

## 15. Trail Guide 2: Crater Floor



To reach the trail-head for the crater floor excursion, we exit the museum and hike west along a trail on the north rim of the crater. This is the same trail that the public uses when guided by museum staff to the northwest corner of the crater. When we reach the northwest corner, however, we will be stepping off that trail so that we can hike down to the crater floor. Permission to leave the public trail must be obtained from museum staff. Once off the public trail, I ask that you walk softly. Try to avoid stepping on vegetation and do not unnecessarily disturb the soil. After we descend below the ejecta blanket, we will reach and follow a 100-year-old trail into the crater that was developed by the Standard Iron Company. You will see a lot of debris from those mining operations while we descend. A decision was made several years ago to leave those artifacts in place for historical purposes, rather than discard them. Please do not disturb the artifacts. The trail-head is also marked by the remnants of a building constructed of red Moenkopi (Fig. 15.1). That building is the original crater museum.

### *Coconino and Kaibab Ejecta*

This excursion begins in a gap along the crater rim. The gap represents the top of a tear fault through the crater wall that has facilitated erosion, providing an excellent cross-section through the rim sequence. At the top of the gap, just a few feet from the public trail, an incredibly white outcrop is visible (Fig. 15.2). The material in the outcrop is weakly consolidated. It is a mass of shocked and ejected sandstone that is transitional to a type of rock flour that was described by Barringer (1905). The material in the outcrop is heterogeneously damaged. Cores of surviving Coconino with traces of cross-bedding can be found in it. Outcrops like this one also contain his Variety A shock-metamorphosed sandstone, which has a higher density than normal sandstone.

This sandstone deposit is in the midst of Kaibab dolomite ejecta. A patchy distribution of both lithologies occur along this portion of the crater rim, in part because there is a hummocky surface to the Kaibab ejecta blanket. Coconino-Toroweap ejecta fill depressions in that surface. En route to the trail-head, we passed a classic example of this hummocky structure (Fig. 7.3). There is a sharp contrast between the level of impact-induced damage in the Kaibab dolomite and this outcrop of sandstone. Several multi-meter-diameter Kaibab boulders are resting on the rim around us and seem to be completely unaffected by the impact event (albeit upside down), yet the sandstone in the outcrop at our feet is almost pulverized. The same contrast exists in the crater walls beneath the ejecta. Kaibab maintains good bedding and is cross-cut with few fractures, whereas the Coconino is often shattered into angular blocks that are only a few centimeters to decimeters in size.

Continue to descend along the tear fault until you reach the Standard Iron Company's trail and a nice bench in the red Moenkopi.

### *Crater Rim Uplift and Overturning Along a Tear Fault*

From this vantage point, we can easily see that the target strata were uplifted by the impact blast and now have a steep outward dipping orientation (Fig. 15.3). Dips of strata in the crater walls are often 30 to 40°. At the top of the normally-bedded portion of the sequence is red Moenkopi siltstone. Below the Moenkopi is Kaibab dolomite and some minor sands. The Kaibab is a buff to yellow-colored rock, but its surface in the cliff is stained red from the overlying Moenkopi. The Moenkopi and Kaibab are overturned on the upper part of the slope.

Offset along the tear fault is also visible from this location. The rock in the cliff on the far side of the fault were uplifted farther than the rocks on this side of the fault. Tear faults around the wall of the crater have given it a pseudo-square shape in plan view (*e.g.*, Fig. 3.1). Shoemaker (1960) suggested the tear faults were activated along pre-existing sets of joints. In this portion of the Colorado Plateau, there is a strong SE-NW trending set of joints and a weaker SW-NE trending set of joints. Some of the joints that cut through the Kaibab have been accentuated by carbonate dissolution, creating cavernous seams that extend all the way to the underlying Coconino-Toroweap. Several of these large crevices can be found within a few kilometers of the crater.

