvania managed

to cut meanders into the erosion-resistant ridges of the Apalachian Mountains. It might also be how a stream perhaps cut across the crater in the Viking image shown below (which is page 59 of the "slides" I presented in the Colloquium meeting; this was a "backup" slide in case someone were to ask about this topic ☺). A crater such as the one shown in the following figure must have been filled and buried when the "stream" cut across it; later, the crater and some remnant of its rim were partly exhumed.



Question 2: As technology progresses, from what you see would humans be able to send a manned mission to Mars to study rock units within the next 200 years?
Interesting to suggest a 200-year timetable. All my life, sending humans to Mars has always been 20 to 30 years away. When Apollo 11 landed on the Moon, it seemed possible that Apollo hardware could be adapted for a Mars journey as early as the late 1970s or early 1980s (see Stephen Baxter's novel, *Voyage*, for an example of what that might have been like). By the time I was a graduate student in the early 1990s, the talk (from the first President Bush) was to try to get humans to Mars by the 50th anniversary of the Apollo 11 moon landing… that is, by 20 July 2019. More recently, when Obama was President, the plan (which NASA is currently still pursuing until the Trump Administration gives new direction, if they choose) was to try to get humans to Mars, at least to orbit or do a close flyby, in the mid-2030s, with landings perhaps in the early 2040s. NASA is still planning for that, though no substantive funds have been committed by Congress and the new President and current Congress could change the plan. Meanwhile, in the last few years we have seen a very serious discussion from a private company, SpaceX, about attempting their own robotic (no humans onboard) landing as early as 2018-2019, with an eye toward sending humans to Mars in the 2020s or 2030s.

As for what will really happen, and when, it is hard to know. If the "always 20–30 years away" rule applies, as it has for most of my life, and if I am lucky to live 100 years, then we're talking about humans on Mars in the 2090s or early 2100s. I certainly hope to see it happen sooner than that, given that this has been a human dream since the first serious rocketry experiments in the early decades of the 1900s. But, regardless of what I think or hope, the bottom line question is: What would motivate the costs involved with sending humans to Mars? I think that if this question had already been answered, we'd have already sent people to Mars, even as much as 30–40 years ago. The motive to send people to the Moon in the 1960s was geopolitical (our economic system and way of life is more capable of space travel than yours; our military hardware is a greater threat than yours; etc.); some of the motives for Europeans to send folks to the Americas in the 1500s-1700s was economic (gold, silver, tobacco, fur, etc.). What motives would there be for sending humans back to the Moon or to Mars or other worlds in our solar system in the coming decades?

Question 1: It was mentioned that the certain types of rock on the martian surface did not hold crater shapes. Is there an estimate on how long it would take for the crater of an impact to (mostly) disappear on the surface?
The question refers to the topic of small (sub-kilometer diameter) impact crater retention that I discussed in the context of sedimentary versus igneous extrusive rock properties. Small crater retention is a function of the rock properties, the conditions under which is it eroding (climate), how long (and how many times) it has been exposed at the surface (cratering rate versus erosion rate), etc. Of course, crater diameter is also a factor, such that very large craters, like the Hellas and Argyre basins on Mars, will persist in some form for billions of years and have a major influence on the geology, geomorphology, and (potentially) climate of Mars. For the relatively small craters, some estimates of erosion rate have been made. In particular, I suggest looking at a paper by Grant et al. (2008 http://dx.doi.org/10.1029/2005JE002465) as a starting point.

Question 2: Space exploration tech is an industry with an inherently high entry barrier. You mentioned that when you started with the company it only had 8 employees. How did a small company of 8 people manage to land their first contract big contract for the space sector? As a SESE student with a background in aerospace engineering, this issue was very interesting to me.

I arrived at Malin Space Science Systems (MSSS) in February 1998. It had incorporated in 1991. The company founder and president, Mike Malin, was a Geology professor at ASU before starting the company. His proposal submitted, from ASU, to NASA in 1985 for a high resolution camera for Mars Observer, which later became Mars Global Surveyor after Mars Observer failed, was selected by NASA in 1986 (see http://dx.doi.org/10.1555/mars.2010.0001). When Malin left ASU in 1991, the intent was to operate this camera, MOC, from a small, private company he set up in San Diego, California. Meanwhile, there were a few opportunities to propose science investigations/instruments for new planetary missions, and after Mars Observer failed NASA funded another MOC to be built for Mars Global Surveyor. Building on this experience and responding to the limited number of opportunities to propose new instruments for planetary missions, the company, MSSS, proposed in 1995 a suite of cameras for NASA's 1998 Mars launch opportunity… an orbiter mission later called Mars Climate Orbiter and a lander mission later called Mars Polar Lander. Cameras proposed for these two missions shared a common electronics design but different optics for the given science tasks. Some combination of the science objectives and capabilities, the proposers' credibility to do the end-to-end job, plus the instrumentation's relatively low mass, low power, small volumetric envelope, downlink data volumes, etc., as well as the price tag (in this case, buying all of the proposed cameras would actually be less costly per camera because of the common designs and shared labor effort) caught the eye of the NASA selection process (i.e., NASA was the customer). Those "Mars Surveyor 98" cameras, called MARCI (http://dx.doi.org/10.1029/1999JE001145) and MARDI (http://dx.doi.org/10.1029/1999JE001144), were the first entry point for MSSS into building space cameras in-house. Operating them at MSSS was also a selling point, as their operation would build on existing ground data systems developed for the Mars Observer & Mars Global

Surveyor effort. From that point, forward, success somewhat begets success… new instruments are proposed based on previous flight heritage, reputation for delivering on time, on cost, on spec, the overall team experience and credibility, and so forth, as well as, and this is important for planetary science missions, the nature of the science investigation being proposed. MSSS does not get selected for every instrument proposed; this is true for any organization and science team who proposes instruments for space science missions.

I should also note that, for space science instruments, NASA has programs to which one's team can propose to do research and development on new instrument types and designs. For example, in December 2016, NASA selected investigations for a program called COLDTech, in which selected investigators will explore instrument strategies and designs for future missions to "ocean worlds" such as Europa and Enceladus. You can look at the COLDTech web site to get a sense of what is involved in proposing such things:
https://nspires.nasaprs.com/external/solicitations/summary.do?method=init&solId=%7B5C43865B-0C93-6ECA-BCD2-A3783CB1AAC8%7D&path=init
Note that programs like this are also a great way to build up the credibility and capability to propose such instruments for space science missions, as well as to address or retire risk to an instrument development effort.

Question 1: Has there been any studies on the erosion rates of the Martian sedimentary rocks and lava flows discussed? Is more than 15 years of imagery required for such studies?
Good question about whether the 15+ years of imaging can be used to estimate erosion rates; in some cases this is indeed possible, particularly on slopes where mass movement is occurring in the modern environent. In general, yes, erosion rate has been a subject of study, going back to the Viking lander sites and earlier studies of Mariner flyby and orbiter images. This is actually a vast topic that spans from the first Mariner 4 images of heavily cratered terrain acquired in July 1965 to present research people are doing. A few recent examples – starting points – would be the papers led by John Grant about the Spirit and Opportunity rover sites (http://dx.doi.org/10.1029/2005JE002465) and the Curiosity rover site (http://dx.doi.org/10.1002/2013GL058909) as well as the Farley et al. (2014, http://dx.doi.org/10.1126/science.1247166) paper which discusses erosion rate at the Curiosity site as a result of a cosmogenic exposure age study. Again, these are merely starting points.

Question 2: What causes the stream channels to become inverted along some portions or their flow compared to other portions that are not inverted?
Inversion of topographic forms is an interesting area of study for Mars as well as Earth (usually in desert settings, but not always). Some reviews are in papers by Williams et al. (2011 http://dx.doi.org/10.1130/2011.2483(29)), Pain et al. (1995; http://dx.doi.org/10.1016/0169-555X(94)00084-5) and Pain et al. (2007; http://dx.doi.org/10.1016/j.icarus.2007.03.017). Inversion can occur when the channel floor sediments, or channel-filling materials (sediments, lavas, etc.) are more resistant to erosion than the rock through which the channel cut. We also have to keep in mind the difference between a channel and a valley; on Mars there are places in which a valley is still a negative-relief feature, at the Martian surface, but the channel within it has become inverted. In a case in which some portion of a given valley or channel has some parts that are positive relief (inverted; ridge) and some parts are of negative relief (channel or valley),

it is typically a matter of rock properties… some rocks cut by the channel were more resistant to erosion and remained in place with the negative-relief form cutting across it, while in other portions of the channel system, the rock cut by the channel was less resistant to erosion than the channel fill or channel floor material, and was thus eroded away.

Question 1: Given the discovery of a widespread presence of sedimentary rocks on Mars than previously thought, how much of an impact does it bear in explaining the past environments on Mars?
Sedimentary rocks provide records of their depositional and diagenetic environments. Given that most Martian sedimentary rocks are probably quite ancient, in the 3.0 to 4.5 billion year range, they have the potential to have recorded not only the nature of early Mars (how wet? how warm? what gases in the atmosphere? atmospheric pressure?, etc.), they have the potential to have recorded events that might have affected multiple inner solar system worlds, including Earth (e.g., solar output) and could provide clues as to what early Earth was like… Earth did not preserve sedimentary rocks that are as old as some that are on Mars. Of course, to know what the sedimentary rocks on Mars are telling us about the Martian pasts requires studying them… investigating the *in situ* (outcrops and stratigraphic relations) as well as in laboratories (geochemistry, mineralogy, trapped volatiles, and so forth). There is huge potential here, based on knowledge gained over the past 100–200 years from study of Earth geology.

