17. Trail Guide 1: Crater Rim East ❖❖❖

We begin our excursion along a paved trail that leads to the museum's overlook platform. Walk down that trail and pause before walking out onto the platform. The bedrock adjacent to the paved trail is red Moenkopi siltstone. It has been uplifted from its pre-impact horizontal configuration. Moenkopi a few meters farther up the slope has been overturned and forms the base of the impact ejecta or debris unit. Overturned Kaibab debris rests on top of the Moenkopi debris. The precise location of the axis of the fold will be obscure here. We will revisit this overturned sequence at several other locations along the east wall of the crater.

With permission of crater staff, we will step from the paved trail onto the Moenkopi and then follow a faint trail (the Astronaut Trail), proceeding roughly east along this portion of the crater's north rim. The path drops down into the Alpha Member of the Kaibab Formation where we will have our first stop.

Crater Stratigraphy

Before taking a closer look at the rock beneath our feet, it will be useful to examine the crater stratigraphy in a dramatic exposure in the southern cliffs of the crater (Fig. 17.1). The basal Kaibab (or Gamma Mbr) outcrops as a cliff-forming unit immediately above lower, talus-covered slopes in the crater wall. The Gamma Mbr is a medium- to thick-bedded sandy dolomite that is normally gray to buff yellow in color. The cliff, however, is stained. A moderately bright red stain comes from the overlying Moenkopi. A dark, nearly black stain also coats large sections of the cliff-face. Although not visible from this vantage point, a small patch of the Toroweap Fm can be found in a cave at the base of the Gamma Mbr. Pleistocene talus and a small amount of mining debris covers the Gamma Mbr and Toroweap Fm to the right (west) of the cave.

The uneven slope above the Gamma Mbr is produced by the Beta Mbr of the Kaibab Formation. It is composed of sandy dolomite that does not outcrop around the crater as well as the underlying Gamma and overlying Alpha Mbrs. This tendency to be a poorly-outcropping and slope-forming unit can be seen particularly well on the slope with a stripe of red drilling mud.

The sharp, cliff-forming unit above the Beta Mbr is the Alpha Mbr. This unit is dominated by medium- to thick-bedded sandy dolomite at its base and an interbedded sequence of medium-bedded dolomite and sandstone at the top. A key marker bed within the Alpha Mbr is a 2-m-thick white sandstone, which Shoemaker traced around the crater and used extensively when identifying fault displacements in the crater wall. It is not the only sandstone horizon in the Alpha Mbr, however.

Although historically called the Kaibab Limestone, the formation is better described as a dolomite or interbedded sequence of sandy dolomites and sandstones. The entire formation is ~80 m thick in the crater walls. I refer readers to Chapter 2 for additional details.

Above the Kaibab is the red Moenkopi Formation. The basal Wupatki Mbr outcrops in relatively massive orbicular knobs and ledges. That unit is covered by a more fissile Moqui Mbr. There is also a very thin, ~30 cm-thick section of fissile Moenkopi at the base of the Wupatki Mbr, although it is not always visible in outcrop. These units formed the eroded, and, thus, uneven pre-impact surface. For that reason, they are not the same thickness in all locations around the crater, although they can be traced continuously along most of the southern crater wall. Additional details of these units can be found in Chapter 2.

Above this pre-impact stratagraphic sequence is a thick deposit of impact ejecta composed of Moenkopi, Kaibab, Toroweap, and Coconino. We will be taking a closer look at those units later in the field excursion.

Museum or Moon Mountain Anticline

The uppermost Kaibab unit in the walls of the crater is chaotic, irregular, and, in places, missing. Here one will find a dolomitic sandstone with individual sandstone and sandy dolomite clasts in a bed about 1 m thick. Shoemaker and Kieffer (1974) interpreted this to be a residual deposit formed on a karst surface. That is, it formed by partial solution of the Kaibab over a fairly long period of time. The unit is sometimes called the “leached Kaibab” unit. Below the unit is an ~4-meter-thick sequence of medium-bedded sandy dolomite, sandstone, and minor limestone. Below that interval is an important marker bed at the crater: the yellow vuggy dolomite. This unit can easily be traced around the uplifted crater walls and found in overturned ejecta debris.

In front of us (Fig. 17.2), two thrust faults cut through the Alpha Mbr, duplicating part of the section and enhancing the uplift of the crater rim. The yellow vuggy dolomite marker bed in the lower plate of the thrust plane is in contact with a duplicate of the same bed in the overlying plate. Fault gouge can be found along the thrust fault, particularly on the west (or left) side of the exposure in Fig. 17.2. The thickness of the gouge is variable, but ranges up to 15 cm thick. The contact is also covered in some places. Farther to the east, the fault and the yellow vuggy dolomite marker bed bend sharply and angle downward. These beds of the Alpha Mbr are arched over a wedge of additional Alpha Mbr rock about 15 m across. This wedge was thrust outward from the center of the crater during crater excavation and crater wall uplift. Shoemaker measured a 30° outward dip on the crest of the arch and estimated ~45° dip on the fault. He also measured 2 m of Kaibab that was repeated in the section, implying ~5 m of throw on the fault.

These types of faults occur in several locations around the crater, in both the Alpha and Beta Mbrs of the Kaibab, and are responsible for a significant portion of crater rim uplift. Shoemaker noted them on the west and north sides. Examples also occur on the east side. Multiple thrusts occur beneath the highest anticlines around the crater, which remain the topographical high-points on the crater rim, such as the northwest corner of the crater (*e.g.*, Barringer Point). The thrusts are often small (as here), but occur multiple times, producing a cumulative effect. Bedding within the Kaibab (particularly the Beta Mbr) is often indistinct, so the amount of bedding repetition cannot always be measured quantitatively. Nonetheless, most of the uplift in the largest anticlines appears to be a direct consequence of the thrusts. Shoemaker suggested that the concentration of these thrusts to the northwest suggests the trajectory of the projectile may have been moving from southeast to northwest.

If we turn around, a thrust fault can be followed down the crater wall to the west, passing beneath a prominent dolomite outcrop, from where it continues to a point beneath the observation platform (Fig. 17.3). Also visible in this section is the white marker sandstone in the middle of the Alpha Mbr of the Kaibab Fm and the yellow vuggy dolomite near the top of the Alpha Mbr of the Kaibab Fm. These previously horizontal units have been sharply uplifted in the walls of the crater and now dip outward. If the field party is small, it can follow the thrust fault to the west and peer beneath the observation deck. Erosion along the thrust fault has formed a chute. If the field party is large, this extra view should probably be avoided.

Next, we want to return to our trek to the east. Follow the trail, which should stay above a small section of near-vertical outcrops within the Alpha Mbr of the Kaibab. The trail will pass into a section of Moenkopi that tracks across and diagonally down the crater wall (Fig. 17.4). We will stop here to discuss the Moenkopi.

Identifying Overturned Bedrock in the Crater Rim

As discussed in Chapter 2, Moenkopi siltstone was deposited in a coastal environment that was constantly being processed by water currents and wind. This generated cross-bedded laminae that can be used to separate uplifted strata and overturned strata. Normally-bedded units will be sitting on top of Kaibab-Alpha. Somewhere up-slope, those units are overturned and duplicated. We will use the cross-bedded laminae to identify that point.

Begin by examining large blocks of Moenkopi near the contact with the Kaibab-Alpha. The top of many cross-bed sets will be sharply truncated, typically at an angle of ~30° (see Fig. 2.6d for an example). At the base of these sets, however, the cross-bedded laminae are truncated at very shallow angles, typically less than 5°. The laminae will appear to tangentially or asymptotically approach the base of the set. The distinct difference between the base and top of a cross-bed set can be used to identify units that are oriented normally or overturned. A schematic illustration of these features and their relationship to parental dunes is also provided (Fig. 17.5).

I invite the group to migrate across the slope, moving increasingly upward in section, to study the cross-bedded laminae and identify the level where blocks have been overturned.

Not all blocks will have an unambiguous indicator of orientation. Some blocks of Moenkopi may have, for example, horizontal rather than cross-bedded laminae. In addition, some blocks have rotated and shifted slightly downhill, obscuring their original orientations. Nonetheless, with careful scrutiny, the duplicated and overturned sequence of the Moenkopi on this portion of the upper crater wall is identifiable.

After locating the overturned section of Moenkopi, follow the Moenkopi across the slope to the east with your eyes. You will see that the trace of Moenkopi disappears. It is replaced by yellow to buff-colored Kaibab. The Moenkopi in that section of crater wall is at a much higher elevation near the top of the crater rim. The jump from Moenkopi to Kaibab in this section of the crater wall was created by differential uplift along a tear fault. Shoemaker (1960) and Roddy (1978) argued that these tear faults formed along pre-existing sets of joints that are particularly prominent in the Kaibab and accentuated by dissolution along those joints.

Additional faults can be seen from this location along the east crater wall (Fig. 17.6). The relative structural displacements can best be seen by following the cliff-forming Kaibab-Gamma unit. The displacements are modest along the crater wall, but dramatic in the southeast corner of the crater where another large tear fault (or, rather, a complex set of tear faults) was produced during crater formation. The additional uplift generated on the north side of this tear fault provides the best exposure of the Toroweap and Coconino Fms in the entire crater. As the excursion proceeds, we will hike above those faults and it will be evident that they are easily eroded and an important structural source for major gully formation in the crater walls.

From this vantage point, we can also glimpse the path we will be taking along the remainder of our excursion (Fig. 17.7). We will be walking along the east rim of the crater. Similar outcrops of uplifted

Kaibab-Alpha are visible along that portion of the crater wall. Also visible is a particularly large block of Kaibab ejecta called Monument or House rock. We will be visiting that location. We will also hike beyond that point to a location near a gate in a fence line that is visible slightly further to the south. We will then turn around. Our hike to the southeast will utilize a trail on the rim of the crater. On the return, we will dip down the crater wall again.