The tear fault in front of us is not a simple fault plane. The fault surface curves as it climbs up the crater wall and is actually composed of multiple fault surfaces (Fig. 15.4). Drag along the tear fault folded the bedrock on the far side of the fault. Although not shown in the figure, there are also two small thrust faults in the Kaibab-Alpha sequence that are roughly orthogonal to the tear fault. These types of thrust faults contributed to rim uplift and can be found in both the Kaibab-Alpha and Kaibab-Beta units. One of the largest thrust fault systems is below Barringer Point, which is slightly farther to the west along the crater wall. It thickened the Kaibab-Beta, producing an anticline in the Kaibab-Alpha and overlying units. The anticline is the highest topographic point around the crater rim. We will have a good view of the Barringer Point anticline from the crater floor and southeast crater rim later in our excursion.

This tear fault, plus the regional distribution of joints and dissolution through the Kaibab, led Hager (1953) to propose an alternative origin for the crater. He envisioned the crater was originally an anticlinal mound. That is, the dipping strata in the cliffs once arched over the crater in a broad dome of rock. He argued that the dome was cross-cut with fractures similar to those visible in Kaibab today. Water infiltrated those fractures and dissolved subsurface lithologies. The dome then collapsed downward along faults (the tear faults), forming a graben that was subsequently been modified by erosion. Like Gilbert (1896), he argued the meteoritic debris was coincidental. He also argued silica glass found around the crater is the erosional remnant of a pure silica volcanic lava flow.

Continue down the trail towards the crater floor where we will re-assemble. As you hike down the trail, you will encounter a landslide. Climb over the landslide with care. Do not descend directly above another person, in case a rock is dislodged. The first time this trail washed out occurred over 100 years ago in September 1906. An interesting report of the event survives (Fairchild, 1907): A “cloudburst” opened up over the crater and the “northern trail leading down the crater wall was obliterated and trains of boulders were swept far out on the floor of the crater, while the shaft-house, tool-house, and other buildings in the middle of the pit had their floors buried in mud.” If you look to the crater floor below, you can still see some of those boulders.

Once we reach the crater floor, we will hike to the north wall of the crater and climb up to an outcrop of impact breccias. Be careful when hiking across the crater floor, because the soft sediments have been burrowed by animals. You may fall through the roof a burrow system and find yourself knee-deep in the soil. If you move too quickly, you risk breaking a leg.

### *Allogenic and Fall-out Impact Breccias*

A gully dissects debris on the crater wall, exposing two types of impact breccia and a layer of Pleistocene talus (Fig. 15.4). The best view of the units is on the west wall of the gully. The lowest unit is Shoemaker’s allogenic breccia. Patches of this material are found scattered around the crater (Fig. 3.3) and form the thick breccia lens on the floor of the crater. Depending on location, allogenic breccia is composed of Coconino, Kaibab, or a mixture of those two lithologies. It tends to be dominated by Kaibab on the crater walls and Coconino in the breccia lens. At this locality, Kaibab dominates the breccia.

Shoemaker and Kieffer (1974) identified most of the clasts as being from the Beta Mbr of the Kaibab Fm. Clasts within the breccia are angular and have irregular surfaces.

Draping the allogenic breccia is a fall-out or fall-back breccia unit that is up to 1 ½ m thick where it fills a local depression on the surface of the allogenic breccia. This unit has a mixture of target lithologies, including bright red fragments of Moenkopi and brilliant white fragments of shocked Coconino sandstone. Lechatelierite and meteoritic debris occurs in this unit and have been recovered from this particular outcrop.

The impact breccias are buried beneath Pleistocene talus. Elsewhere along the gully, the talus rests directly on allogenic breccia. The fall-out breccia appears to have been eroded from those surfaces prior to the deposition of talus.

From this vantage point, we also have a good view of the east and southeast walls of the crater (Fig. 15.5). The Gamma Mbr of the Kaibab Fm forms a cliff that can be traced around the crater wall. Several displacements of the Gamma Mbr are visible, including a huge displacement along a tear fault in the southeast corner. This tear fault is similar to the one that occurs in the northwest corner, but the displacement is greater. The units on the left (north) side of the tear fault were uplifted 45 m higher than those on the right side of the fault, which exposed 90 m of Coconino sandstone.