Question 2: Is there any kind of geographical concentration of sedimentary rocks on the surface of Mars?
Maybe, maybe not. Earlier (above) there was a question about why it seemed that the exposures of sedimentary rock are mostly at equatorial latitudes, and I explained that I think this is a bias based on what is exposed by erosion and tectonism (Valles Marineris being the “tectonism”) versus what is obscured by mantles of dust and/or mid- to high-latitude younger materials (mainly dust, ice). But there are other geographic relations to consider, as well. For example, there are three major volcanic regions: Tharsis/Syria/Sinai, Elysium/Zepheria, and Syrtis Major, as well as some minor ones. There are vast lowland plains, largely in the northern hemisphere. Some of these areas may have fewer exposures of sedimentary rock at the surface or available in the near sub-surface… that doesn’t mean they don’t exist in these regions, but that they are more deeply buried/obscured, for example. The better exposures are likely in the heavily cratered regions of Mars (the thrust and focus of my Colloquium talk).

Question 1: At one time the atmospheric pressure on Mars there is evidence of an ancient fluvial environment across the surface of Mars, but there is no current water anywhere? could have been higher, slowing evaporation. Would this explain why
This question came to me somewhat incomplete, missing the last phrase of the last sentence. Regardless, I can attemt to address the part of the question that is present… And, yes, the evidence known since the Mariner 9 orbiter mission, the first to map the entire planet, is that there may have been stream systems (of various types; see the Mars Channel Working Group 1983 report, http://dx.doi.org/10.1130/0016-7606(1983)94<1035:CAVOM>2.0.CO;2 for an in-

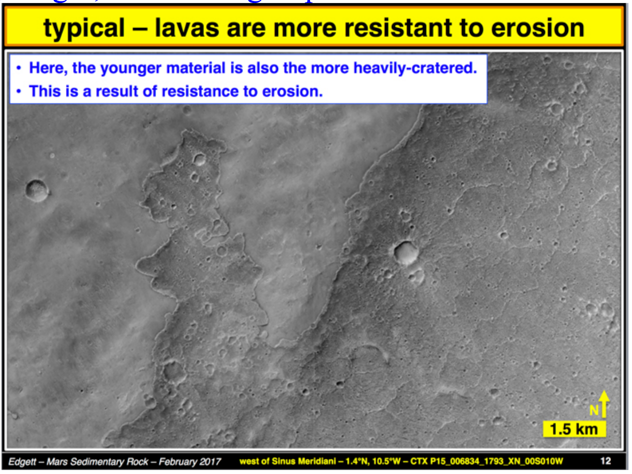
depth presentation on this) and that these largely occur in ancient terrains, suggesting that, over time, Mars had less liquid water and lower atmospheric pressures. This topic is pretty big and vast and touches on all kinds of questions about the history of Mars, how it lost much of its early atmosphere, the role of the planet's magnetic field(s) and loss of magenetic field in protecting the loss of atmosphere, and so on, as well as the impact on the geology, geomorphology, prospects for life on Mars, and so forth. This is a big topic and motivator behind Mars science. As for water today, certainly there is some amount of water vapor in the atmosphere, there is water ice in the polar and mid-latitude regions, and there is an open question about whether geomorphic features observed on Mars are telling us of the presence of flowing liquid water (or mudflows, debris flows, etc.) in the present or recent environment(s).

Question 2: Would it be possible that several large comets made mostly of ice could have impacted Mars long ago when it was warmer and then melted, to create the water needed for the depositional layers we see today on Mars' surface?
There is a whole body of scientific research literature about the question of cometary delivery of water to Earth, water to other inner solar system bodies (ice at the lunar poles, ice at Mercury's poles, ice on Mars, for example). There is also a body of literature not so much about delivery of water from comets but about the effect of comet and asteroid impacts on Martian (not to mention Earth, for large impacts on Earth) climate and geomorphology. An example of the latter would be the papers led by Teresa Segura (http://dx.doi.org/10.1126/science.1073586 and http://dx.doi.org/10.1029/2008JE003147). This is just a bit of what work has been done on these topics.

Question 1: Has there been any talk about the 2020 rover's landing site or what its main mission will be?
Yes. The Mars 2020 rover would launch in 2020 and land in 2021. It's main job is to collect and cache samples for a possible future retrieval and shipment to Earth for study in Earth labs (i.e., Mars Sample Return). The NASA/JPL web site has a lot of information about the mission, its objectives, and instruments: http://mars.nasa.gov/mars2020/
There has been a series of workshops to discuss and down-select candidate landing sites; the most recent was held this very month (Feb 2017). The outcome of that workshop was discussed in this 11 Feb 2017 article in Nature: http://dx.doi.org/10.1038/nature.2017.21470). And this 11 Jan 2017 article by the Project Scientist and Deputy Project Scientist described the mission and its objectives: http://dx.doi.org/10.1029/2017EO066153.

Question 2: If we could somehow drill down and get a drill core sample, would this be able to tell us, more accurately, the age of different eras on Mars?
I am assuming you mean a long core (many meters or even kilometers)… but, yes, certainly this might be one approach. There are others. Basically the issue is to find materials from which absolute dates can be determined, reliably, based on the array of methods routinely applied to materials on Earth, meteorites, samples returned from the Moon and other bodies, etc.

Question 1: You mentioned that the younger surface was the heavily cratered surface and that it was more resistant to erosion. Is it possible that the cratered rock composition is a more erosion resistant material and the areas without craters are actually younger, but may be covered by dust and deposition, so difficult to analyze?
The question refers to an example shown in the Colloquium talk on “slide” 12 (below) in which the orbiter camera view shows two surfaces, one heavily peppered with small impact craters of < 1 km diameter, the other much less cratered at this scale. The stratigraphic relation between the two materials is that the cratered unit embays the less-cratered unit… this means that the cratered unit is younger. The embayment relationship is “planetary geoscience 101” textbook stuff… BUT the fact that the younger unit is the more heavily cratered seems to violate the other textbook “planetary geoscience 101” tenet that older surfaces are more heavily cratered because they have been exposed, longer, to incoming impactors.



typical – lavas are more resistant to erosion

- Here, the younger material is also the more heavily-cratered.
- This is a result of resistance to erosion.

Edgett – Mars Sedimentary Rock – February 2017 west of Sinus Meridiani – 1.4°N, 10.5°W – CTX P15_006834_1793_XN_00S010W 12

It turns out, especially for such small craters, that there are a bunch of factors to consider, besides relative age, in assessing which surface represents the younger material. A key factor is the ability of a given rock unit to resist erosion in the modern/recent environment… which is what I was talking about. Of course, other factors can include how recently the surface was exhumed, how long it might have been buried and whether or not that buried surface had craters on it, among other things. The ability of the material to form craters at the time of impact can also be in issue… perhaps a much softer material, like unconsolidated dust, will not retain a new crater very long at all if the impactor did not penetrate through the dust and reach an underlying consolidated material (e.g., bedrock).

Question 2: Have you taken images of the sandstone formations that show cross-bedding indicative of higher energy fluvial environments that may be from water transport coming from sources other than ice melt?
At the Curiosity rover field site in Gale crater, there are, indeed, examples of cross-bedded standstones interpreted as eolian, such as the Stimson formation (see http://www.hou.usra.edu/meetings/lpsc2017/pdf/2014.pdf) and there are also cross-bedded sandstones interpreted to be fluvial, such as an outcrop called Shaler (see http://www.hou.usra.edu/meetings/lpsc2014/pdf/1648.pdf).

The statement or question about "ice melt" is interesting… it is not clear to me that any sedimentary rock thus far observed on Mars, particularly up-close, *in situ*, by rover instruments, has an unambiguously-identified relationship to former ice, ice melt, etc. Thus I do not know where the notion comes from; ice melt is tough to be certain of, in the context of Mars studies, in my experience. Of course, there is indeed a body of scientific literature in which ice melt or snow melt is hypothesized or speculated to have played a role in creation of landforms (e.g., fluvial and alluvial) and sedimentary deposits.

Question 1: What is the most expensive camera the company you work for has made?
This is actually a tough question to answer. The reason behind the cost of a given "camera" is variable. The company didn't actually build the Mars Orbiter Camera (MOC) for Mars Observer or Mars Global Suveyor, though the company operated these and was a participant in building the second one. Overall cost, end-to-end, for the MOC project, spread out from 1985 through 2008, was almost $44 million in "real year dollars," as documented in Table 3 of http://dx.doi.org/10.1555/mars.2010.0001. This cost included development, building, delivery, operations, etc., of two cameras. Figure 7 of that paper also shows what causes costs to increase.

Another reason it is tough to answer the question is whether one includes the cost of Research and Development (R&D) that precedes the camera selection for flight on a spacecraft mission. Some factors also lower the cost… if you have already built and flown it, then a build-to-print copy costs less than the first version of the camera. Flight heritage of the instrument and/or its constiuent parts can lower cost because it lowers risk. Often, the types of issues that raise the cost, especially after selection, are things like requirements changes, including improved knowledge of the environments to which the instrument will be subjected (e.g., vibration induced by drilling or coring devices on a rover), knowledge of how the instrument will accommodated on the spacecraft (sometimes this can require a complete re-design to fit within a smaller or differently-shaped volume envelope, a different mass, etc.). Such requirements changes typically come from the customer… e.g., NASA or its subcontractors to whom our company, MSSS, is contracted.