From our current position in the field of Moenkopi blocks, the field party should climb up the slope of the crater wall to the crater rim trail that circumnavigates the crater.

If time allows, however, the field party can follow the Moenkopi to the tear fault before climbing to the rim. Exposures indicate the fault is complex, diverging into several sub-parallel faults, particularly as it cuts through the Moenkopi. Where the fault cuts through the Kaibab, gouge is visible in the walls of a ravine that has been eroded deeply into the fault.

Relative displacement on the tear fault along the gully is ~24 m (Shoemaker and Kieffer, 1974). It has juxtaposed the overturned Moenkopi debris layer (this side of fault) against the white marker sandstone in the middle of Kaibab-Alpha (far side of fault). Farther down the slope, it has juxtaposed the upper part of the Kaibab-Alpha (this side of fault) against the upper part of the Kaibab-Beta (far side of fault).

The group still needs to reach the trail on the crater rim before continuing the excursion. From the tear fault, the climb up to the crater rim is very steep and over unstable rock. It may be prudent to return to the Moenkopi boulder field and climb to the rim from that point.

Once on the rim trail, follow it to the southeast along the east wall of the crater.

Traversing Impact Ejecta

This portion of the rim trail weaves over and through blocks of Kaibab that were excavated from the crater. Roddy *et al.* (1975) calculated that 175 million metric tons of rock was deposited on the crater rim and the surrounding landscape. The debris is composed of angular to sub-angular blocks. The smallest debris components identifiable in the field are millimeter in scale and range to blocks that are several meters in size. Shoemaker and Kieffer (1974) report that the size frequency of this debris follows a classic fragmentation law, such that the cumulative mass of debris is a simple power function of the particle size. The exponent of this power function is such that 50% of the total mass falls in the largest 3 phi intervals. The data, however, appears to be lost. Size frequency data for the smallest size fractions (0.03 to 16 mm or +5 to -4 phi units) of Kaibab and Coconino ejecta were independently gathered by Grant and Schultz (1993). They found modes at 0.074 and 0.21 mm for Kaibab and Coconino samples, respectively, without any identifiable power-law distribution. The mode for this fine fraction of Coconino ejecta is approximately equal to the average grain size in the original Coconino target rock (~0.19 mm; Table 2.1).

A cursory comparison of the size-frequency data at the crater suggests the power law exponent may be different than that for ejecta observed around some experimental explosion craters. For example, less than 25% of the ejecta mass is in the 3 largest phi intervals (smallest grain sizes) at the ~230 m diameter Pre-Schooner II crater (Frandsen, 1967), compared to the 50% reported for Meteor Crater by Shoemaker and Kieffer (1974).

A careful examination of bedding features within the *in situ* Kaibab beds below and the Kaibab debris here on the crater rim can be used to demonstrate that the debris is largely overturned, although we will not take the time to repeat this exercise. It is, however, worth noting that additional rotation of some blocks can produce diverging orientations. We will be discussing other details of the ejecta blanket later in the excursion.

Additional Views of Crater Interior

Approximately mid-way to the fence line in the southeast corner of the crater, it is worthwhile to stop and re-examine the crater interior from this perspective. In the foreground, slightly south of our present position, we see that the Kaibab continues to sandwich red Moenkopi along the east wall of the crater (Fig. 17.8). All three members of the Kaibab are visible below the Moenkopi. The uplifted and outward dipping orientations of those strata are also clearly visible here. Keen-eyed observers may also spy small thrust faults in the Kaibab-Alpha.

Sweeping our gaze around the crater towards the south crater wall, we see that the Kaibab is truncated against a large tear fault (Fig. 17.9). This is the same section we examined earlier from our perspective on the north crater rim (Fig. 17.1 and 17.6). The Kaibab is uplifted much higher on our side of the tear fault. That additional uplift provides the best exposure of the Coconino Fm in the walls of the crater. Beyond the tear fault, all three members of the Kaibab can be traced across the face of the southern cliffs.

Looking across the crater to the west, we see the same simple Kaibab-Moenkopi-ejecta stratigraphic sequence repeated (Fig. 17.10). The lower crater walls are covered with Pleistocene talus, so very little exposure of the Toroweap and Coconino Fms are found there. Barringer Point is one of the highest points along the crater rim. From this vantage point, the anticlinal nature of that feature and underlying thrusts in the Kaibab-Beta are visible.

Remnants of mining operations are visible on the crater floor. White patches of disturbed debris mark the locations of several shafts and boreholes. The top of the Main Shaft is enclosed in a large fence, as is the nearby Shaft #3. The top of the East Shaft is covered. This shaft was crudely cribbed and has been used in the past for studies of the crater's subsurface. That is, for example, the source of the pollen being used to reconstruct the environment at the time of impact (Chapter 13). Collectively, the shafts reveal that ~30 m of lake sediments sit on top of an impact breccia lens. The breccia lens is ~175 m thick and was produced when the excavation flow stopped and remaining allogenic breccias along the transient crater wall collapsed. At the time of impact, the water table was within the Coconino, so artesian spring flow filled the crater with a small lake. As the climate became arid ~11,000 yrs ago, the lake dried and a small amount of playa sediments were deposited. Silica Hill is a small knoll on the crater floor with the highest level of lake sediments. Shoemaker and Kieffer (1974) hypothesized that the knoll of lake sediments is on top of a topographic high or "central peak" that formed when allogenic breccias collapsed.

Kaibab, Toroweap, and Coconino Ejecta on Crater Rim

In the east-southeast portion of the crater rim, one finds an immense block of uncovered Kaibab ejecta (Fig. 17.11) that Barringer called Monument Rock. The block is often called House Rock today. We approach this boulder from the north. We want to walk past the rock, turn around, and look at it from the south for the best view. While standing next to the rock, it is usually a worthwhile exercise to imagine the energy necessary to excavate it from the crater, carry it upwards, and deposit it many meters beyond the crater rim. The block, however, is only one among countless numbers of blocks that were excavated, form a blanket of debris that was ~20 m thick on the crater rim, and that stretches from the rim of the crater to distances in excess of a kilometer. The enormity of the energy involved in crater formation often begins to become tangible at this location. This is also a region where some of the most heavily-shocked Canyon Diablo specimens were recovered (*e.g.*, Heymann et al., 1966), including diamond-bearing meteorites that Nininger (1956) and Moore *et al.* (1967) found to be concentrated on the crater rim and virtually absent on the distant plains. See Chapter 9 for additional details.

While at Monument Rock, let's also pause for a moment to discuss a couple of features that astronauts encountered in the impact-cratered terrain of the Moon. Monument Rock is often called House Rock for two reasons. First, from the observation platform at the museum, there is a telescope trained on the rock labeled "house-size rock." Second, and more importantly for our discussion, it is reminiscent of House Rock at North Ray Crater, which was explored by John Young and Charlie Duke during the Apollo 16 mission. North Ray Crater is similar in size to Meteor Crater, ~1 km in diameter, although it is older and suffered more (and different types of) erosion (Fig. 17.12). On the southeast side of the crater, there is a large rock that the astronauts called House Rock (Fig. 17.13). The astronauts approached the rock, but, because of the steepness of the slope, they were unable to reach it. Nonetheless, it is a memorable feature in a memorable mission and has lent its name, at least informally, to Monument Rock.

This is also a good point to consider how impact cratering has affected the landscape. Here, in northern Arizona, the impact crater is an isolated feature. One can look in all directions and not see another impact crater. The uniqueness of Meteor Crater is misleading. One might conclude, wrongly, that impact cratering is a minor geologic process. On Earth it may seem to be a minor process, but that is simply because Earth is such a dynamic geologic planet that other processes (*e.g.*, erosion, sedimentation, volcanism, plate tectonics) constantly destroy evidence of impact cratering. If we go back to the Apollo 16 landing site, we would find North Ray Crater in a field of impact craters (Fig. 17.12D). Two craters of nearly the same size, Kiva and Ravine, are immediately adjacent to North Ray Crater. Imagine that scene here: if, while standing on the rim of Meteor Crater, we could see two other impact craters of similar size and, moreover, a surface covered with hundreds to thousands of smaller impact craters. It is clear the Moon provides a better record of impact cratering than does the Earth.

A short distance south of Monument Rock we encounter additional mounds of impact debris (Fig. 17.14). The character of the debris changes, however. The trail crosses or passes adjacent to sandstone debris. This is our first encounter with sandstone from the Toroweap and Coconino sandstones that underlie the Kaibab Fm. This material was excavated from a pre-impact depth of at least 80 m.

This material, and another patch of sandstone on the north rim, intrigued Barringer and his colleagues with the Standard Iron Company. He describes them as impact-ejected rays of material. He was essentially describing what we now understand to be heterogeneities that can develop in ejecta blankets, leading to hummocky ejecta blankets and concentrated rays of ejected debris. In some cases, however, a transition from Kaibab to Coconino debris can reflect erosional remnants of ejecta that were deposited on a topographically variable surface that was created by tear faults in the underlying crater walls. A clear map identifying the source of this type of ejecta patchiness has not been developed in past studies. An example of the first source of the patchiness, however, is visible on the north rim. Although we will not visit that locality on this excursion, it is illustrated in Chapter 8 (Fig. 8.4).

Tear Fault in Crater Wall

If we continue south on the rim trail and pass through a gate in the fence line, we encounter additional Coconino- Toroweap ejecta. Coconino and Toroweap lithologies are not easily separated in these deposits and were mapped together by Shoemaker. We will stop near a winch (Fig. 17.15) that was used to haul supplies to and from the crater floor during mining operations. It is a nice historical reminder of original focus of exploration activities at the crater and the impetus for understanding the structure's origins. The winch sits above the tear fault that is responsible for the dramatic off-set in the Kaibab-Gamma Mbr that we viewed from the north and east rims of the crater (Fig. 17.1 and 17.6). A tremendous amount of fault gouge is visible in a ravine below the rim that continues nearly all the way down to the crater floor. The structural complexity of the crater rim along tear faults will also be visible. A number of small faults, one of which may reflect the partial collapse of the crater rim, is visible in the flank of the ravine. In my previous edition of this guidebook, I wrote that a detailed structural map of this section of the crater wall and rim is still needed, with an interpretation of the kinematics implied by those structures. An undergraduate student accepted that challenge and prepared a short report (Denton and Kring, 2016), the results of which are illustrated in Figs. 18.18 and 19.13.