Return to the crater floor and hike towards a covered shaft on the east side. Stop at the mid-point.

#### *Sedimentation on the Lower Crater Wall and Crater Floor*

Looking east, we see two sedimentary units on the lower crater wall (Fig. 15.6). The oldest debris occurs in triangular patches that begin near the base of Gamma Mbr of the Kaibab Fm (or at the top of the Coconino-Toroweap Fms) and descends towards the crater floor. The Toroweap Fm is only 1 ½ m thick at the crater, so most of the sandstone visible near the patches of talus is Coconino sandstone. Shoemaker and Kieffer (1974) correlated soil profiles within the talus with soil profiles in the Hopi Buttes region northeast of the crater. They determined that the talus formed at the same time as the late Pleistocene Jeddito Fm. They surmised that the talus was deposited during a pluvial episode during the Wisconsin glacial period. After the talus was deposited, the slope stabilized and a soil formed before the deposits were cut by deep gullies.

Coarse alluvium pours through those gullies and onto the crater floor. This deposit also has a soil of late Pleistocene age and corresponds to the highest soil within the Jeddito Fm (Shoemaker and Kieffer, 1974). The alluvial fans were produced in another pluvial episode during the Wisconsin glacial period. The flow of material through the fans produced levied channels that are still preserved. Although erosion has been modest since the alluvial fans were deposited, it has consumed the lower margins of the fans. Small alluvium-filled channels are dissecting the alluvial fans where they interface with playa sediments on the crater floor.

If we turn around and look west, we see a small hill protrudes from the crater floor (Fig. 15.7). This feature is called Silica Hill. It is composed of Pleistocene lake beds, which imply the level of a lake in the crater was once higher than the hill. The top of the lake sediment is 69 m above the current water table, indicating the water table has fallen dramatically since the late Pleistocene.

Several exploration shafts surround Silica Hill and one of them penetrates the hill. Most of the shafts have been filled in, but Shoemaker was able to examine the walls of the shafts before they were lost. In four shafts (I, II, IV, and V) around Silica Hill, he found three basaltic volcanic ash layers about 5

m below the surface. These are late Pleistocene ashes that were deposited during eruptions in the San Francisco Volcanic Field near Flagstaff, possibly from Saddle Mountain. In contrast, he did not find any ash in Shaft VI on the top of Silica Hill, which suggests the lake level had fallen below the summit of Silica Hill prior to the volcanic eruptions. Any ash that fell on the island was eroded into the surrounding lake.

Shoemaker correlated lake sediments in Silica Hill with the lower to middle stratigraphic levels of lake sediments elsewhere on the crater floor, implying that the base of the lake sediments of Silica Hill is 15 m higher than elsewhere in the crater. Based on this correlation, Shoemaker and Kieffer (1974) suggested the lake sediments of Silica Hill were deposited on top of a topographic high or off-centered “central peak” on the original crater floor. Structural uplift of underlying bedrock is not expected in a crater this small, nor is there evidence of it in exploration boreholes and geophysical surveys. However, observations of lunar craters suggest uneven topography can form on the surface of the breccia lens during collapse of that debris from the walls of the transient crater.

Silica Hill is surrounded by playa sediments that were deposited after the lake disappeared. They are beneath our feet (Fig. 15.8). In the walls of the Main Shaft, Shoemaker measured a total thickness of 1.8 m. The playa sediments are composed of pink aeolian silt that blows in from outside the crater. In a trench cut into the playa beds, he found two volcanic ash layers that he correlated with the eruption of Sunset Crater. Using that ash as a chronometer, he determined that 30 cm of playa sediments have been deposited since the eruption. The eruption occurred ~900 years ago, possibly in 1064 or 1065 (Smiley, 1958).