Another issue about estimating the cost is a matter of what is being purchased? MSSS can build and deliver a camera that meets the customer's requirements/specs… this is some combination of hardware and flight software; sometimes perhaps also ground data systems software and/or ground support equipment. MSSS can also do the camera and is operations… adding operations adds cost to the "camera" (on the other hand, if our operations of a customer's camers is considered by them to be less expensive than having someone else operate it, then they might to take us up on the offer). Supporting a science team also adds cost. So, overall, the cost of a "camera" is dependent on many factors, including the extent to which the company is involved in the operation and science after it is built, delivered, and launched into space. If MSSS is operating the camera, the overall, end-to-end cost goes up, too, if the mission is extended beyond its original primary mission duration. Of course, per year and per science benefit, such costs are a bargain… most of the cost is in instrument development (i.e., before launch).

Another reason that cost of "the most expensive" camera can be tough to estimate is that sometimes these are sold as packages… MSSS build several cameras for the Mars

Reconniassance Orbiter, Mars Climate Orbiter/Polar Lander, Lunar Reconnaissance Orbiter, the Mars Science Laboratory, currently for the Mars 2020 rover… when building several at the same time that share identical parts, software, and labor force, this helps keep cost down per camera.

Question 2: Have you seen any gradation's in layering between the sandstone and mudstone on Mars?
At the Curiosity rover site in Gale crater, we have seen abrupt contacts between sandstones and mudstones, such as the erosional unconformity described by Watkins et al. (2016; http://www.hou.usra.edu/meetings/lpsc2016/pdf/2939.pdf), we have seen sandstones interbedded with mudstones (e.g., http://dx.doi.org/10.1130/abs/2016AM-283972), and we have seen some examples that might be nice transitions, fining upward, mudstone to sandstone, such as at the Salsberry Peak outcrop (http://www.hou.usra.edu/meetings/lpsc2017/pdf/1523.pdf).

Question 1: Why is the erosion of units slowing down on Mars in recent years versus past years' rates?
The slowing of erosion rate is hypothesized, based on an array of observations that go all the way back to the initial global imaging investigations from the Mariner 9 orbiter mission in 1972. This is connected with the same lines of reasoning that fluvial processes used to occur, long ago, forming various forms of channels and valleys. I have referenced some papers about this, above in this document, but the literature is actually quite vast, going back to even before 1972. Basically, the slower erosion rate is connected with the loss of atmosphere (and thus, reduced atmospheric pressure) as a function of time. And much of that loss likely happened early, during the first 1.5 billion years of the planet's history. As atmospheric pressure declined, liquid water was less likely to occur at the surface and erode the landscape, winds were less vigorous in their alteration of landscapes, and so forth. This is, of course, a gradualist view of Mars; there may have been "peaks and valleys" in erosion rate as the atmosphere also responded to changes in the planet's obliquity and to large impact events, volcanic eruptions, etc.

Question 2: Why are the younger rocks more resistant to erosion than the older rocks? Does time affect how cemented the rocks become, and if so why wouldn't the older rocks be more resistant?
This question is a generalization of a specific example I showed (and is repeated in the document, above) in "slide" 12 of the Colloquium talk, in which a specific lava flow surface was younger than the rock and terrain it embays, yet this lava flow was more heavily cratered than the older rock unit – that is, cratered with < 1 km diameter craters – because of its resistance to erosion. However, the concept is not fully generalizable… younger rocks are not always more resistant to erosion than older rocks, nor are younger rocks always better at retain meter- to decameter-scale impact craters. The point being made was that, for these small impact craters, the ability of a given rock unit to resist erosion is so important that its "crater population" is not capable of telling us about relative or absolute age… Crater retention is actually a complext interplay of how large the craters are, how resistant the target rock is to erosion, how long the surface was exposed such that craters could form in it, whether that surface was buried and exhumed (and how many times), and so forth. The issue of crater retention has led to much confusion, especially for surfaces that actually do not retain craters, about the age of those units, over the decades between Mariner 9 (1972) and the early days of the Mars Reconnaissance

Orbiter (2006)… the issue has become clearer to Mars geoscience investigators over the past decade, but there are still new things, like I showed in my Colloquium presentation, that people are still realizing – in part as a result of the particulars of the Gale crater field site investigated by the Curiosity rover for the past 4.5 years, and in part because of the > 99.1 % coverage of Mars at 6 m per pixel achieved by the MRO Context Camera over the past decade (with much of that progress also having occurred over the last 5 years).

Question 1: In regards to the cementation of the lithified sandstones and conglomerates that were found, What does that tell us about the chemical composition of the water that once flowed?
This is a great question and still under investigation. A very important question, which has been hard to chip away at, is the composition of the cement and how the cement is emplaced. This has been, in part, a major research objective of Kirsten Siebach…see, for example, this recently published paper: http://dx.doi.org/10.1002/2016JE005195 and this recent extended abstract: http://www.hou.usra.edu/meetings/lpsc2017/pdf/2499.pdf. She is not the only one working on this topic, of course, but when I have a question about the cement in sandstones observed by Curiosity, she is the first person I talk to.

Question 2: Is the reason for the sedimentary rocks not retaining craters as well as the lava flows, because that the sandstone is more susceptible to weathering, or is this observation being used to deduce a difference in age between the rock types?
The canonical examples of Mars sedimentary rocks, since the initial publication that laid out the case that they exist (http://dx.doi.org/10.1126/science.290.5498.1927) and through the overview/summaries on this subject published in the first half of the present decade (http://dx.doi.org/10.2110/pec.12.102.0001 and Chapter 2 of http://dx.doi.org/10.7907/Z9FN144M), is that they are light-toned and relatively uncratered (no small craters or just a few, eroded, small craters). This was taken as evidence that the rocks are relatively easy to erode… friable rocks, rocks made up of small grains that eroded out and blow away in the wind, etc. Of course, as shown in my Colloquium talk – for example, the surface that Curiosity's heat shield landed on – we now know there are some sedimentary rocks exposed at the Martian surface that retain small impact craters as well as do lava flows… that they are much more resistant to erosion. This simply wasn't obvious or recognized before Curiosity landed (e.g., as described in https://gsa.confex.com/gsa/2014AM/finalprogram/abstract_244787.htm).

Question 1: What other areas might you study in the future? Is it expected that these other areas will contain predominantly the same sedimentary rocks?
By "you," I am not sure whether to assume the question is about me, personally, or about the collective "you" of the Mars science community, or perhaps a specific science team such as the Curiosity rover team.

For the Curiosity rover team, the plan is to continue driving up through (and studying) strata exposed on the lower north flank of Aeolis Mons (also known as Mt. Sharp). We have been, and will continue to see, different layers of sedimentary rock that mark changes and transitions in the recorded environment. Since mid-2016, we have been driving up through recessive strata of the Murray formation, which is dominated by rocks of grain sizes smaller than coarse silt (called "mudstone" though the term "mud" does not necessarily mean "wet")… some of the rocks are a bit coarser; we have seen some of them are very fine to fine sand sandstones. Eventually the stratigraphy will give way to a unit thought to be more "rich" in clay minerals and then to a thick package of sulfate-bearing rocks. There are a lot of papers that cover these topics, of what we expect to find, based on orbiter as well as rover remote observations. Some of the essence was captured in the pre-launch paper about the Curiosity mission (http://dx.doi.org/10.1007/s11214-012-9892-2) and this more recent summary (http://dx.doi.org/10.1029/2016EO043009).

As for the broader Mars scientific community, much attention, right now, is on where the next big Mars rovers will go… one from NASA and one from ESA. If the landing sites are not places that previous missions have been (e.g., one candidate site involves a return to the Spirit rover field site in Gusev crater), then we'll see new rocks. In this Q&A document, above, I gave a link to an article about the short list (now 3) of candidate landing sites for the NASA Mars 2020 rover mission. One can search online for the current list for the ESA ExoMars Rover mission… some good sites were in contention for that mission, as well. Also, there is the Mars Exploration Program Analysis Group (MEPAG), which meets periodically and discusses the goals and objectives for Mars Exploration, including sample return initiatives, humans-to-Mars efforts, and the big-picture science, which includes what rocks to go study and sample. Their web site is here: https://mepag.nasa.gov and their Goals and Objectives documents are here: https://mepag.nasa.gov/reports.cfm?expand=science

Question 2: Or are there other types of rocks that are predicted to be found and what might those types of rocks suggest about Mars history?
Yes. I would not say, so much, "predicted," as "interpreted"… i.e., there is a lot of data from orbiter instruments, such as infrared spectroscopy experiments, which provide clues as to what rocks are present – at least, those that are not obscured by mantles of dust. There are clay-mineral-bearing rocks, sulfate-mineral-bearing rocks, chloride-bearing rocks or materials, rocks of various igneous varieties, and so forth. The literature is vast; there are good entry points at ASU SESE into this topic through the work being done with Mars orbiting missions, Mars rover missions, and Mars meteorite investigations.

Question 1: What causes exhumation on Mars if there isn't plate tectonics?
This is a great question that I think about all the time. I can't think of a specific paper to point to about, this, either, though there might be one. Hynek and Phillips (2001; http://dx.doi.org/10.1130/0091-7613(2001)029<0407:EFEDOT>2.0.CO;2) touch upon it, a bit. I think one part of the exhumation story is that Mars has not been without tectonism. Known since the Mariner 9 orbiter investigation in 1971-1972 is that the Tharsis region, which has some of the really big volcanoes, is a huge "bulge" in the planet. The processes which created the bulge also created low "troughs" to the east and west and perhaps warped the Martian crust globally… so think of large scale intracratonic warping on Earth and scale it to Mars… perhaps. Another aspect of exhumation would be the processes that expose buried rock to the atmosphere such that formerly-buried materials of poor erosion resistance are removed (e.g., by wind), causing

undermining and collapse if they are capped/covered by more resistant material. Some of that exposure could be tectonic (I think this is a contributor to the widening of the Valles Marineris, for example), some could be impact-induced (impact cratering changes topography and redisributes material). My answer, here, is incomplete because this is an open area of study and investigation.