This is also a useful vantage point for peering again at the northwest "corner" of the crater. That "corner" is also cut by a large tear fault. Slightly west of that tear fault the crater rim rises to Barringer Point. The thrusts in the Kaibab-Beta that underlie the anticline are sometimes easier to see here (Fig. 17.16) than from the stop earlier on our excursion.

From this point, we want to retrace our steps through the gate. When we reach Monument Rock, we will descend the crater wall in a diagonal line towards the north, until we reach outcrops of Moenkopi.

Fold Hinge in Moenkopi

Erosion and the angle of light hitting south-facing slopes makes a study of folds in the overturned rim sequence easier on our return hike. A good example of a hinge within the Moenkopi is visible on the slope north of our position (Fig. 17.17). The Moenkopi core is enveloped by a fold in Kaibab, whose apex is in the sky. Once the hinge has been located, we will walk to it. Please be careful when approaching the hinge. The fissile Moqui shale is fragile and we want to avoid damaging it so that its orientation will be apparent to future visitors. We also do not want to dislodge any of the adjacent blocks of vertical to near-vertical Kaibab limestone.

In the immediate vicinity of the Moenkopi hinge, we can see that the Moqui core is surrounded by blocks of Wupatki, which is, in turn, surrounded by blocks of Kaibab-Alpha. As illustrated in a schematic diagram in Chapter 7 (Fig. 7.2), the units are both structurally and stratigraphically overturned.

Hinges in the Moenkopi are not everywhere visible around the crater. Indeed, in some sections of the crater wall, the Moenkopi is not exposed because it lies encased within folded Kaibab. Erosion after the impact has cut into the overturned sequence, however, and occasionally exposed Moenkopi cores. This is illustrated schematically in Fig. 7.4.

Next we want to hike uphill and return to the trail on the crater rim.

Kaibab Ejecta beyond the Crater Rim

We return to the trail in the midst of a Kaibab boulder field that extends outward from the crater rim towards the surrounding plain (Fig. 17.18). Although this material was visible on the hike out, it is easier to appreciate with the sun behind us.

This is one of two boulder fields that impressed Barringer. The other boulder field sits on the west flank of the crater and contains the charismatic Whale Rock. The symmetry of these boulder fields is one of the reasons he favored a north to south trajectory for the impacting asteroid.

Beyond the immediate boulder field, one can also see isolated mounds of debris that are often pinnacled by a large block of Kaibab (Fig. 17.19). These features accentuate the hummocky topography of the ejecta blanket. In a larger impact event, ejected boulders like those visible will produce secondary craters.

We continue our return trek to the museum along the rim trail.

Fold Hinge in Kaibab

As we begin to turn the "corner" along the crater wall, another fold hinge is visible (Fig. 17.20). In this case, the fold hinge occurs in Kaibab, rather than Moenkopi. Beds on the lower limb of the fold have vertical dips. Tracing those beds around the hinge, they become increasingly overturned. Beds on the top of the slope mirror perfectly the beds on the lower limb and are clearly inverted or upside down. Within the Kaibab fold is a pale red core of Moenkopi. Erosion has barely reached that level, so very little of the Moenkopi is visible. Nonetheless, it nicely illustrates how Moenkopi is sandwiched within the overturned Kaibab sequence.

Breccia Deposits and Pleistocene Talus on Crater Walls

En route to the museum, we will have several opportunities to view the interior face of the crater's north wall. Breccia deposits and post-impact alluvium are easily seen, particularly when highlighted by shadows in the late afternoon (Fig. 17.21). The upper portion of the crater wall is composed of near vertical cliffs. The lower 2/3 of the wall, however, has a much shallower slope. Those slopes are defined by Pleistocene talus, but they have a core of allogenic and fall-out breccia. Lechatelierite and meteoritic debris is included within the fallback breccia. Large blocks of debris that slid with the allogenic breccias towards the crater floor during the modification stage can also be seen along the crater wall. Authigenic breccias along shear planes within and at the base of those blocks can be found when examined more closely. Ravines with a fairly regular spacing cut through the fallback and allogenic impact breccias. Although that provides for good exposure of the breccias, erosion along the ravines is slowly destroying the deposits.

Hopi Buttes

Before climbing over Moon Mountain and returning to the museum, one has a good view of the Hopi Buttes northeast of the crater (Fig. 17.21). If we begin our scan directly to the east, we are peering towards the Painted Desert, which is dominated by the Chinle Fm, which sits on top of the Moenkopi Fm. Towards the north, sequentially younger Jurassic and Cretaceous strata are found. The highest and most-distant mesas towards the northeast are capped with Cretaceous bedrock, which records the recession of the Cretaceous Seaway that once cut through the middle of North America, connecting the Gulf of Mexico and Arctic Ocean. Many of the mesas and buttes towards the northeast are carved from the sandstones and shales of the Jurassic-Cretaceous sequence. However, a large number of the buttes are, instead, Tertiary diatremes, which are called the Hopi Buttes. These diatremes contain fragments of the mantle, lower crust, middle crust, and the sediments that encompass them, providing a fascinating cross-section of the Earth. Despite the diatremes' similarities to kimberlites in South Africa, they do not contain any diamonds. Those are only found in the shock-metamorphosed specimens of Canyon Diablo found here on the rim of Barringer Crater.

Unfortunately, samples of those meteorites and related shock-metamorphosed target rocks are not found (or no longer found) on the rim of the crater. They are, however, displayed in the museum and I invite everyone to examine them there.

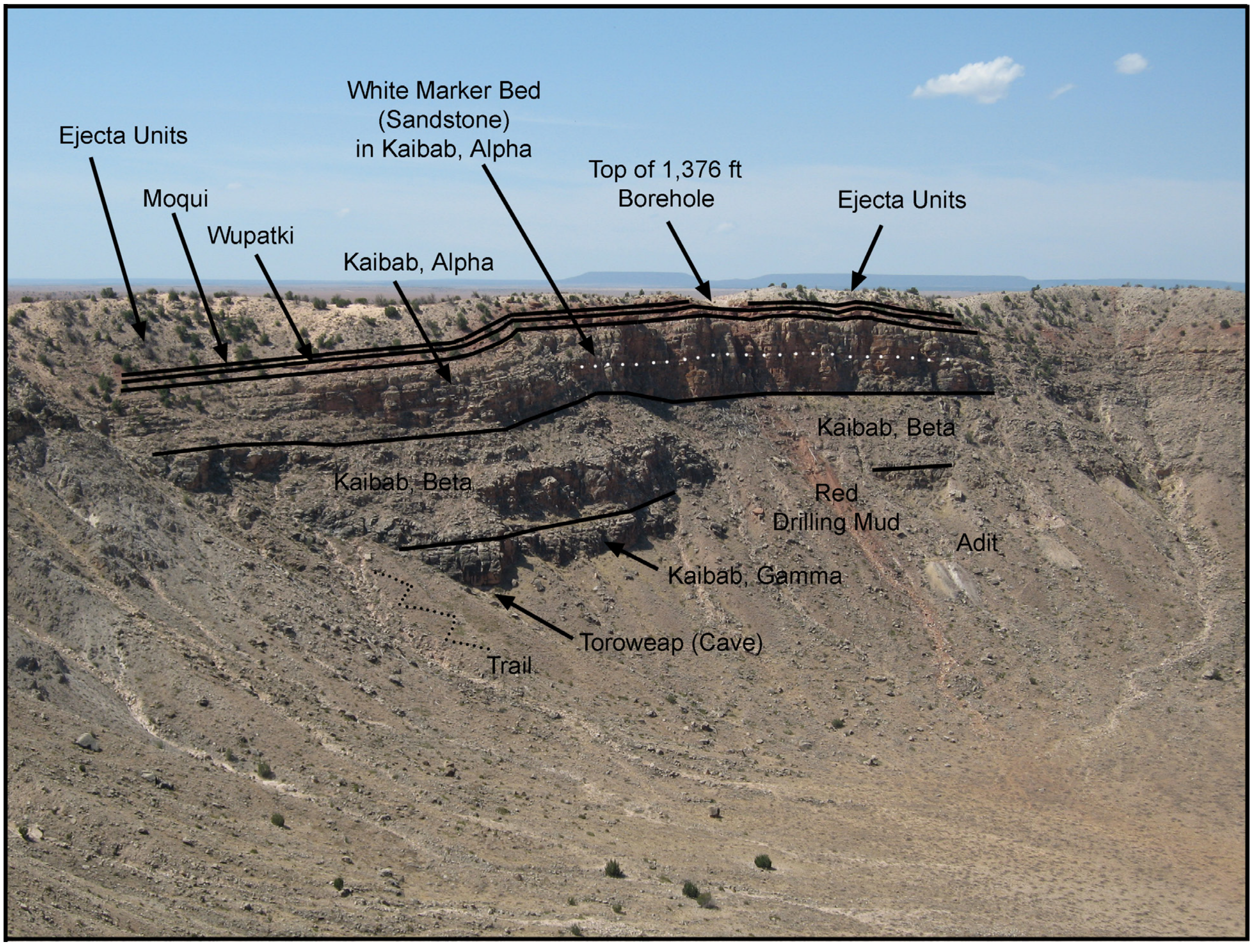


Fig. 17.1. Stratigraphy of the upper crater wall, as viewed towards the south. Target units shown are the Toroweap Fm, Gamma Mbr of the Kaibab Fm, Beta Mbr of the Kaibab Fm, Alpha Mbr of the Kaibab Fm, Wupatki Mbr of the Moenkopi Fm, and Moqui Mbr of the Moenkopi Fm. The Coconino Fm is not visible in this particular exposure (but is visible in the southeast corner of the crater). The position of a white marker sandstone bed in the middle of the Alpha Mbr of the Kaibab Fm is shown with a dotted white line. Ejecta from the target lithologies is visible on top of the Moenkopi beds. Also visible is the top of a 1,376 ft deep borehole through target lithologies on the south side of the crater. That borehole encountered fractured rock with meteoritic debris. See Chapter 4 for details.