Continue hiking across the crater floor towards the southeast corner of the crater, where we will begin our hike up to the crater rim. En route, we will pass several remnants from mining operations. We will stop at Shaft II on the east side of the crater floor. If time allows, one can also detour to the Main Shaft in the crater center.

#### *Probing the Crater Floor in 100-Year-Old Exploration Shafts*

A large steam boiler and winch sits in the center of the crater floor (Fig. 15.9), immediately east of the Main Shaft, which is enclosed by a safety fence. (Do not enter this fenced area.) The Main Shaft is a large 2-compartment shaft suitable for commercial production of meteoritic ore. Unfortunately, water was encountered at a depth of 210 ft (63 m). Pumps were installed, but they could not mitigate the flow of water and work ceased at a level of 230 ft (69 m) when the walls at the bottom collapsed. A building used to stand over the main shaft (Fig. 15.10). Shaft III is adjacent to the Main Shaft and also surrounded by a safety fence.

Shaft II is on the east side of the crater floor and now covered by a set of doors (Fig. 15.9). The shaft is 43.3 m (145 ft) deep. The upper 30 m (100 ft) of the shaft is composed of lake sediments with the volcanic ash described above. Below the lake sediments is 10.3 m (35 ft) of fall-out breccia. The unit is generally massive, but there is a subtle grading upwards from coarse debris at the bottom to finer-grained debris at the top of the unit. The basal 1.3 m (5 ft) is particularly coarse. The shaft penetrates 3 m (10 ft) into the allogenic breccia lens on the crater floor, where it bottoms. The allogenic breccia is composed entirely of Coconino sandstone. Some of the blocks are more than a meter in size. Superficially, the blocks look like they represent several levels of shock, indicating that there was a lot of mixing on the walls of the transient crater before the material was deposited.

A dump around the top of the shaft contains debris from all levels in the shaft. Much of the dump has an inverted stratigraphy, because material removed from the bottom of the shaft was dumped on

material previously removed from the top of the shaft. However, the miners also dumped material on different sides of the shaft as they plunged deeper. Fall-out breccia dominates the surface on the east side of the dump. Allogenic breccia dominates the surface on the southwest side of the dump. Lacustrine sediments dominate the northwest side of the dump.

Material from the fall-out unit contains severely shocked Coconino sandstone, including vesicular silica glass. Shocked Coconino is also found in material from the allogenic breccia, but shock levels are less severe. Microscopic examination might be needed to classify the shock level. The lacustrine sediments are dominated by thinly-laminated, calcareous siltstones with fossils of the organisms that lived in the lake. Although not apparent in the dump, the lake sediments also contain shock-metamorphosed debris. In the shaft, the lower 1.5 m (5 ft) of lake sediments contain many blocks of lechatelierite. Shoemaker measured one block of lechatelierite that was 30 cm across. These low density materials were able to float while water flooded the crater and a lake grew. Eventually they became water-logged, sank, and were buried by the first lake sediments. Lechatelierite blocks may have floated up directly from fall-out breccia deposited on the crater floor, but some of them may have also been washed into the lake from the crater walls.

The contact between the fall-out breccia and lacustrine sediments is sharp. There is no intervening alluvium. Based on this observation, Shoemaker and Kieffer (1974) concluded the lake formed immediately after the impact event and, thus, that the water table was at least 30 m higher in the Coconino sandstone than it is today.

Unfortunately, the cribbing in this shaft is no longer safe and work in it has been suspended. Before the shaft was closed, however, I was able to sample the first horizon of lake sediments deposited on top of the fall-out breccia on the original crater floor. Pollen in that sample was used to improve an environmental reconstruction of the vegetation at the time of impact. (See Chapter 12 for more details). Plans have been made to replace the cribbing, so that we have a permanent research and educational facility that provides access to both the impact breccia lens and overlying lake sediments. We are still working to acquire the necessary funds for the project.

Continue hiking towards the southeast corner and begin climbing out of the crater along an old mule trail. The trail will switch back and forth across Pleistocene alluvium. We will stop when we reach the base of the cliffs along the southern wall of the crater.