Question 2: What are the mineralogical differences between lava flows you cataloged and what implications does that have for erosion resistance?
I will have to assume, here, that "you" does not refer to me, personally, as I have not caloged the mineralogical composition of lava flows. In fact, answering this question is challenging and complex because the collective Mars sceince community does not have all the answers. Most of the volcanic terrains, the lava flows, on Mars are mantled with eolian dust, such that orbiter remote sensing instruments (particulary near- and thermal-infrared) cannot address the lava composition because of the obscuring dust. There is a whole body of literature on this topic, of course, and much of it generated from the Mars Global Surveyor Thermal Emission Spectrometer (TES) and Mars Odyssey Thermal Emission Imaging System (THEMIS) investigations operated by Prof. Phil Christenenen at ASU SESE. So I would recommend looking at their research. Other information about lava flow composition comes from measurements made on the ground, of basalt boulders/etc. weathered/eroded from lavas in Gusev crater by the Spirit rover team, and from Mars meteorites (some of which investigated at ASU SESE). Regarding implications for erosion resistance, Mars lava flows were generally (mostly) fairly fluid – we know from their morphology, which goes back to research also performed at ASU under the late Prof. Ron Greeley. These fluid lavas may have included ultramafic as well as mafic varieties – generally basalts… there were also more silicic lavas, here and there, perhaps, based on a variety of observations (see recent Sautter et al. paper for which I gave the DOI link, above in this document). Basalt and basalt-like rocks are fairly resistant to erosion on Earth, let alone the drier, colder, Mars.

Question 1: Could the study of soil, rock, and other geological aspects of mars tell us if there was anything special in the martian water or its composition? and possibly what definitively happened to mars that made it the dead planet it is?
Yes, and there is a whole bunch of scientific literature on this (too many to cite here)… There is water adsorbed to regolith particles and eolian dust, water inside rocks an minerals, water in the atmosphere, water in the middle and high latitude ices. These all contribute to our understandign of the history of water on Mars and the Martian atmosphere (e.g., D to H ratio in water contributes to understanding atmospheric loss with time). I recommend caution about the word, dead, though… dead implies life (organism) and we do not know whether Mars ever had life nor, if it did, whether any organisms survive to this day. Dead is a word that implies absence of life where life was once present. Alternatively, dead might refer to inactivity… e.g., the absence of volcanic and tectonic activity… and this, too, has some unknowns attached to it… i.e., by way of crater retention age studies, some volcanic surfaces on Mars have been proposed to be only a few million to a few tens of millions of years old… this would imply Mars had magmatic activity over most of its 4.5 billion year history, and that such magmas could still exist today. We still don't know everything ☺.

Question 2: Could permafrost in the polar regions of mars contain anything of importance geologically to the story of mars? could it show us a frozen snapshot of the soil and morphology over time?
Yes. And the Phoenix lander in 2008 dug into the regolith at a high northern latitude and hit ice right away. So you could review the papers that came out of that mission to see what was learned. Certainly, there is much more one could learn, especially about relatively recent climates and climate changes on Mars, by investigating the ice record (e.g., ice cores) in subsurfaces ices at middle and high latitudes or exposed at the surface in th polar regions. In the south polar region, the ice record includes frozen carbon dioxide. There is a workshop that occurs every few years in which Mars scientists gather to discuss results and plan future possible investigations (e.g., landers, rovers) for the polar regions and the record of climate in these materials. The most recent one was held in September 2016 (http://www.hou.usra.edu/meetings/marspolar2016/)… you can look at the extended abstracts from that meeting and also go look at the special issues of journals published from the previous workshops in this series… they go back to about 2000 or 2001.

Question 1: How was the age of Gale crater determined?
Time machine. No. I wish.
The best attempts were made using crater counts (diameter and number per unit area) on what is thought to be the remains of Gale's ejecta blanket. The work is detailed in papers by Thomson et al (2011; http://dx.doi.org/10.1016/j.icarus.2011.05.002) and Le Deit (2013; http://dx.doi.org/10.1002/2012JE004322). They did the best that anyone can really hope to do, short of careful field work, sampling, and lab analysis. Now, their basic conclusions about when the Gale impact event occurred was bolstered by the determination of a bulk age for sediment deposited in a mudstone drilled by Curiosity… that bulk age of about 4.0 billion years is older than the age estimated for Gale crater (roughly 3.6 to 3.8 billion)… that work was laid out by Farley et al. (2014 http://dx.doi.org/10.1126/science.1247166) and is a big deal because it was the first time one could really try do get an age for something on Mars.

Question 2: What are the chemical differences between sediments from Mars than those found on Earth?
This is a great question with a vast answer and much literature that could be cited. Having said that, I'll boil it way down, here… and you can go look at the literature for details. A key difference is that the Martian crust is generally mafic (some would say "basaltic") while on Earth we have a continental crust that is more "sialic" or "felsic". Sure, we have a basaltic oceanic crust, too, but much of the subaerial creation of sediment occurs in continental rocks. So, it is fairly common on Earth, after chemical weathering--in particular--has has done its thing, that what survives, in bulk, is the most abundant chemically resistant mineral, quartz. So a lot of clastic rocks on Earth, such as sandstones and siltstones, are quartz-rich. This is not the case on Mars. Also, all those other rock-forming silicates… the olivines, pyroxenes, and feldspars… on wetter Earth, they weather to clay, clay transports to lakes, seas, and oceans, and we find these clays (and quartz silts) in mudstones (shales). On Mars, there is certainly clay, but the weathering has been less vigorous and we have actually found feldspars and pyroxenes preseved

in the mudstones we have examined at the Curiosity rover field site; these seem to have been preserved for more than 3 billion years. Again, I am really boiling this down. Another major difference is that Earth has more biogenic sediment (Mars… does it have any at all?). Limestones and dolomites have not shown up on Mars. There is much more that is known and can be said on this topic; I encourage you to dig into the literture on this.

Question 1: Some people think there could be an ice layer under martian surface, could it be possible to detect it using some of the cameras and radiometers you use and develop?
Subsurface ice, indeed, has been detected by instruments onboard orbiting spacecraft. In particular, the Gamma Ray Spectrometer (GRS) experiment on Mars Odyssey, detects the hydrogen in subsurface ice—this is mostly at high latitudes (60 to 90 degrees latitude). Another key source of information about buried ice comes from radar experiments on Mars Express (instrument called MARSIS) and the Mars Reconnaissance Orbiter (instrument called SHARAD). These look at dielectric constant information to interpret the presence of subsurface ice. Your specific question about using cameras… certainly there is a literture that goes all the way back to the Mariner and Viking missions of the 1960s and 1970s that makes use of specific geomorphic observations (e.g., the nature of impact crater ejecta blankets; the presence of "aprons" and "lineated valley fill" and so forth) to hypothesize or speculate on the presence or former presence of subsurface ice. More recently, thanks to the combined capabilities of the Mars Reconnaissance Orbiter HiRISE camera built by Ball Aerospace and operated at the University of Arizona, and the Mars Reconnaissnce Orbiter Context Camera (CTX) built and operated by my employer, Malin Space Science Systems, we found brand new impact craters forming at middle and high latitudes that are exposing subsurface ice… the first paper on this was published in 2009 (http://dx.doi.org/10.1126/science.1175307)… there have been other papers on this, since then.

Question 2: How similar or different are sedimentary rocks of Mars to Earth sedimentary rocks so we can say the past environment of Mars could have been similar to Earth's?
Some of the similarities and differences in composition are addressed, briefly, I some of my answers to questions above. The more important issue in terms of interpreting past environments is, perhaps, the textural and structural aspects of sedimentary rock units. That is, the physics of sediment transport and deposition operate the same, though "g" (gravity) is different. Sediments transported and deposited in liquid (e.g., water) will create textures and structures familiar to us on Earth, even if the constituent clasts (the grains) differ (e.g., basalt lithic fragments versus quartz sand on Earth). Same is true for eolian (wind) transport and sedimentation, though not only gravity differs but so does atmospheric pressure. There is a vast literature on the topic of sediment transport and deposition on Mars and similarities to Earth… a starting point might be this paper from a few years ago:
Grotzinger J. P., Hayes A. G., Lamb M. P., and McLennan S. M. (2013) Sedimentary processes on Earth, Mars, Titan, and Venus. In *Comparative Climatology of Terrestrial Planets* (S. J. Mackwell et al., eds.), pp. 439–472. Univ. of Arizona, Tucson, DOI:10.2458/azu_uapress_9780816530595-ch18.

So, to get at the question of similarities between past Mars and Earth environments—which I mentioned in the Colloquium talk as being a key reason for an Earth geoscientist to be interested in the Martian sedimentary rock record—the issue is mainly about having an analog, in Mars, for rocks that were not preserved on Earth. That is, Earth has no Hadean sedimentary rock record; even its earliest Archean record is gone. But Mars has preserved a record from those times, a time when the impact cratering rate was high and the planet's crust was young. So, while the chemistry and mineralogy may differ, the types of environments and how they are preserved in rock, on Mars, might give us clues, a flavor, of what early Earth might have been like. It is the only planet available to us (i.e., our inner solar system) that can help us pick away at some of the questions about environments on early Earth, including – on Earth at least – those in which the earliest organisms might have been present.

Question 1: What other methods do you use to determine a volcanic field on mars? besides the ripples.