Fig. 17.2. Museum or Moon Mountain thrust faults. Thrust faults within the Kaibab-Alpha duplicate part of the section, generating a wedge of material that creates an anticline and additional uplift of the crater rim. The thrust fault can be traced using the yellow vuggy dolomite unit within the Kaibab-Alpha (top panel). The wedge of material injected beneath the anticline is ~15 m across (bottom panel). The thrust fault was mapped by Shoemaker (1960) and described by Shoemaker and Kieffer (1974).

Fig. 17.3. View of outward-dipping beds in the wall of the crater and a thrust fault that cuts across a slope of Kaibab-Alpha towards the west. The yellow vuggy dolomite marker bed is visible in the upper plate (upper right of image) and the white marker sandstone bed is visible in the lower plate (lower center of image). The fault continues beyond the field of view and continues to cut down the slope beneath the observation deck of the museum complex.

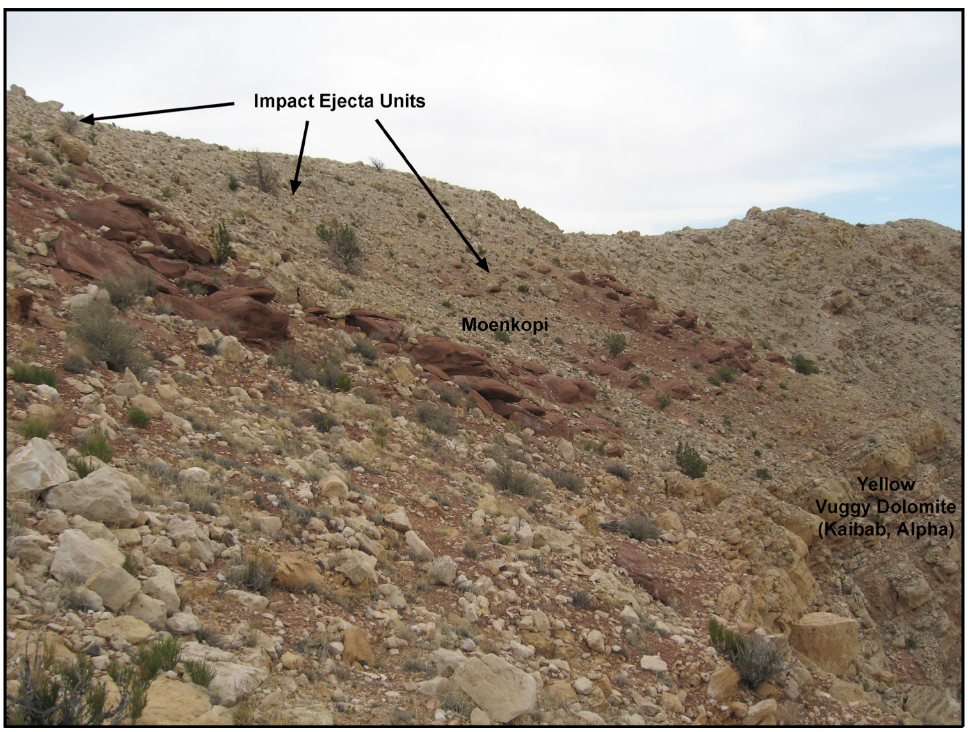


Fig. 17.4. A sequence of Moenkopi units with cross-bedded laminae that can be used to demonstrate the overturned sequence that characterizes the ejecta units at the crater. In this particular view to the east, the stratigraphic sequence begins with normal Kaibab-Alpha (including the yellow vuggy dolomite marker bed), normal Moenkopi, overturned Moenkopi, and overturned Kaibab at the top.

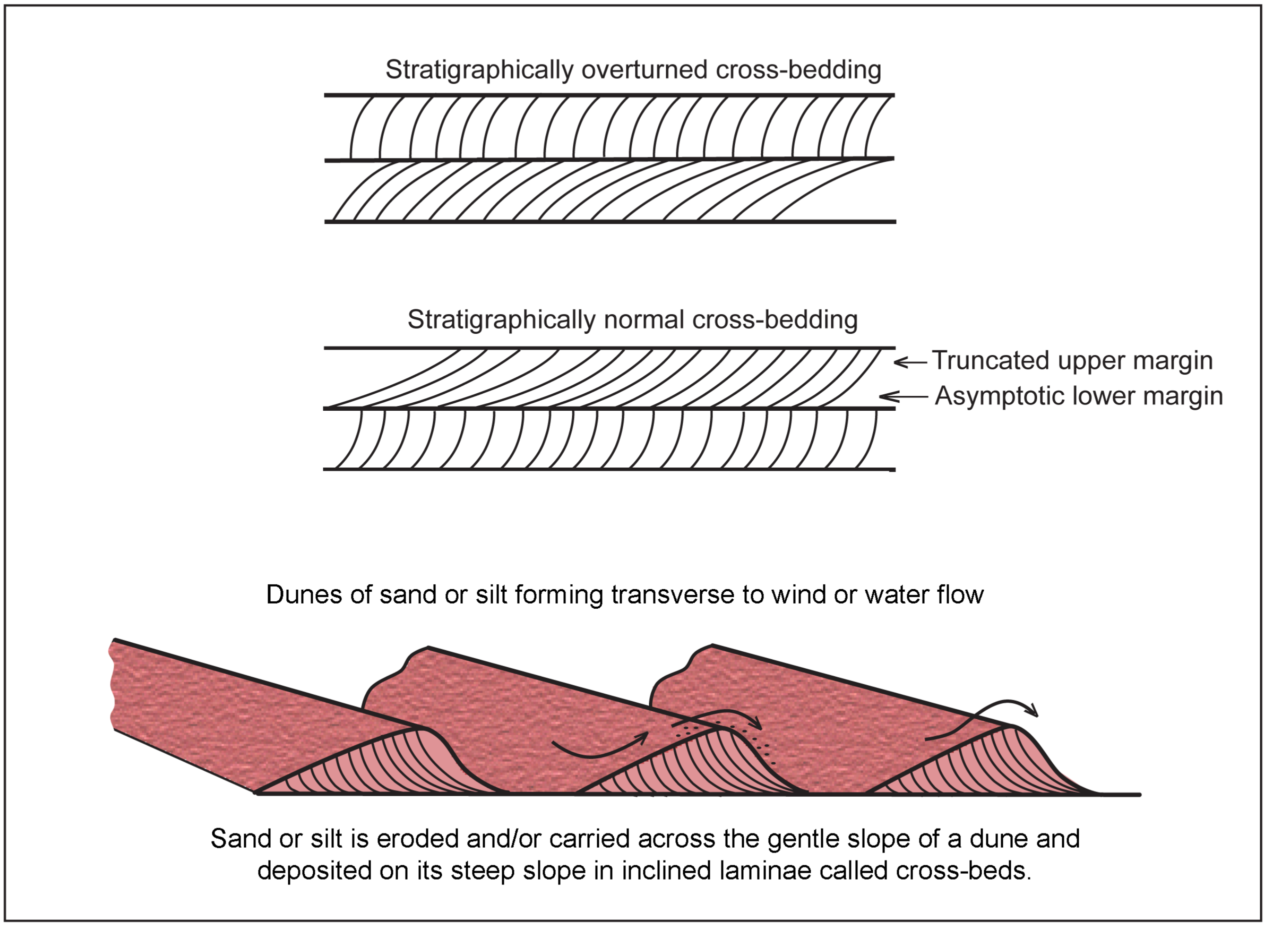


Fig. 17.5. Schematic diagram illustrating the formation of cross-bedded laminae in the Wuptaki Member of the Moenkopi Formation. The geometry of the cross-bedded laminae can be used to determine the orientation of the Moenkopi strata in the rim of Barringer Crater. When the strata are in their normal orientation, the cross-bedded laminae asymptotically approach the lower margin of each set and are truncated at the top of each set. In the overturned part of the crater rim, the truncated margin of a set is below the asymptotic margin. This is an illustration of simple cross-bedding. Within the Moenkopi one can find more complex forms of cross-bedding (like trough cross-bedding), which can also be used to determine the orientation of strata. However, some silt was deposited in higher velocity currents, producing horizontal laminae. In these cases, one has to find other geopetal features (like mud cracks) to determine the orientation of strata.