### *Toroweap Cave*

The Toroweap Fm is much thinner at the crater than it is in the Grand Canyon. Only 1.5 m is found between the underlying Coconino Fm and overlying Kaibab Fm. A small cavernous exposure is visible to the right (southwest) of the trail (Fig. 15.11). Large fractures in the Gamma Mbr of the Kaibab Fm feed water into the boundary region, enhancing erosion of the Toroweap. The dissolution of Toroweap appears to be a post-impact phenomenon. However, elsewhere in the region, large subsurface caverns have been found immediately below the Kaibab-Toroweap contact. Thus, caverns may have existed in the target sequence prior to impact.

Continue hiking up the trail. Three stops are planned for the remainder of the climb to the crater rim.

### *Hauling supplies*

During mining operations, a lot of supplies had to be transported into the crater. Mules carried some of that material on the trail we are following. Material was also winched to and from the crater floor along a slide that was built on the crater walls. Remnants of the wooden staging can still be seen on the slope (Fig. 15.12). A mule-driven winch sits at the top of the slide on the crater rim. The primitive elevator is no longer in service.

Mining activity within the crater was widely followed by newspapers across the country. In 1906, The Arizona Republican published a summary of the operations and Barringer's impact hypothesis after the first four holes had been drilled in the crater floor and concluded: "It is fortunate indeed for Arizona, that this wonder came into the possession of the men who became deeply interested in it and who at the time had the money and pluck enough to exploit it (February 26, 1906)." Newspaper stories sometimes had a few facts wrong or were intentionally exaggerated. For example, based on the presence of diamonds in Canyon Diablo meteorites, The Indianapolis Star reported (October 6, 1912) that the mining syndicate was trying to recover a half-mile thick diamond.

### *Thrust Faults and Anticlines in Crater Walls*

Looking towards the northwest corner of the crater (Fig. 15.13), we can see the tear fault that we utilized in our earlier descent to the crater floor. The drag fold on the west side of the fault is easily visible from this perspective. Scanning around the crater wall to the west, we see Barringer Point, which is the highest point on the crater rim. The Beta Mbr of the Kaibab Fm is unusually thick beneath Barringer Point because of one or more thrust faults. The thickened sequence contributes to the uplift of the crater wall and has created an anticline.

Another thrust fault can be seen beneath Moon Mountain (Fig. 15.13). In this case, a section of the Alpha Mbr of the Kaibab Fm has been duplicated, forming another anticline and topographic high.

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. They occur on the west, north, and east sides of the crater. The thrusts are often small, but can 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 and Kieffer (1974) suggested that a concentration of thrust faults in the northwest wall of the crater indicates the impacting asteroid was moving from southeast to northwest. I concur, although I worry that we may be biased by what we can observe. If thrust faulting occurs at depth, lower in the crater walls, it is hidden from us and not factored into our analysis. For that reason, new studies of other structural indicators are underway to further test the trajectory.

### *Breccia at the (Permian-Triassic) Kaibab-Moenkopi Boundary*

In some parts of the crater, a breccia occurs at the Kaibab-Moenkopi boundary. An example is visible along the trail (Fig. 15.14). The breccia is often dominated by Kaibab clasts, as is the lower portion of the outcrop here. Another outcrop of this breccia occurs along the north wall of the crater (Fig. 15.15) where it can be traced for over 100 m. Several other outcrops occur on the south wall of the crater near our present location. The matrix is often sandy and weathers differently than enclosed dolomite clasts.

There are three possible origins for the breccia: (1) the breccia is a karst product that existed at the top of the Kaibab before impact; (2) the breccia was formed by shear between the Kaibab and Moenkopi during the impact; and (3) the breccia was produced when debris on the transient crater wall was injected between the Kaibab and Moenkopi during impact.