I am not certain what is meant by "ripples" in the context of identifying a volcanic field. Typically, volcanic landforms on Mars are identified by the presence of vents/edifices and flows. The major volcanic features were identified in images acquired by the imaging instrumentation on Mariner 9 in 1971-1972. Additional, definitive volcanic landforms were not really recognized until Viking orbiter images revealed them (e.g., Syrtis Major region) in 1976-1980. Still others weren't fully recognized until some of the more recent missions, Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter. And, of course, some identifications made, over the years, were wrong, others remain uncertain or speculative. There are also open questions about how to distinguish lava flows from mudflows, how to distinguish pyroclastic deposits (at all), and how to recognize, with certainty, very ancient flows, vents, and edifaces. There is a vast scientific literature on all of this, as well, and not all investigators agree on what is volcanic (except for the most obvious features like Olympus Mons).

Question 2: Is there any better way to observe sedimentary outcrops on mars, other than from meteorite impacts.

I am not certain that I understand the connection being made, in this question, between impact craters and sedimentary rock outcrops. Perhaps this is about the observations presented in the Colloquium talk, about some sedimentary rock outcrops being heavily peppered with small (sub-kilometer diameter) impact craters, while other examples of sedimentary rock are not. But, yes, to interpret anything we see in images from Mars – whether acquired by orbiting, descending, airborne, landed, roving, etc., platforms, requires brining every tool and every observation available, to the effort. There is not one single criterion, alone, by which to distinguish sedimentary rocks from igneous, for example, though some cases may be easier than others. There is so much more that I could write, here, but my best suggestion for a starting point is to look at the seminal paper on Mars sedimentary rocks (http://dx.doi.org/10.1126/science.290.5498.1927)
and the overview/review of the first decade of exploring sedimentary rocks (http://dx.doi.org/10.2110/pec.12.102.0001), and then look at some of the 2014–2017 papers from the Curiosity rover team. As a starting point.

Question 1: Are the sedimentary rocks found on mars similar to sedimentary rocks found on earth?
This question has generally been addressed in answers to similar questions, above/elsewhere in this document. In terms of texture and structure, yes, certainly clastic sedimentary rocks are similar on Earth and Mars because the same basic physics governs sediment transport and deposition. If we were to find chemical sediments (e.g., evaporites), they, too, would be similar. The key differences are in composition (more mafic or "basaltic" on Mars than Earth; little to now limestone and dolomite) and biogenicity or influence of biology on texture and structure (e.g., no sediments made of body parts like shells and corals; no bioturbation structures). Now, the latter, about biogenicity, who know, maybe one day we'll find something like that. I would read through answers to similar questions in this document for a more complete answer; thanks.

Question 2: Do you think the WATSON will bring any new information or just further the conclusions you reached with the MAHLI images? If so, what kind of new information are you expecting?
WATSON is a build-to-print copy of the MSL MAHLI camera that will be onboard NASA's Mars-2020 rover. It is part of the SHERLOC instrument package. A recent description and illustration of SHERLOC and WATSON is in this 2017 extended abstract:
http://www.hou.usra.edu/meetings/lpsc2017/pdf/2839.pdf

WATSON is capable of the full range of types of observations that MAHLI can and currently does make on Mars (see, for example, http://dx.doi.org/10.5194/gi-5-205-2016).

The Mars 2020 rover site is likely to not be the same site as for Curiosity – i.e., not Gale crater. Thus, WATSON will be capable of the same kinds of observations as MAHLI, but will be observing different rocks, regolith, and eolian sediments, somewhere else on Mars. So, everything will be new. As for what new information is expected, that will be easier to answer when we know where it will land. Right now there are 3 sites in contention, as described in this February 2017 article: http://dx.doi.org/10.1038/nature.2017.21470.

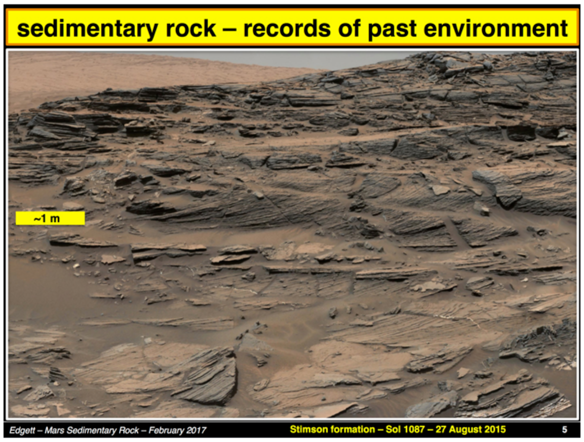
Question 1: Mr. Edgett discussed minerals commonly seen on Mars. Are there any unexpected minerals that have been found? If so, why were they unexpected?
Yes. Perhaps the most unexpected mineral, that comes readily to mind, is tridymite. This was found in a mudstone sample at the Curiosity rover site in Gale crater. There is a publication from 2016 that describes the find and what it might mean: http://dx.doi.org/10.1073/pnas.1607098113. Tridymite is a form of SiO_2 (as is quartz) that forms at low pressure and high temperature.

Question 2: I have always been fascinated with sand dunes, and the images I've seen of sand dunes on Mars are beautiful. Is there anything different, as far as we know, about the sand dunes on Mars comapred to sand dunes on Earth? At what rate do we think sand dunes are forming on Mars?

The thing most different about the dunes on Mars is probably their composition… that many of them, in bulk, are mafic ("basaltic") while, on Earth, examples of basalt sand dunes are fairly rare (an old reference, which I wrote as a student at ASU, talks about this: http://dx.doi.org/10.1006/jare.1993.1061 but I am certain this overview could use some updating based on the greater volume of scientific literature and knowledge available today (e.g., that old paper is sparse on examples that might perhaps occur in Africa, South America, continental Asia, etc.). The general morphology of dunes is similar (see my answers to other questions about the dunes on Mars vs. Earth elsewhere in this document) but there are some recent observations of features which seem to differ (see 2016 paper http://dx.doi.org/10.1126/science.aaf3206 for example). There is also a literature (several papers) on the rates at which dunes are moving. The changes in ripple positions and orientations, and so forth (you'll have look them up). Every few years, there is a workshop about dunes on other words; this year it is in St. George, Utah, in May 2017 (http://www.hou.usra.edu/meetings/dunes2017/). This would be a great meeting to attend and come up to speed and talk with some of the researchers who are active in this field.

Question 1: One of the first slides in your presentation was of a pillow basalt ridge sort of peeking out of sand. At first glance, I thought I was looking at cross bedding of lithified sand dunes. Is cross-bedded sandstone one of the types of sedimentary rocks we could see on Mars, or am I way off?

I am not certain which "slide" is referred to, here, but it might be "slide" #5, early in the presentation, shown here:


sedimentary rock – records of past environment

Edgett – Mars Sedimentary Rock – February 2017

Stimson formation – Sol 1087 – 27 August 2015

5

And this is indeed a picture of a cross-bedded, mafic (a.k.a. basaltic) eolian sandstone. I am not certain why there might have been an impression that the image shows pillow basalts. The rock unit in which this eolian sandstone occurs is discussed in this 2017 extended abstract by Banham et al.-- http://www.hou.usra.edu/meetings/lpsc2017/pdf/2014.pdf

Question 2: I realize this lecture was about the sedimentary record on Mars but I was wondering if there is any evidence of metamorphism of the sedimentary rocks?

I am not aware of a specific example of a Martian metamorphic rock, but it is possible I've missed something in all of the literature generated over the past two decades (for example, analysis of meteorites from Mars. That said, I would certainly not be surprised if, someday, our surface explorations turn up examples of contact metamorphism (magma interaction with country rock).

Question 1: How can we apply the knowledge that has been gained, over the last decade and a half of martian sedimentary environments, to other planetary bodies besides our own?
Certainly. See, for example, the Grotzinger et al. (2013) chapter in a Univ of Arizona publication, cited above. Each world differs, but the laws of physics and chemistry are the same everywhere, so these other worlds (Venus and Titan, for example) offer "natural laboratories" in which to explore how the processes (sediment genesis, transport, deposition, diagenesis, etc.) are similar or different from one place to the next. Titan is a spectacular world to consider, as it rains, there are rivers and lakes, but the liquid is not water and the clasts are, more likely than not, pieces of ice.

Question 2: How can the remains of various sedimentary rocks and features on Mars help us to reconstruct what the surface of Mars may have looked like in the distant past?
I think that the short answer might be "the same way we are able to do so for Earth." For example, consider the awesome map reconstructions of the environments recorded in the Colorado Plateau (North America) rock record by Ron Blakey (e.g. https://www2.nau.edu/rcb7/) and the related work for the whole Earth (e.g. https://deeptimemaps.com). To do a similar body of work for Mars might require much more field work to be done on Mars, of course. ☺

Question 1: In how many years Ken Edgett sacrifice his life in Mars sedimentology?
I am not certain what is being asked ☺. I don't think "sacrifice" is quite the right word. I have been studying Mars geology and geomorphology since a summer internship I did in 1986, so, by one measure, I have devoted much of the last 31 years to the study of Mars. Much of that work has, indeed, been on sedimentology, from my work as a student at ASU on Martian sand dunes to my present work on the sedimentary rocks observed both from orbiting and roving cameras.

Question 2: Is it possible the studying of Mars rocks and surface will appear for us if their was life on Mars or still from any kind of creatures or even plants or bacteria?
Indeed. The search for evidence of past or present life on Mars is a key motivator for its continuing exploration. The Curiosity mission is focused on looking for records (in rock stratigraphy) of environments that might have been habitable in the distant past. It also has instrumentation that can detect organic molecules that are in the rocks and minerals that the rover samples. The European Space Agency's (ESA) Trace Gas Orbiter, which reached Mars in October 2016, has instruments to look for trace amounts of gas in the atmosphere that could be suggestive of biological activity (e.g. methane). The ESA ExoMars rover and NASA Mars-2020 rover, both now planned for a 2020 launch, both have a more focused interest in seeking potential or actual biosignatures in rocks and regolith. The goals for the biological exploration of Mars are captured in the MEPAG documents I mentioned above (https://mepag.nasa.gov/reports.cfm?expand=science), as well.