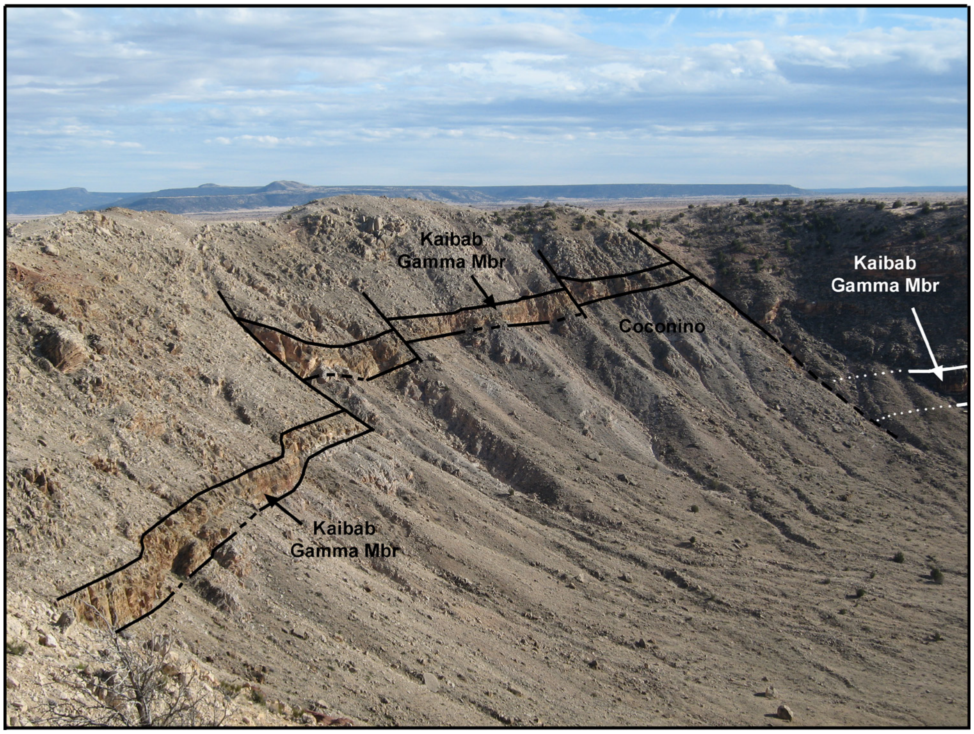
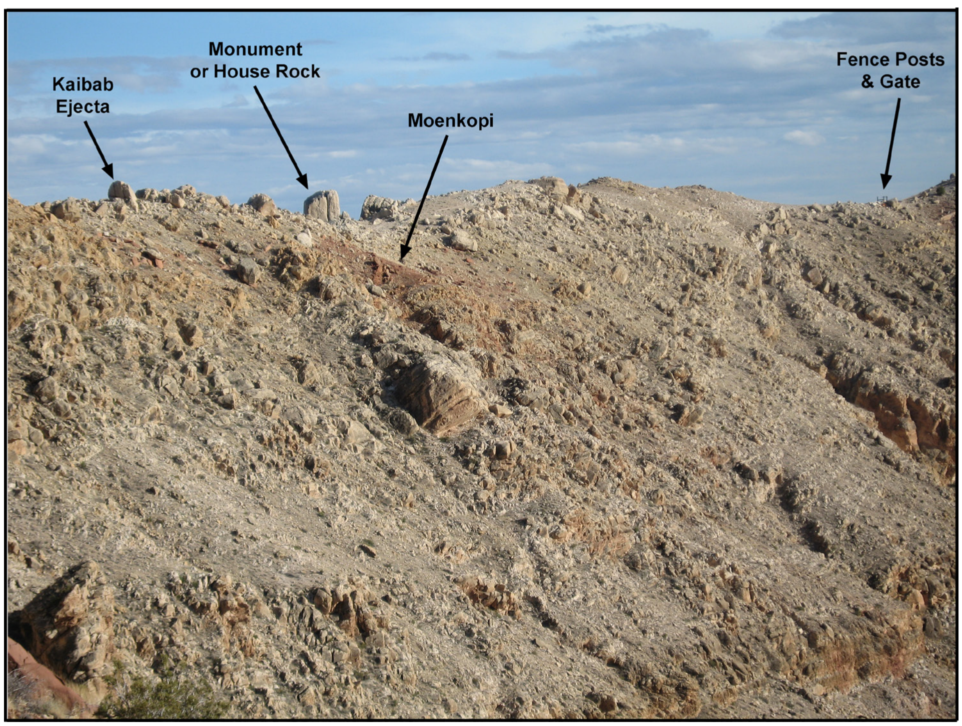


Fig. 17.6. View towards the southeast corner of the crater. The Gamma Mbr of the Kaibab Fm is outlined to help show tear fault displacements along the east crater wall. A very large displacement occurs in the southeast corner of the crater. On this side of that large tear fault, the Coconino Fm is visible. It is the thickest sequence of Coconino exposed in the crater wall. The crater wall farther to the west (right) is shown in Fig. 17.1.

Fig. 17.7. Zooming in on the east rim of the crater, one can spy Monument Rock within a boulder field of Kaibab ejecta that was deposited above normally-bedded and overturned Moenkopi. We will be hiking along the crater rim and will eventually stop within that boulder field. We will then continue towards the south and turn around near the fence posts and gate. We will backtrack along the inner crater wall.



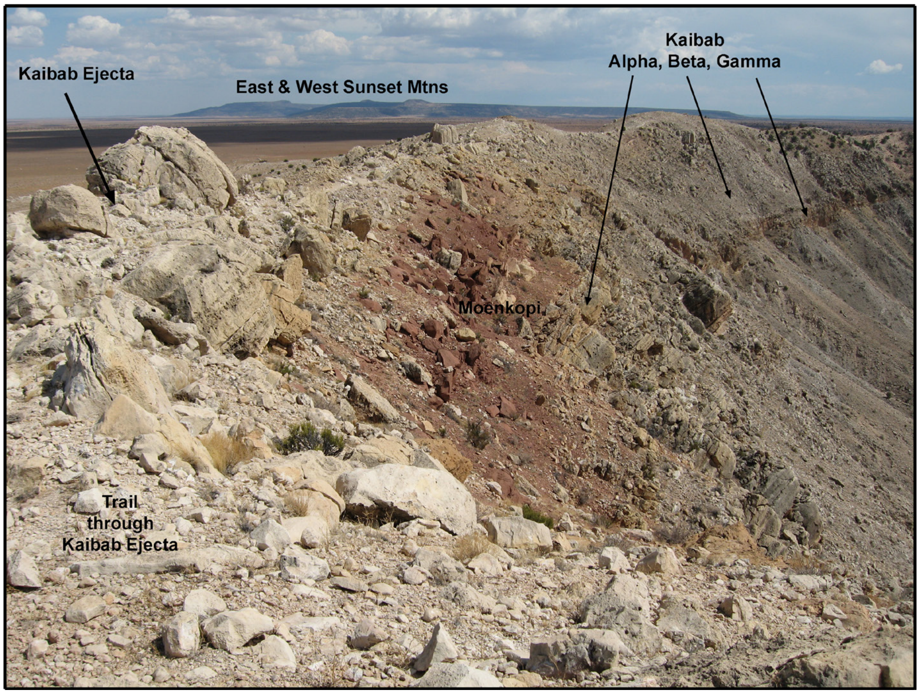
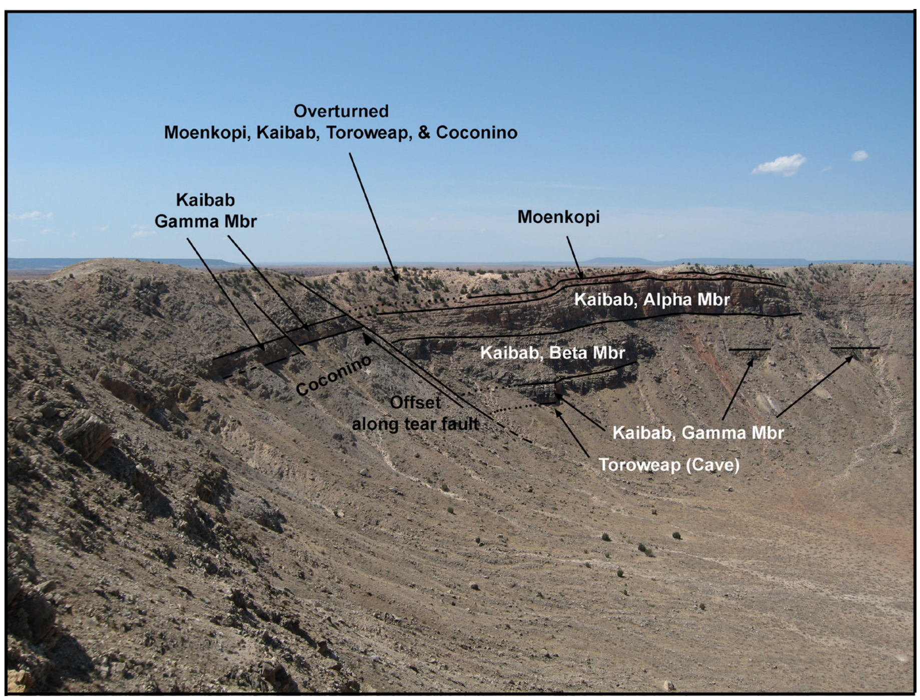


Fig. 17.8. View of upper crater wall from a trail along the rim of the crater. The trail is winding through Kaibab ejecta. Lower on the crater slopes, one can see the outward dipping normally-bedded strata of the Kaibab Fm, including all three members of that formation (Alpha, Beta, and Gamma). If one looks carefully, small thrust faults that thicken the Kaibab sequence will be visible from this location. The bedded and ejected Kaibab units sandwich the red Moenkopi. Farther to the south, the Quaternary volcanics of East and West Sunset Mountains are visible.

Fig. 17.9. This is a closer view of the stratigraphy and one of the fault displacements that were previously seen in Fig. 17.1 and 17.6. The total displacement along the tear fault is more than 45 m. On this side of the fault, ~90 m of the upper Coconino Fm are exposed.