Shoemaker and Kieffer (1974) described a similar unit adjacent to the museum complex. At that locality, the uppermost unit of Kaibab has irregular to chaotic bedding with clasts of sandstone and sandy dolomite. They interpreted the unit to represent a karst surface that developed during the late Permian and/or early Triassic. Breccias in the uppermost interval of Kaibab have been described elsewhere on the Colorado Plateau, particularly in Utah. Paul Knauth (personal communication, 2007) told me that several examples also occur in the Grand Canyon region. Those breccias, however, are dominated by chert pebbles.

The breccia may be more complex than previously appreciated and is currently being re-investigated. The study is not complete, but a description of some of the observations will be provided for our discussion.

Although the outcrop described by Shoemaker and Kieffer (1974) is composed entirely of Kaibab clasts, some outcrops elsewhere in the crater contain red clasts. These are sometimes red-stained Kaibab clasts, but in many cases are true Moenkopi clasts (Fig. 15.16), which is inconsistent with scenario (1). The sand matrix does not appear to be a simple sediment deposit, infiltrating and burying karst dolomite cobbles. Rather, it sometimes appears to be injected through fractures in clasts (Fig. 15.15). The unit is sometimes compressed into small folds, whose limbs can be sheared (Fig. 15.17). Fractures and displacements also occur within Kaibab-dominated outcrops of the breccia unit (Fig. 15.18 and 15.19). Elongated clasts are sometimes aligned, as if part of a flow (Fig. 15.20). The presence of Moenkopi and Kaibab clasts, injection textures, and internal shearing of clasts seems to point to scenarios (2) and (3). The folding of breccia horizons, however, suggests the breccia unit already existed. That either points to scenario (1) or requires formation and lithification of the breccia early in the cratering process and then folding late in the cratering process. Finally, a block of Kaibab-dominated breccia was found on the rim of the crater. If it was not moved during earlier exploration phases at the crater and is a part of the ejecta blanket, then it points to scenario (1) or the special circumstance of formation and lithification of an impact breccia early in the cratering process. Alternatively, there may be two types of breccias at the Kaibab-Moenkopi boundary, one that existed in the target sequence and another that was generated during the impact. The outcrop in front of us hints at a two-step formation process.

Continue hiking towards the crater rim.

#### *Coconino-Toroweap Impact Ejecta*

When we reach the rim of the crater, the ground will be paved with ejected debris from the Coconino-Toroweap Fms (Fig. 15.21). These sandstones dominate the surface of the ejecta blanket on the south side of the crater. Only small patches of that type of debris are found on other sides of the crater.

The sandstone ejecta is dominated by cobble- to small boulder-size fragments. These fragments are much smaller than the immense boulders of Kaibab that we observed at the beginning of our excursion. Immediately after the impact event, this Coconino debris was probably covered with a layer of fall-out debris. Erosion removed it.

The Coconino is formed from an aeolian sand. The blocks of debris on the surface are laminated,

but it is sometimes difficult to determine if the laminae are cross-beds. Rare examples of the truncated interface of a cross-bed can be found, however (Fig. 15.21 inset). Appropriately, the sandstone is being eroded to produce another generation of aeolian sands. The new sand forms small dunes on the southern flank of the crater. Long wind streaks of sand stretch from the crater towards the northeast, reflecting the prevailing southwest wind. The sand dunes lap up against two-needle pinyon pine and juniper trees. The latter were examined by Barringer's team. Tree-rings indicated some of the trees are more than 700 years old (in 1905), or more than 800 years old now. This is the minimum age of the crater.

A short distance to the west is the top of the 1,376 ft deep borehole that was drilled through the crater wall and into a fractured and/or brecciated sequence contaminated with meteoritic debris. (See Chapter 3 for details.) Even farther to the west are the "Silica Pits," which are composed of finely comminuted Coconino. At that location, fractured versions of the blocks at our feet occur in a massive and brilliantly white matrix of "rock flour."

That deposit is covered with a breccia that contains red Moenkopi fragments. Because the only outcrops of Moenkopi on the south side lie below the crater rim on the interior crater wall, those Moenkopi-bearing deposits are candidates for surviving fall-out breccia. Shoemaker (1960), however, mapped them as post-impact alluvium. Although they may be secondary deposits, they contain many of the eroded remnants of fall-out debris, including Class 4 and 5 shock-metamorphosed Coconino sandstone.