Question 1: Has the sandstone that's been discovered by Opportunity differed in formation? Compaction Vs Cementation.

There are many differences between the sandstones observed by the team operating the Opportunity rover versus the Curiosity rover, including the questions of cement, compaction, etc. To date, there isn't a publication which compares the sandstones from the two sites, and many of the sandstone observations from the Curiosity site haven't been written into papers (the analysis and discovery effort is still on-going). But there are some papers and abstracts on sandstones at both sites. Speaking very generally, the sandstones at the Opportunity site were more sulfate-rich, lighter in tone, and were mostly (but not exclusively) eolian (eolian as interpreted by the rover team; there are differing interpretations published by others). At the Curiosity site, the team interpretations include sandstones deposited in fluvial, deltatic, lacustrine, and eolian settings, and there is a wider variety of sandstones in terms of sorting, grain size, compostion, etc. A lot of the research is still on-going.

Question 2: Do you think that the cementation that occurs in the sandstone comes from silica cement, or is there another mineral that can fill this void, as hematite and Calcium are in low abundance.

Excellent question, about the cements in the sandstones… I'll assume we're talking about the Curiosity field site in Gale crater because I am less familiar with the sandstones at the Opportunity site. The issue of cements came up in one of the other student questions in this document, and I suggested taking a look at the recent papers and extended abstracts by Kirsten Siebach as a starting point. It is, thus far, not looking like the cement is silica, and usually not something connected with calcium (carbonate or sulfate), though there are some pore-filling Ca-sulfates in some cases. This issue is an interesting and challenging one that folks are working on.

Question 1: Since the robot with MAHLI since 2012, is there a chance that errors could have happened and affect the result?

I am not certain what this question is asking. Errors induced by what?

Question 2: What are the challenges do you think you guys will face in the future?

I am not certain who is referred to by "you guys". There are many challenges, on many fronts… aging spacecraft at Mars, building new spacecraft heading for Mars, funding, time to actally do data analysis and report on results, all kinds of ~~challenges~~, er, fun. ☺

Question 1: Can MAHLI be used as a precursor for imaging on other planets such as Titan?

The MAHLI is a small, focusable camera on the end of the Curiosity rover robotic arm; it can focus on targets as close as 21 mm out to infinity; it's close-up images are of a scale in the range of 14 to 100 microns per pixel. A copy of MAHLI, called WATSON, is being built right now to go on the robotic arm of the Mars 2020 rover.

I am not certain about the context of the term, precusor, in this context. To me, a precursor in planetary missions is usually a word we would use to describe fly-by or orbiter missions that eventually help support (either via the data they collect, the data they can relay, or both) landed missions, including mobile platforms like rovers.

That said, yes, indeed, a camera like MAHLI would be great for a landed mission, of one type or another (mobile or fixed) to Titan. The design would have to be somewhat different, though, because the Titan surface environment (or sub-liquid environment if we're talking about a submersible for one of the lakes, for example) is so different from Mars. For one thing, it is much colder. For another, there is rain, there is "humidity"… the camera lens and mechanisms would have to be able to deal with those environments. Then there is also the possibility that some of the surface materials, containing organic molecules, could be gooey or something. Titan certainly would post interesting design challenges for instruments like MAHLI, which are intended to operate for a long time on the surface (or sub-lake environment). What a cool mission it would be, though, right?

Question 2: Since I began astrophysics all the hype has been focused on Mars. But year after year no findings have resulted in the declaration of life or panspermia from Mars. Yet, we still send highly regarded technological achievements, such as MAHLI, and invest millions in Mars exploration. What is the end game?
This is a great question. For the past two decades (and so it might also be the case in the coming decade), NASA's planetary science exploration has been largely governed by a document called the Decadal Survey. The second, most recent one came out in 2013 (https://solarsystem.nasa.gov/2013decadal/) and represents a vast survey of the science priorities established by practicing, professional planetary scientists. In this report, which NASA is using as guidance for their current program, some of the highest priority is given to the on-going search for life on Mars but also on "ocean worlds," particularly Europa and Enceladus. This kind of survey and prioritization effort will start up again, soon, for the next decade, and is subject to adjustment as the science community's knowledge and understanding continues to shift with new research and results.

In that 2013 Decadal Survey, the thinking for an "end game" for life on Mars was to prioritize returning samples from Mars, to Earth, for which a case can be made that they might contain evidence of biosignatures. The Mars 2020 rover mission puts the Mars program on a path to do that job, but it is only focused on collecting the samples. A whole other mission would have to be funded to retrieve the samples and bring them to Earth, and then a whole other effort would have to occur, on Earth, to curate and study the samples. Those later steps are not currently funded. Meanwhile the Decadal Survey also considered the question of life on Europa, and in the last couple years NASA has been gearing up for a more intense examination of Europa via a Jupiter-orbiting spacecraft that would fly by Europa many times (like Cassini does for Saturn's moons) as well as a mission to land on Europa and seek signs of life (the Science Definition Team report on the lander concept just came out a few weeks ago:
http://solarsystem.nasa.gov/docs/Europa_Lander_SDT_Report_2016.pdf

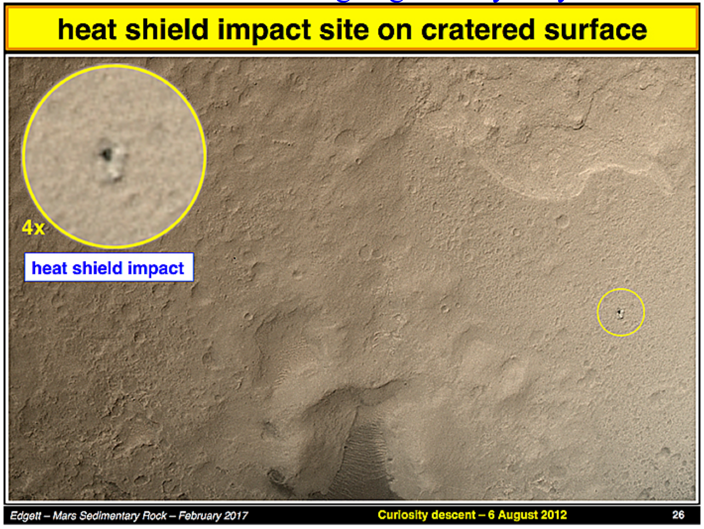
At the same time, there are mission concepts, studies, and proposals in the works for missions to other worlds that seem promising for life, such as Enceladus and perhaps Titan. And, of course, there are science efforts underway and in development to seek evidence of life on worlds orbiting other stars.

One thing to understand about why so many missions have focused on Mars is that Mars is relatively close to Earth and relatively less expensive to get to, with a given single spacecraft. It is actually possible to start from nothing and have a mission orbiting Mars or operating the the Martian surface within a period of less than a decade. A variety of strategies have resulted in fairly inexpensive Mars missions (India's Mars orbiter, for example), missions that can go to multiple places on the surface, missions that can follow up on the results of a previous mission (Phoenix landed to get a look at ice detected using the Gamma Ray Spectrometer on Mars Odyssey… we went from discovery to surface confirmation in less than 10 years). Mars is a place where these multiple-missions can occur in a decade, can occur over the course of a person's career. By comparision, Cassini is the only mission to the Saturn system since the Voyager flybys in the early 1980s. The Cassini Project started in the late 1980s and didn't get to Saturn until the mid-2000s. These outer solar system missions take longer, the spacecraft typcially carry many instruments because the opportunity to get a spacecraft out there are few and far between. The Europa missions now being developed may get us some data in the late 2020s, and the people working on this missions did study after study after study since the 1990s before some funding finally was put in place. So, outer solar system missions span much longer periods of time to get spun up to the point where the spacecraft and instruments are being built, and then to get to the actual destination. In general, you might say we could just do fewer Mars missions, but it is not obvious that this would increase the number of missions to other worlds. On top of all of this, there is the fact that reaching Mars has now become "easy enough" that smaller countries (e.g., United Arab Emirates) and even private companies (e.g., SpaceX) are working toward launching missions to Mars.

It is not clear that there really is an "end game" for Mars. It is the most habitable place in our solar system for humans (sure, you'd have an easier time colonizing Antarctica or making the Sahara bloom), so there is a sense of inevitability that people will eventually go and live there… perhaps. Separate from the search for life on other worlds or the inherently interesting geologic history (to me) of Mars, there is always that possibility that people may eventually be living there. Doesn't mean it will happen, but it could.

Question 1: In the picture of the rover descending to mars you talked about the shield being dropped first. We could see an image of this object crashing into the surface before the lander touched down. In the image we see a plume of sand-like ejecta moving out around the crashed object. You said that this rock type could actually be from lava flow and would be much harder than something like sandstone, so why are we seeing such a uniform and sand-like ejecta from lava flow?