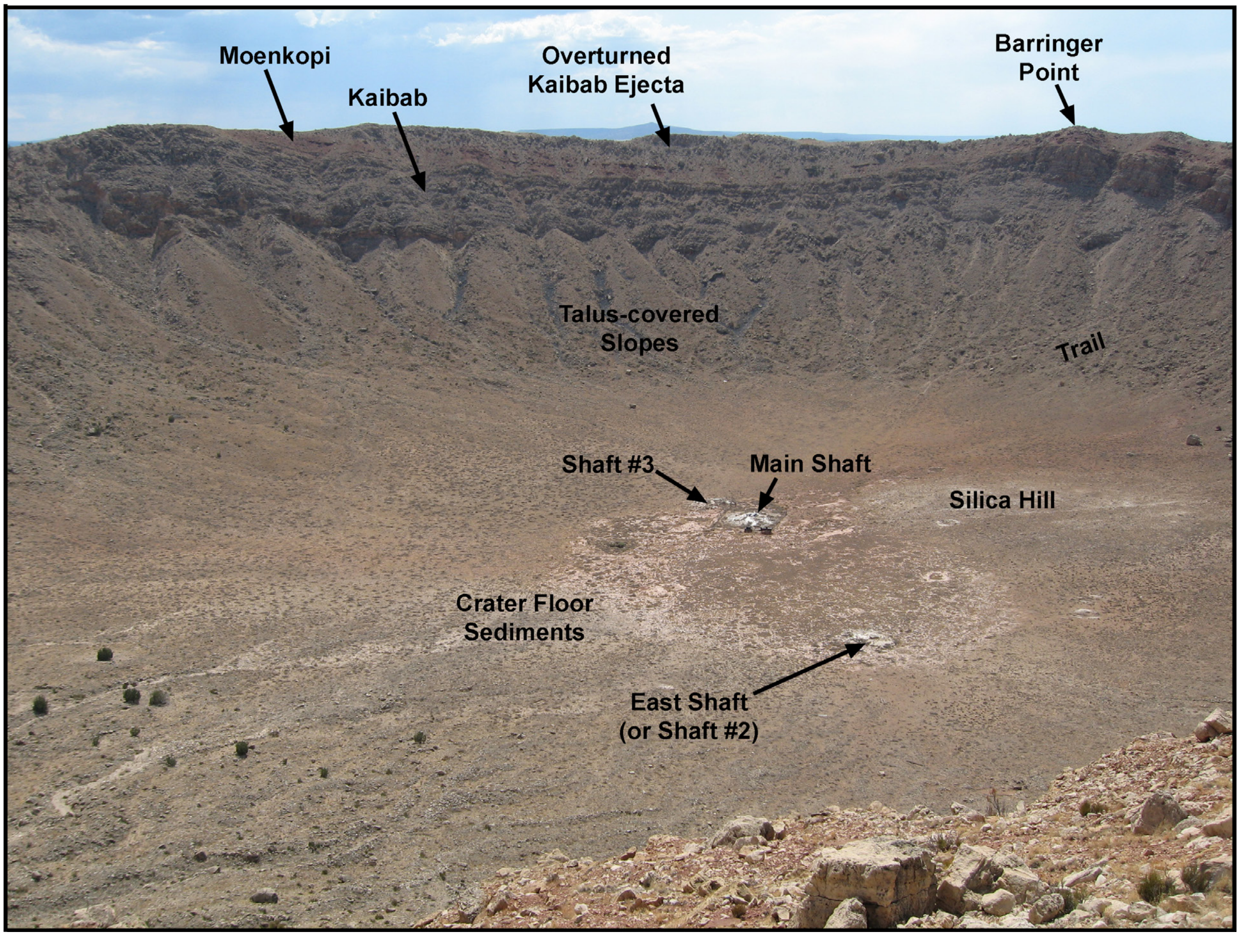


Fig. 17.10. View of the west crater wall and the crater floor from the trail on the east rim of the crater. The stratigraphy of the upper west crater wall is similar to that on the east crater wall. The highest point along the rim of the crater is visible on the horizon. Thrust faults have thickened the Beta Mbr of the Kaibab Fm beneath Barringer Point, creating an anticline. A trail from the northwest crater rim to the crater floor traverses talus-covered slopes. On the floor of the crater, one can see a topographic high (Silica Hill) surrounded by playa sediments. Several exploration shafts were sunk into the crater floor, three of which are identified in the image. The Main Shaft and East Shaft penetrated ~30 m of lake sediments, ~10 m of fall-back breccia, and bottomed in an ~175 m thick allogenic breccia lens that is dominated by blocks of Coconino sandstone, including one slab with an area of 20,000 square meters.

Fig. 17.11. Monument or House Rock is one of the largest boulders that is visible in the ejecta blanket. It is a large block of Kaibab within a boulder field of ejected Kaibab. A small, dark green tree is growing at the base of the rock in the foreground. Over 7,000 metric tons of rock are exposed in the block above erosional surface at the base of the exposure. This is one of the blocks used to determine a cosmogenic exposure age and, thus, an approximate age for the crater. (See Chapter 12 for details.)

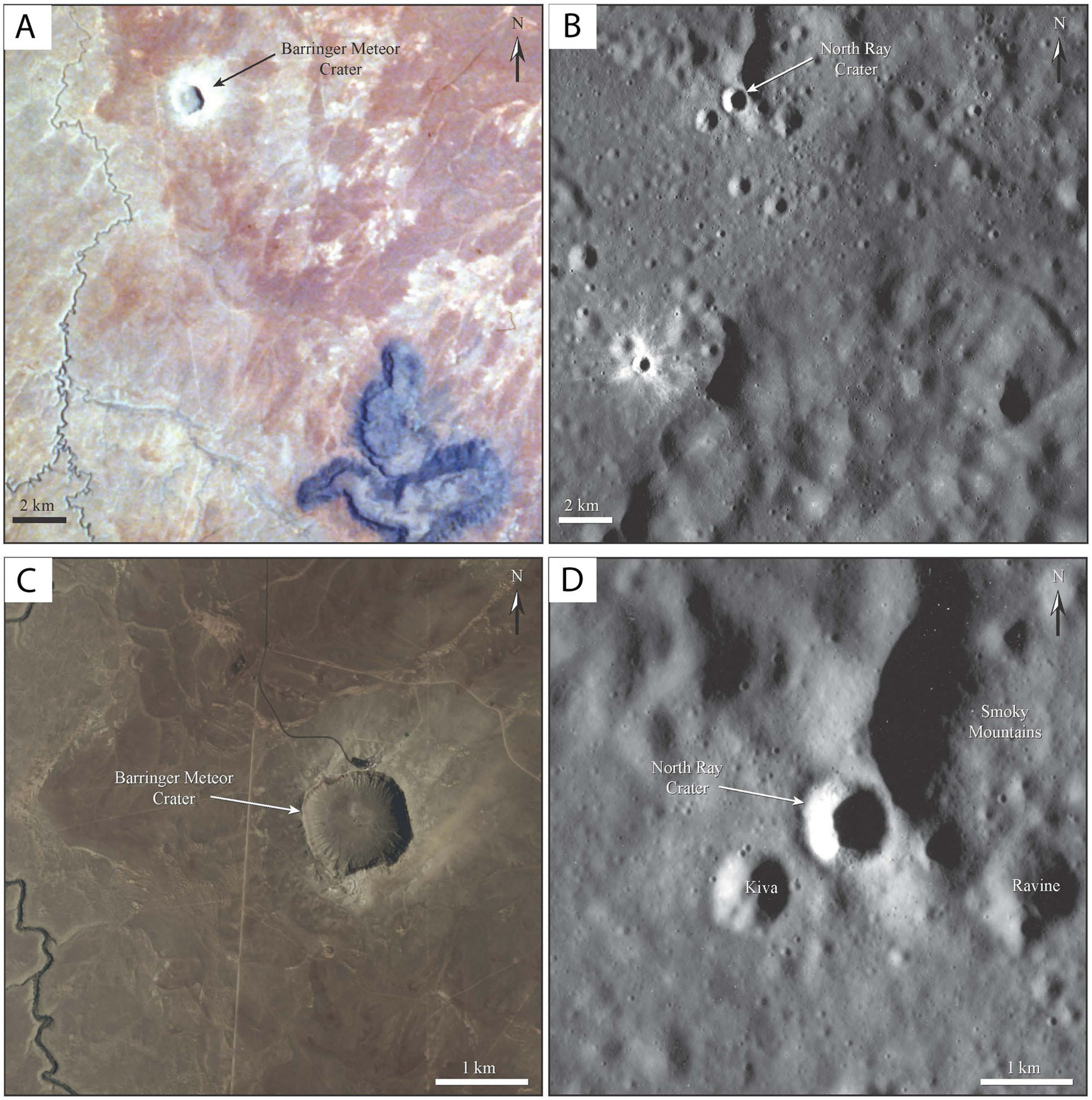


Fig. 17.12. Comparing the ~1 km diameter Barringer Meteorite Crater in northern Arizona with the ~1 km diameter North Ray Crater at the Apollo 16 landing site on the Moon. (A) Barringer Meteorite Crater region, with the sinuous Canyon Diablo to the west and the dark basaltic West Sunset Mountain to the southeast. Scale bar is 2 km. Space Shuttle Columbia image STS 040-614-058). (B) Shown at the same scale is the Apollo 16 landing site with North Ray Crater. South Ray Crater is a younger, bright-rayed crater to the southwest. Apollo Image Atlas AS16-P-4558). (C) Barringer Meteorite Crater stands alone in this USGS photograph. Scale bar is 1 km. (D) Shown at the same scale, North Ray Crater is adjacent to Kiva and Ravine craters, both of comparable size. Apollo Image Atlas AS16-P-4558. As one gazes from the rim of Barringer Meteorite Crater, imagine a landscape with two additional craters of comparable size and countless numbers of smaller impact craters. I thank Celeste Mercer for collating these images for one of our training exercises at the crater for postdoctoral researchers.