To examine hinges in overturned Moenkopi and Kaibab, however, we need to follow the rim trail towards the east. We will use the Crater Rim East trail guide for the remainder of the hike back to the museum.



Fig. 15.1. The remnants of a stone building sit at the top of a tear fault through the crater rim. The building was the original museum at the crater. It sits on top of the impact ejecta blanket, which has an inverted Moenkopi, Kaibab, and Coconino sequence.

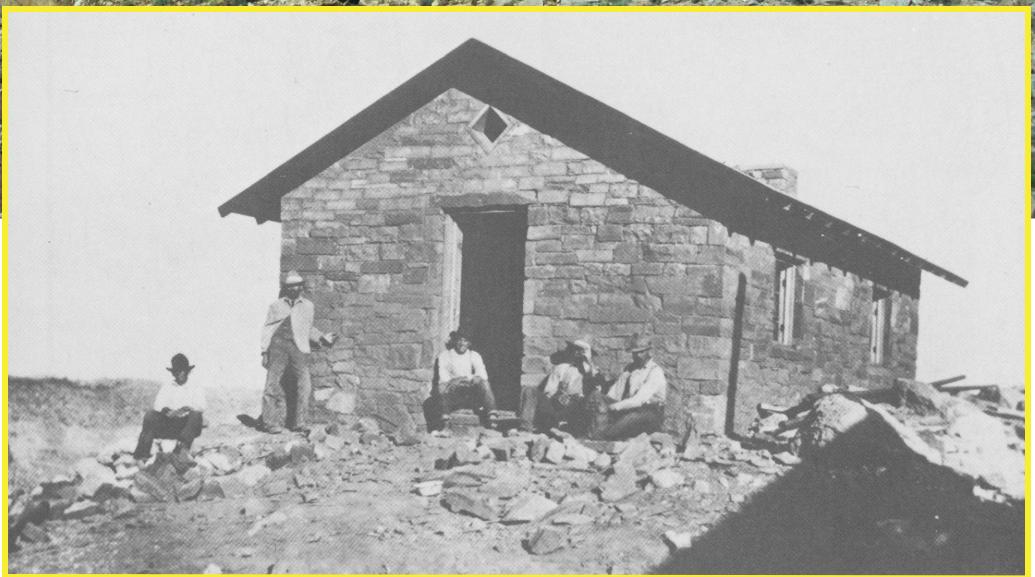




Fig. 15.2. Outcrop of shocked and ejected Coconino sandstone. The sample is transitional to "rock flour" and may contain remnant cores of relatively unshocked Coconino sandstone. Shock may have created a slatey cleavage within these types of units that is distinct from pre-existing target cross-bedding. This outcrop of Coconino debris was deposited in a depression on a hummocky surface of Kaibab ejecta. The Coconino debris in this outcrop is more severely damaged than Kaibab material in the area.