The question refers to "slide" 26 in the presentation, shown below. Curiosity's heat shield landed on a rock unit heavily peppered with small (meter- and decameter-scale) impact craters. Before Curiosity landed, the "conventional wisdom" about Mars was that a surface like this was likely to be composed of lava, on the basis of its ability to retain these small craters (i.e., erosion resistance). It turns out, when the rover drove there and took a look, that the rock is actually a well-cemented sandstone. That said, the plume that came up when the heat shield hit the ground was not an indicator of the bedrock property, this was dust that had been deposited on top of the rock… such dust was readily seen when the rover was driven to the edge of this rock unit, too (“slide” 28 in the presentation). Generally, this part of the rover field site in Gale showed a dark gray sandstone bedrock that was coated with dust that had settled from the atmosphere, before Curiosity and its heat shield arrived. The coating is generally only a millimeter, or so, thick.



heat shield impact site on cratered surface

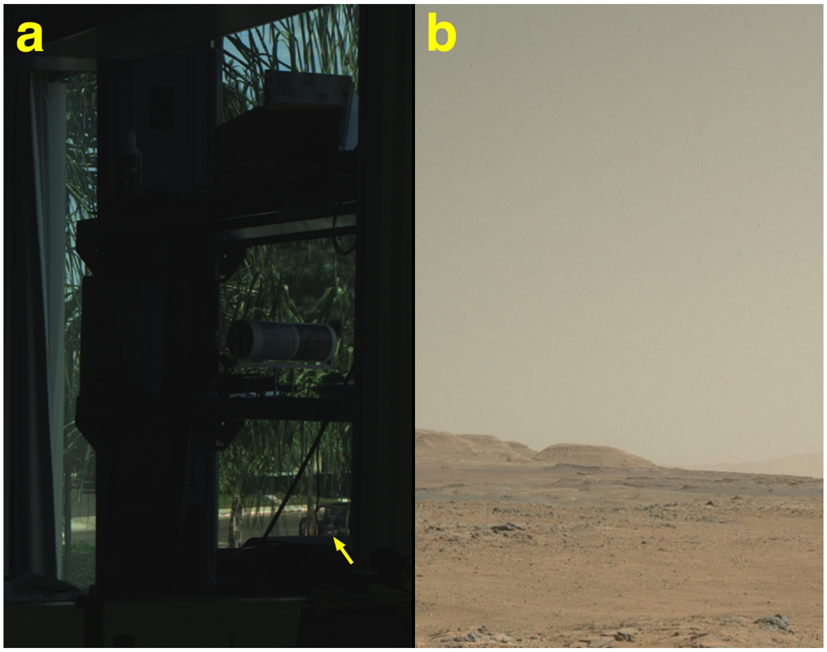
Edgett – Mars Sedimentary Rock – February 2017
Curiosity descent – 6 August 2012
26

Question 2: To know the true color of images we are taking would we need something of known color to compare it to that is measured on earth? How are you able to false color an image to make it look like the planet is the same distance to the sun as Earth, and has Earth's atmosphere? Are you approximating this, or is the calibration and adjustment done in a precise manner? If so, could you explain this exact process?
To dig into the issues of true color and false color, I recommend looking at the papers by ASU SESE Professor Jim Bell, particularly about the Spirit and Opporutnity Pancam experiments and papers from Mars Pathfinder by Justin Maki of JPL. There are other relevant papers, of course. Honestly, ASU SESE has this question covered; Jim Bell is your resident expert.

That said, there are several schools of thought regarding what “true color” means, at least, in my opinion (which could be wrong). For example, go outside on a sunny day and look at some nice, green grass. Now look that same grass in shadow (shadow of a tree, your own shadow, etc.). What color is the grass? What is the “true color” of the grass? This question gets into issues of illumination source (sun, lamps, etc.), incidence angle, influence of scattering elements in the atmosphere (dust, fog, clouds, etc.), etc. One approach to dealing with these issues is to consider white balance… digital cameras have ways to set white balance for different illumination conditions… for example, if you are in a room with fluourescent lights, your eye/brain is typically performing a white balance and you probably don’t even realize it… if you take a picture with a digital camera, in that room, things will seem to have a greenish cast; but your eye (for most people) isn’t noticing this… the brain is doing a white balance. You can also do a white balance on that digital camera image, either by selecting an appropriate setting programmed into the camera, or by doing it after the fact using image processing software.

In essence, the “make it look like the planet is the same distance to the sun as Earth, and has Earth’s atmosphere” thing that I was talking about during the Q&A session after my Colloquium talk was refering to this concept of white balance, using software to adjust for Mars illumination conditions such that the scene would look as if it were viewed on a sunny day on Earth. Doing so has some science advantage by permitting a more direct comparison of the rocks and dirt with those that we are familiar with on Earth.

And, yes, there are calibration techiques, in which the cameras (look up the Jim Bell calibration papers for Pancam, for example) take pictures of well-characterized color and gray materials brought from Earth to Mars, these can be used to adjust the images to approach “true color”.



One thing that helps, on the Curiosity rover, is that the color cameras use Bayer Pattern microfiltered CCD detectors. You can search online to see what a Bayer pattern is and does. The intent of this Kodak invention was to be able to acquire digital camera images that show a scene in colors that are similar to what the typical human eye can see. Thus, even without any image processing, except a standard color interpolation to accommodate the Bayer pattern, Curiosity’s color cameras, on Mars, more or less show what your eye would see (except if your brain does an unconcious white balance, like it does in a fluorescent-lit room). For example, the figure, above, shows portions of two pictures from Curiosity’s MAHLI camera. Neither has been processed. What you see in the Earth picture are a blue sky, green plants, a black parking lot, etc., and what you see on Mars is what you’d see on Mars (arrow points to a vehicle in the parking lot). This is from the MAHLI Calibration Report: (http://pds-imaging.jpl.nasa.gov/data/msl/MSLMHL_0013/DOCUMENT/MAHLI_TECH_REPT_0001.PDF).

I hope this answer helps, somewhat. You really do have the world’s expert, at ASU SESE, if you want to know more.

Question 1: What evidence do we have about the evolution of the stream channels that eroded the surface sedimentary structures?
I am not certain that I understand what is being asked. There have been all kinds of research efforts, summarized in the scientific literature, going all the way back to the discovery of channels on Mars in Mariner 9 images in 1972. There are papers about the evolution of landscapes, over time, as a function of how much of the erosion was caused by runoff, streams, etc. There are also papers about specific landforms and features that involved fluvial erosion and sediment transport and deposition, such as the "fossil delta" in Eberswalde crater (e.g., see this paper by Leslie Wood: http://dx.doi.org/10.1130/B25822.1 as just one example). I hope this answer is helpful.

Question 2: Were there enough sampling locations to allow for an accurate interpretation of the sedimentary geology of Mars? Or are we assuming Mars is less dynamic than Earth and thus can assume a model based off of only a handful of locations?
I am not certain how to answer this question. Spacecraft have only landed, succesfully, in seven locations, only four of those had rovers, and only two of those examined rocks for which there is agreement that sedimentary rocks were present. The areas explored, on the ground, are fairly limted. Then there the observations made by orbiting instruments; for sedimentary rocks, most relevant are cameras and infrared spectroscopy instruments… together, these have provided an array observations at different scales, some of which address sedimentary rock occurrences, physical properties, and structures; others of which address some aspects of mineral composition. Elsewhere in this document I have given links to some of the relevant overview papers.

As for "assuming"… I try not to assume. In my Mars work, especially at the start of the Mars Global Surveyor Mars Orbiter Camera investigation, when we were seeing our first very high resolution views of the planet from orbit, I learned very quickly that all our collective and individual scientific assumptions about Mars were wrong, and then I found that we (the science community) also make a lot of hidden assumptions. I tried to learn to ferret those hidden assumptions out, too. The key is to dump all assumptions and start fresh, really look at the data (e.g., images) and see what Mars is trying to tell us… and be careful not to build an interpretive house of cards on top of someone else's previous house of cards. It's actually quite challeging to do this well.

Honestly, there is so much we still do not know, still have not observed, regarding the Martian rock record. I think, like what occurred on Earth, it will take a few hundred years and a few thousand (or more) geologists with boots-on-the-ground and great lab equipment to do the full-up story.

Question 1: Has a rover ever visited the large fluvial features to verify the sedimentary lithology, and if so are there any sedimentary structures present?
A set of inclined (clinoform) sandstone beds examined by the Curiosity rover team at a field site called Kimberley is perhaps the closest example to what you ask (see http://dx.doi.org/10.1126/science.aac7575). These were interpreted as the result of small deltas at a stream/lake interface. Eventually, as it continues to drive up the lower flanks of Aeolis Mons (also known as Mt. Sharp), the Curiosity rover team will examine a huge channel in a canyon that runs down the side of the mountain (e.g., see this paper by Fraeman et al. 2016 – http://dx.doi.org/10.1002/2016JE005095).

Question 2: Are there any hypotheses as to how a dune field could be so perfectly preserved and llithified? Although ripples are often preserved in the rock record, I'm not sure I've ever seen an entire dunefield surface, preserved so well.
I don't think anyone has given much thought to how this dune field ("slides" 16-18 in my presentation) became buried and lithified and then exhumed in such a manner that it still looks like a dune field… except me. I suspect burial had to be quite rapid so that the eolian sands could not react, could not blow away. I could be wrong. One rapid burial mechanism might be deposition of a thick covering of tephra (volcanism) or dust/fines from an impact cratering event. There is an amazing basalt(!) sand dune field near Moses Lake, Washington (http://dx.doi.org/10.1029/2000JE001469) that got covered by several centimeters of ash from the big May 1980 eruption of Mt. St. Helens. The sands eventually "dug themselves out"… I wish someone had documented exactly what happened to get the sand out from under the fine tephra, but some things that might have contributed do not occur on Mars… rain and water runoff, bugs and small animals digging, and plants that can blow in the wind and locally scrape away the ash (or grow up through it, disrupting it).

There are some examples on Earth of dune fields that were more deeply buried and preserved more or less intact. An example occurs in Namibia, where the sands were innunated by lava (http://dx.doi.org/10.1144/jgs.157.3.513).