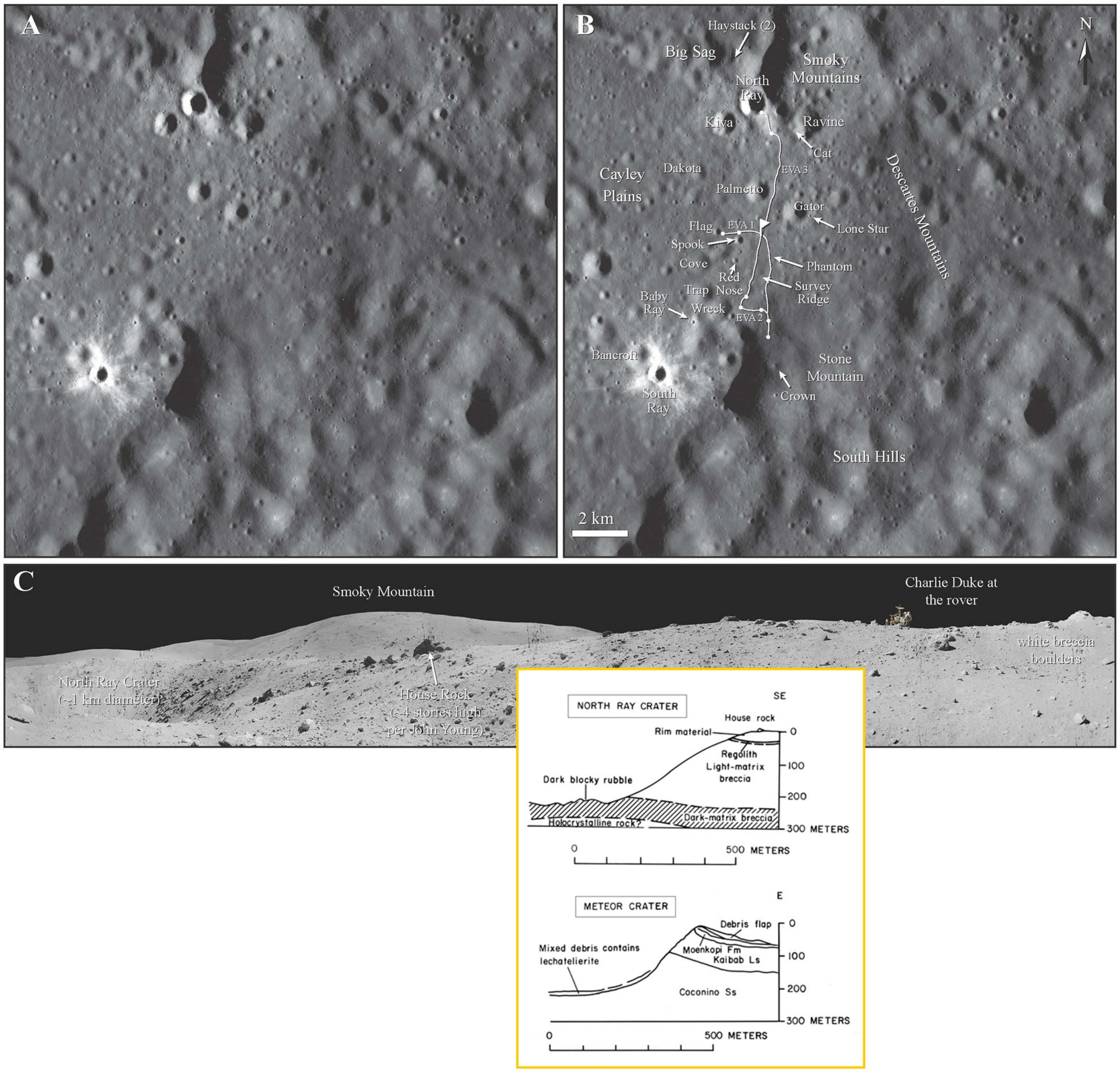


Fig. 17.13. Comparing the ~1 km diameter Barringer Meteorite Crater in northern Arizona with the ~1 km diameter North Ray Crater at the Apollo 16 landing site on the Moon. (A) The Apollo 16 landing site with North Ray and South Ray craters. Apollo Image Atlas AS16-P-4558. (B) The traverse that the Apollo 16 astronauts implemented (modified after Stooke, 2007). (C) A ground-level view taken by astronauts from Apollo 16 station 11 at North Ray Crater. NASA image JSC2007e045381. House Rock is labeled near the rim of the crater. The inset shows a cross-section of the rim of North Ray Crater, with the location of House Rock, and a similar cross-section of Barringer Meteorite Crater (a.k.a. Meteor Crater) at the same scale. I thank Celeste Mercer for her help obtaining digital copies of the photographs.

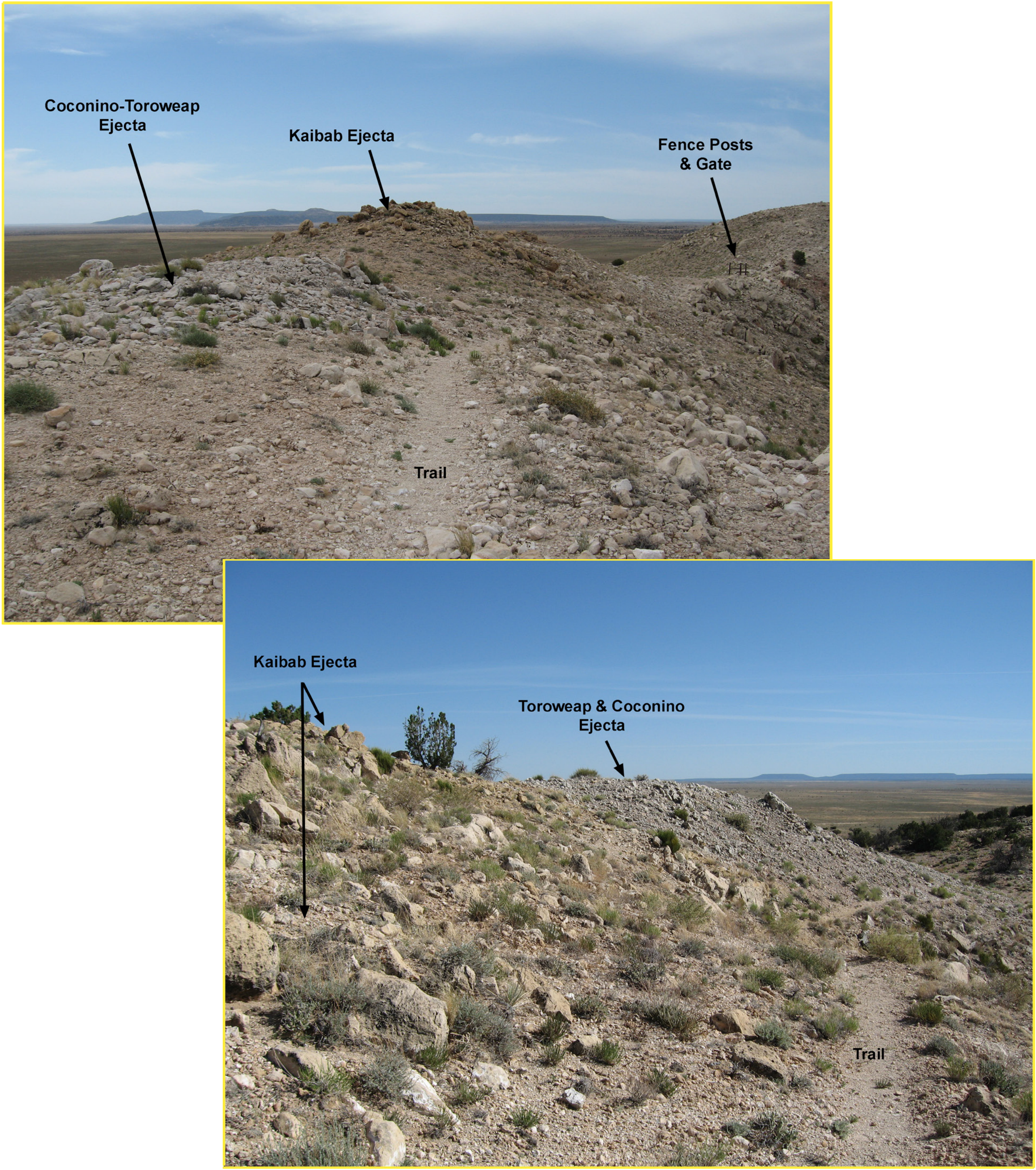


Fig. 17.14. Trailside outcrops of co-mingled Kaibab and Coconino-Toroweap ejecta deposits. The Coconino-Toroweap deposit was first mapped by Barringer (1910) as a ray of debris. There are two potential sources for this type of juxtaposition: (a) Coconino debris fills depressions in a hummocky surface on the ejected Kaibab debris unit (as shown in Fig. 8.4) or (b) material drapes a rim sequence with differential uplift (*e.g.*, on either side of a tear fault), which may be modified further by differential rates of erosion (as shown in Fig. 7.4).

Fig. 17.15. A winch on the crater rim is a reminder of the mining exploration that once occurred at the crater. This winch was probably mule-driven and transported supplies down a slide raised above the rocky crater wall below. The winch is at the top of a large tear fault in the crater wall and rim (which is not visible in the photograph). In the middle distance, one can see blocks and mounds of Kaibab ejecta.

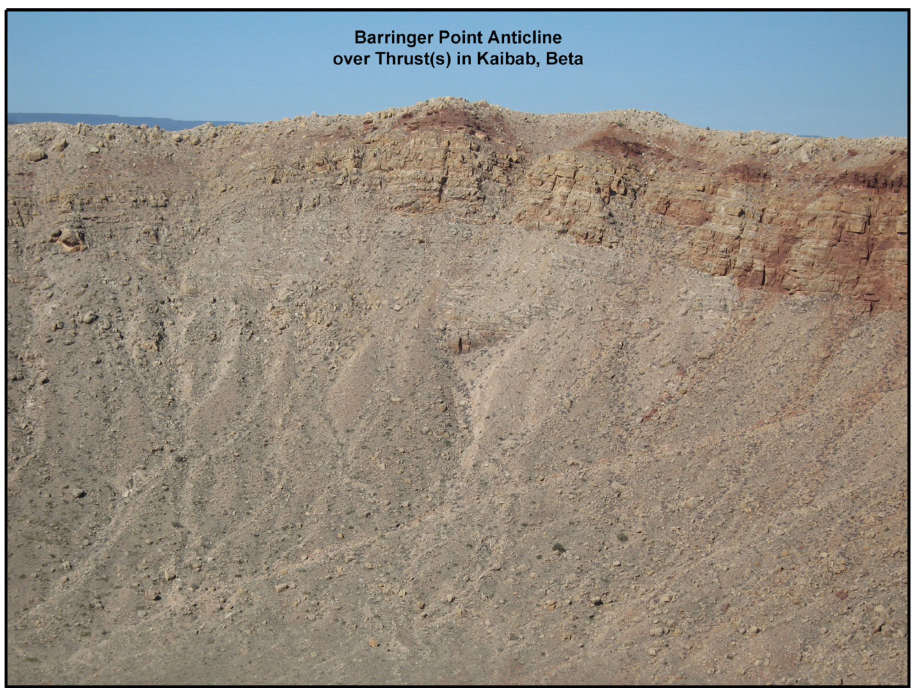


Fig. 17.16. View from southeast crater "corner" of the Barringer Point anticline in the west-northwest portion of the crater wall and rim. Thrust fault(s) within the Kaibab-Beta have thickened that part of the sequence, creating additional uplift of the overlying Kaibab-Alpha, Moenkopi, and ejected debris. Barringer Point is one of the highest topographic points on the crater rim.

Fig. 17.17. Structurally and stratigraphically overturned Kaibab and Moenkopi, with an exposed hinge within the Moenkopi. Crater center is to left and the ejecta blanket lies beyond the top of the crater rim on the right. As can be seen in the lower left (above), the crater wall rocks have been uplifted so that they have an outward dipping slope. The top of the Kaibab reaches near vertical dips. The hinge within the Kaibab is eroded, but a trace of the fold is indicated with a dashed line. At the upper far right, the Kaibab is overturned. Within that Kaibab fold is a Moenkopi fold. Erosion has exposed the hinge in the Moenkopi fold. The location of the hinge within the overturned rim is shown above and a close-up of that hinge is shown to the right. The hinge is visible within the fissile Moqui Member of the Moenkopi. The orbicular Wupatki Member is visible between the Moqui and Kaibab (right).

Fig. 17.18. A field of Kaibab boulders is strewn across the east flank of the crater. Finer-grained ejecta has probably been eroded from the ejecta blanket, exposing larger blocks within the shattered and overturned sequence. Subtle mounds of additional ejecta are visible in the middle distance, including a mound of Coconino-Toroweap debris (near bushes and a pole in the upper left corner).

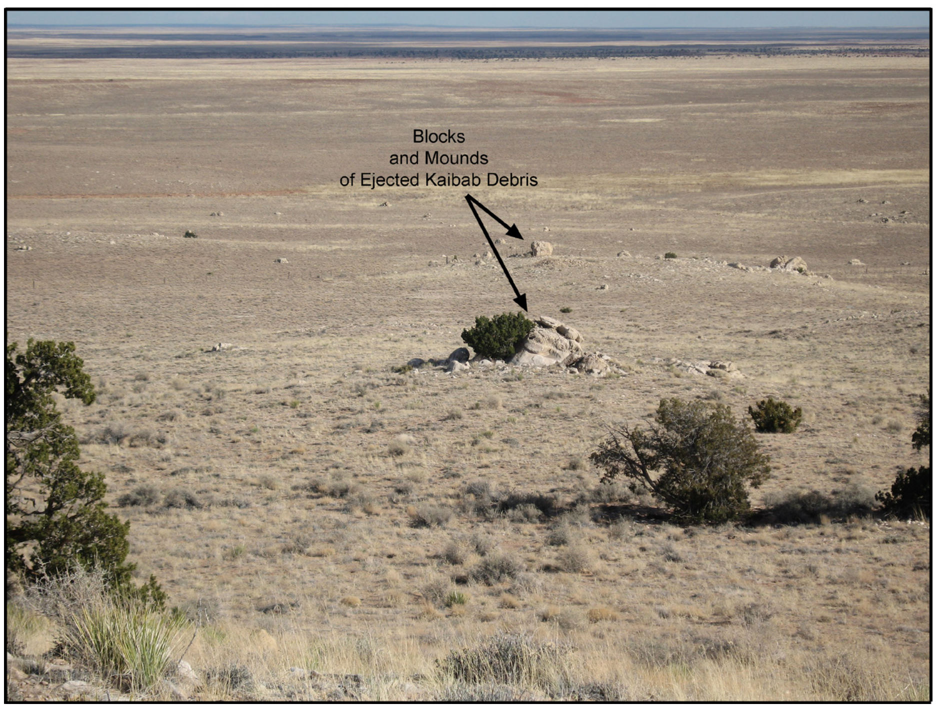


Fig. 17.19. A mixture of large blocks and finer-grained debris within the ejecta blanket is accentuated among the erosional remnants of distant mounds of Kaibab ejecta. The light- colored soil in the fore- and middle- ground is dominated by Kaibab detritus. A transition to red Moenkopi- derived material is visible in the distance.

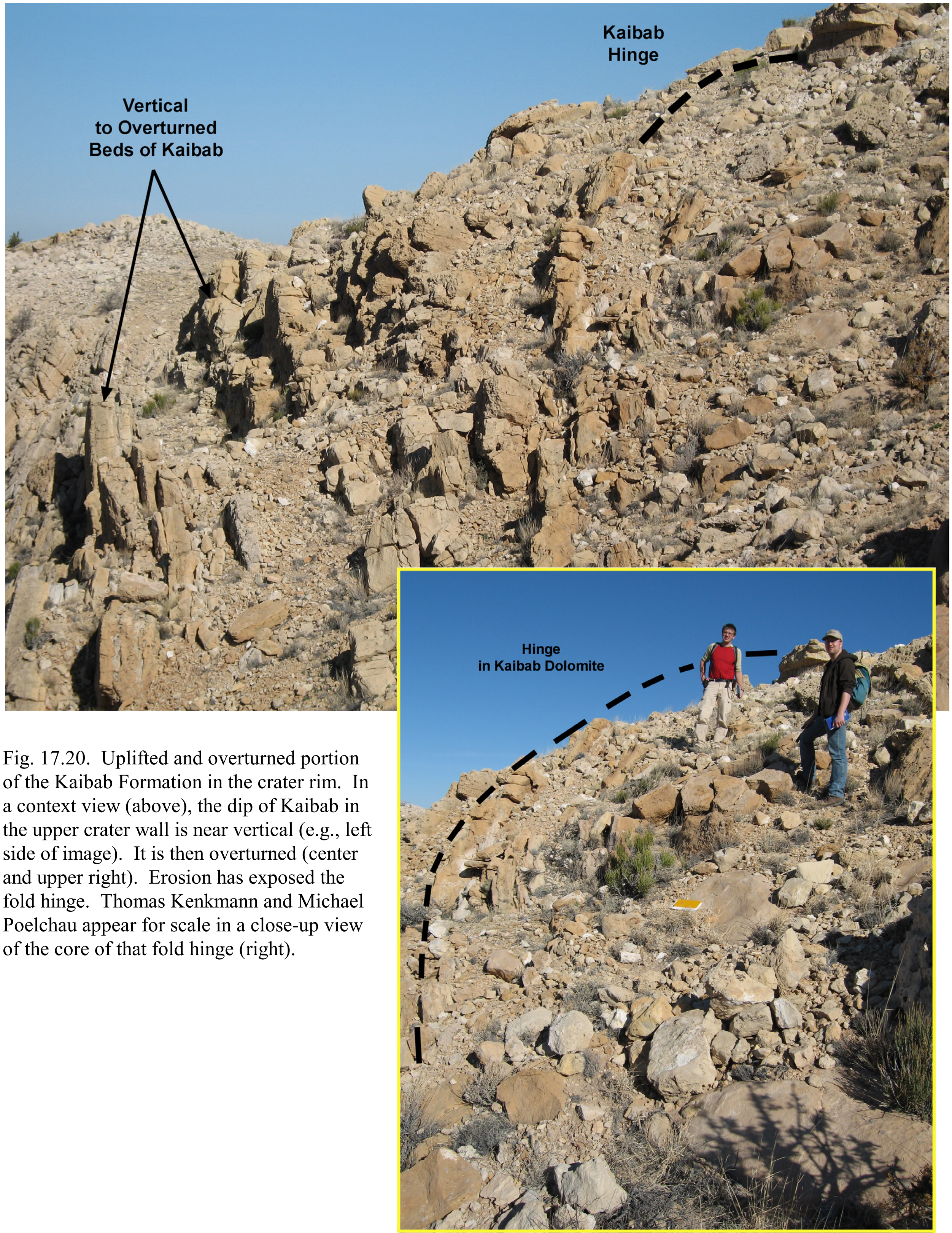


Fig. 17.20. Uplifted and overturned portion of the Kaibab Formation in the crater rim. In a context view (above), the dip of Kaibab in the upper crater wall is near vertical (e.g., left side of image). It is then overturned (center and upper right). Erosion has exposed the fold hinge. Thomas Kenkmann and Michael Poelchau appear for scale in a close-up view of the core of that fold hinge (right).

Fig. 17.21. Impact debris coats the interior wall of the crater (right). Within the shallower-sloping deposits on the lower crater walls, an allogenic breccia is draped over bedrock. The allogenic breccia is draped, in turn, by fall-out breccia. Both are mantled by Pleistocene talus that eroded from the steep upper crater walls. The allogenic breccia is dominated by Coconino and Kaibab debris, whereas the fall-out breccia has a large Moenkopi component. Lechatelierite and meteoritic debris are found within the fall-out breccia. A final view towards the northeast (below) reveals the Hopi Buttes and several mesas. The mesas are carved from Triassic, Jurassic, and Cretaceous sandstones and shales. The Hopi Buttes are the erosional remnants of Tertiary diatremes.