Question 1: Do sandstone and breccia weather differently on Mars? In what way(s)?
Probably. And how they weather (and erode) will differ depending on the specific properties of the rock. We haven't really encountered a good breccia at the rover sites (well, not at the Curiosity site), but we have definitely seen conglomerates (kind of like a breccia but the clasts more rounded) and their erosional expression, as I showed during the talk, is very different from the various sandstones encountered. The thing is, though, the sandstones don't all whether and erode the same way, either… some are very fine to find sands and erode recessively, some are porous and pebbly sands that are somewhat recessive, some are very well cemented, almost no pore space, and very erosion-resitant (forming cap rocks on buttes and mesas). This is an area of on-going research and discovery, in the context of Mars, that is.

Question 2: What is the breccia composed of?
Martian breccias would be composed of whatever rocks were brecciated and then cemented, and the composition of what is cementing them. The best example Martian breccias are actually the samples that have been found on Earth; they fell to Earth as meteorites in northwest Africa and have been receiving a lot of study, with techniques unavailable on Mars rovers and landers, since they were first announced in 2013. These breccias are amazing because each clast is a piece of some other Mars rock. Example papers:
Agee et al (2013; http://dx.doi.org/10.1126/science.1228858);
Whittmann et al. (2015; http://dx.doi.org/10.1111/maps.12425);
McCubbin et al. (2016; http://dx.doi.org/10.1002/2016JE005143)

Question 1: I'm a primarily an astrophysicist working in instrumentation. I know this has little to do with your talk, but what kind of interesting/unexpected challenges are inherent in designing a camera for use in space?
Great question. I am not entirely certain how to answer it, because you try to design, up-front, to the specific science, engineering, and environment conditions the camera is expected to encounter. For example a mission to Jupiter might have to deal with both the radiation environment (most challenging for observing at Europa, Io, and closer to the planet) and have to deal with the thermal environment at Venus if the cruise to Jupiter involves a Venus flyby. Then, the radiation environment at Jupiter might also be a matter of mission design… orbiting Jupiter in a manner that swings out past Callisto, for example reduces the amount of time spent in the "radiation belts". And so forth. Designing for the Martian surface will differ from desiging for orbit… on the surface, the camera is in an atmosphere, there is dust, wind, sand, etc., and large diurnal temperature variations.

The most "interesting" or "unexpected" challenges typically happen when pushing the frontiers of what the existing technology can do and these efforts are banging up against some constraint such as instrument mass or volume envelope, available money(!!), launch schedule, etc. For deep space missions, you can't go out and repair something if it breaks and you need it to last a long time (whatever the mission duration is supposed to be, plus margin), so you have to rely on parts that are well tested and/or have previous flight heritage (have flown in spacecraft before)… and for something like Jovian radiation environments you may need radiation-hardened or –tolerant parts and materials, and so forth. So, often, one challenge is that you are not using the latest technologies that, say, someone has in their smart phone. Downlink data volumes are also an issue, thus, for example, the Curiosity MAHLI is a 2-megapixel camera instead of the 20-megapixel, or more, that you might wish to fly.

Really, the biggest challenges can occur if requirements change while you are well on your way to building the instrument, or when trying to adapt an existing, heritage instrument to a new environment (for example, MAHLI on Curiosity and WATSON and the Mars2020 rover are identical, but the vibration environments each experiences on the end of their respective robotic arms might differ because the tools which create vibrations, on these arms, are different). Of course, some of the worst challenges happen if an accident occurs. This is why some strategies involve building a flight spare (a copy of the instrument, ready to be swapped out even at the launch pad if necessary); another approach is to have all the spare parts to be able to build a copy, if something goes wrong.

For some examples, some of the challenges that came up during the Mars Observer and Mars Global Surveyor MOC camera development effort are described here: http://dx.doi.org/10.1555/mars.2010.0001.

Question 2: You mentioned in your talk that dust (I think) thinly covers much of the Martian surface. Does this make it difficult to perform, say, spectroscopic observations of the surface in order to determine its composition?
Yes. And at ASU SESE, under Prof. Phil Christensen, you have a group of researchers who have a lot of experience with this fact, through their thermal-infrared remote sensing from orbit (Mars Global Surveyor Thermal Emission Spectrometer; Mars Odyssey Thermal Emission Imaging System) and on the ground (Mars Exploration Rover Mini Thermal Emission Spectrometer). Also you have this experience with visible and very near-IR observing via camera in Prof. Jim Bell's research group. The dust is a real challenge to learning more about the composition of Mars. As you can imagine, there is also dust suspended in the atmosphere.

That said, the good news is that Mars isn't **all** dusty. There are places where the winds are active enough to keep dust from settling, to keep sand moving along. The Curiosity rover is presently (Feb 2017) in such a place, a corridor of sand transport where we see wind moving the sand around and we see bare bedrock with no dust on it. Orbiter instruments doing multi- and hyper-spectral observations, too, have been focusing attention on such dust-free or dust-poor regions of Mars.

Question 1: Have you observed any geological phenomena that appear to be unique to Mars?
"Unique" might be too high a bar to set because it means "relative to the entire universe". One thing that is interesting on Mars that differs from Earth is that the south polar residual cap, the part that remains even through summer, includes frozen carbon dioxide. This frozen CO_2 is layerd and erodes by sublimation and collapse, forming really cool "swiss cheese" depressions among other things. Certainly something like this does not occur on Earth because of the temperatures involved for frozen CO_2. But landforms composed of CO_2 and landforms that form by sublimation are not unique to Mars, even in our solar system.

Question 2: You mentioned that the sedimentary history of Mars goes back further than what is observable for us on Earth. What could this reveal about Earth's early history?
Yes, the point was that the tectonic conditions on Earth (and Venus, probably) have been such that Earth doesn't really have well-preserved sedimentary rocks from more than about 3.8 billion years ago…indeed, when I ask the experts on Earth's Archean, I get different answers about whether Earth's sedimentary record goes back as far as 3.8 billion… apparently it depends upon how much metamorphism you can stomach ☺. Mars' record – because much of it is the planet's most ancient, heavily cratered terrain, likely extends back before 4.0 billion years ago. What we could learn about early Earth from these rocks on Mars would probably come mostly from analogy… each planet began with a different endowment of elements/chemistry, different

amounts of water, etc., but the physics of sediment transport and deposition would have been the same (modulo different gravity and atmospheric density) such that we could gain some insight into what early Earth environments might have been like… for example, the relative proportions of sediment generated and moved around by impact events versus wind and water… also, it is thought that life on Earth began during that early time for which there is no record… does the early, older Martian sedimentary rock record give us new clues as to the types of environments and energy sources available to organisms, if they existed? And is there a record of them having existed on Mars (that would be something huge)? Also, one might gain insight into events which affected environments on both planets, such as the nature of the impact of the early Sun's output on surface environments on these planets.

Question 1: In a few images from your slides the streams seemed to transition from negative relief to positive, what is physically happening that causes transitions like this?
A similar question was asked, above, and I answered it, there. Whether preserved as positive or negative relief is a function of the materials' resistance to erosion.

Question 2: You mentioned that the company you work for builds a lot of cameras, but it seems like you've done a lot of research on the images they produce as well. It is a little surprising to me that a company would be involved in both the means of acquiring scientific data as well as the processing of it. Can you speak to whether this research is funded by the company and how you've come to be involved in both sides of the project?
The company, Malin Space Science Systems (MSSS), was founded in 1991 by a former ASU geoscience professor, Mike Malin. His main interest, at the time, was to hire staff to operate the Mars Observer Camera and for him and his science team to study the data from the private company rather than doing this work in a university environment (which happened to be ASU). So, the company actually began with an intent to operate a camera in space and study the data. Building cameras was also of interest but began a few years later as contracts came in (earlier in this document, above, I described some of this…how the camera business got going). When I came to MSSS in 1998, it was pretty much established that we do all three things: build space cameras, operate space cameras, and do research with the data from spacecraft instruments. This "trinity" works very well together, as we have scientists and engineers working toward the same success, as a team, and learning from each other. Cameras we build for science missions (e.g., so far, mostly planetary missions, but could easily be for solar, astronomy, or Earth-observing science) are based on science investigation proposals… the science goals and objectives drive what measurements need to be obtained, which drives the requirements that feed into the camera and operations design. Having the science be central to the effort has been vital to to the success of the science intruments we have built, whether to be operated at MSSS or to be operated elsewhere, like the THEMIS VIS and LROC instruments operated at ASU SESE.

You asked "whether this research is funded by the company" and the answer is, generally, no, it is funded through proposals to organizations such as (and usually) NASA. These can be relatively small research projects with 1-3 years funding or they can be full-up science instrument projects, in which we build, operate, and do some of the science research, like we are doing with the color cameras on the Curiosity rover.

You also asked how I had "come to be involved in both sides of the project". For my part, this was intentional. The best way to do the science that interests me, which involves looking at images from Mars – lots of images from Mars – and trying to interpret what Mars has to tell us about itself, is to be involved with acquiring the images. When I started in 1998, I was helping to selecte targets for the Mars Global Surveyor Mars Orbiter Camera. This involved spending almost every day, 7 days a week, looking at image mosaic maps (on a computer screen) of Mars to decide what to take pictures of. The decision process was hypothesis-driven… i.e., trying to address a hypothesis about Mars, sometimes from the prior scientific literature and sometimes a new hypothesis developed on the basis of images coming in from Mars from this mission. This process of selecting the targets is very much a part of doing the science and feeds into the overall science outcome of the mission. Got get to another level, moving from not just helping to operate the camera and write up research results, the next thing was to actually propose new investigations for Mars that make use of cameras… in these proposals, you lay out the background and the hypotheses to be tested or at least addressed, then you lay out how those investigations drive the instrument design in a certain direction (e.g., for MAHLI on Curiosity we needed to be able to distinguish silt from very fine sand because of the depositional setting implications, the transition from saltation (higher energy) to suspension (lower energy)). So the three things go together – instrument design/build/test, instrument operations, and science outcome (results, success, etc.).