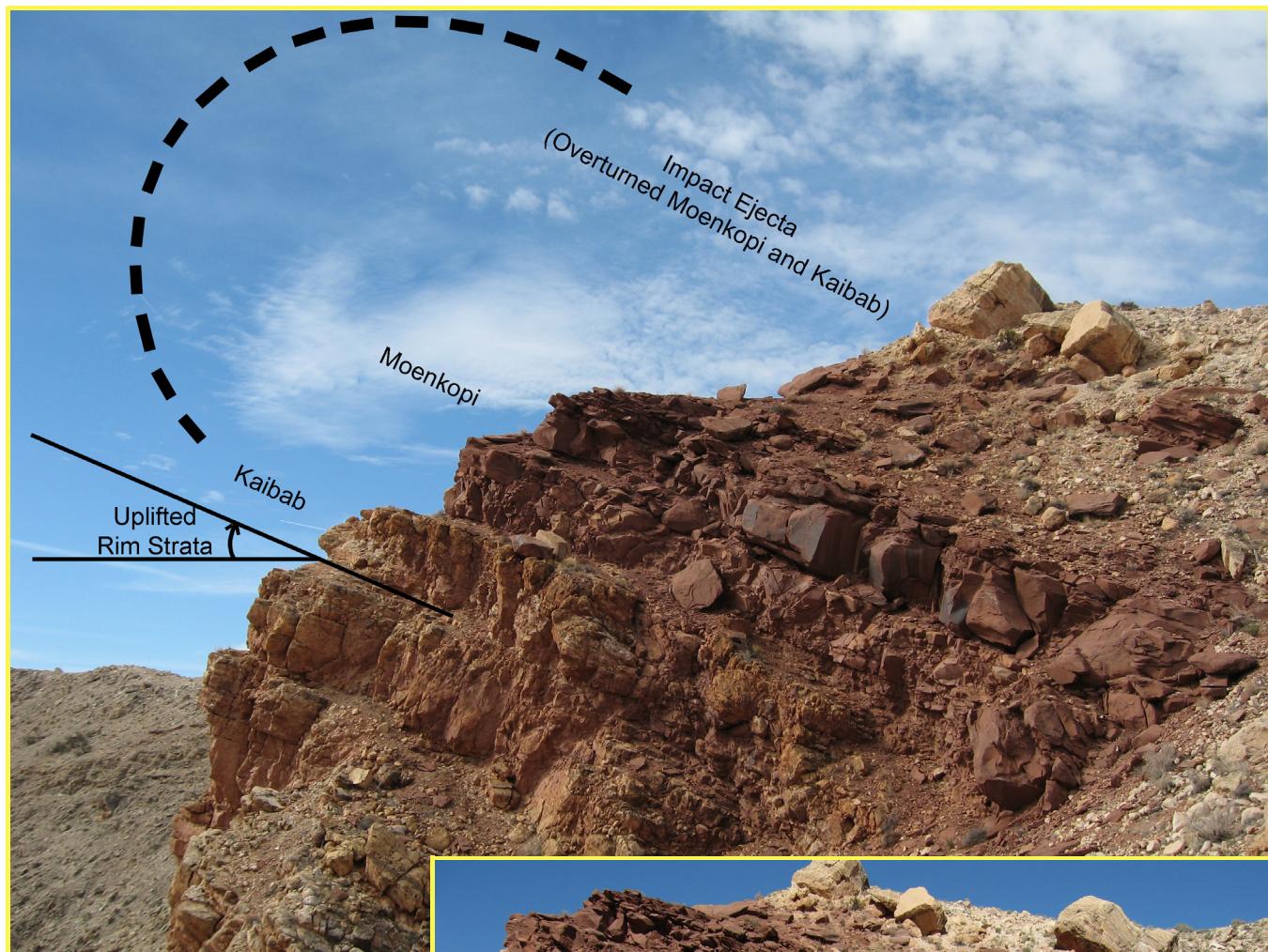


Fig. 15.3. View of structure in the crater wall. Strata that had a horizontal pre-impact orientation were uplifted during crater excavation (above). Dips are often 30 to 40 degrees. The strata were also overturned and ejected. This further enhanced rim height and distributed debris over the surrounding landscape. Crater wall uplift was not uniform. Differential uplift was accommodated (or facilitated) by tear faults (right) that may have been produced along pre-existing joints. Offsets along these tear faults range from meters to several tens of meters. The structure illustrated (right) is simplified. Small thrust faults, for example, also occur in this part of the crater, but are not easily seen in this image.





Fig. 15.4. Outcrop of allogenic breccia, fall-back breccia, and Pleistocene talus (upper left). Close-up views of allogenic breccia (bottom left), fall-back breccia (above), and fragment of impacting asteroid eroding out of fall-back breccia (left center). Fall-back breccia contains Moenkopi, whereas allogenic breccia is dominated by Kaibab and Coconino.

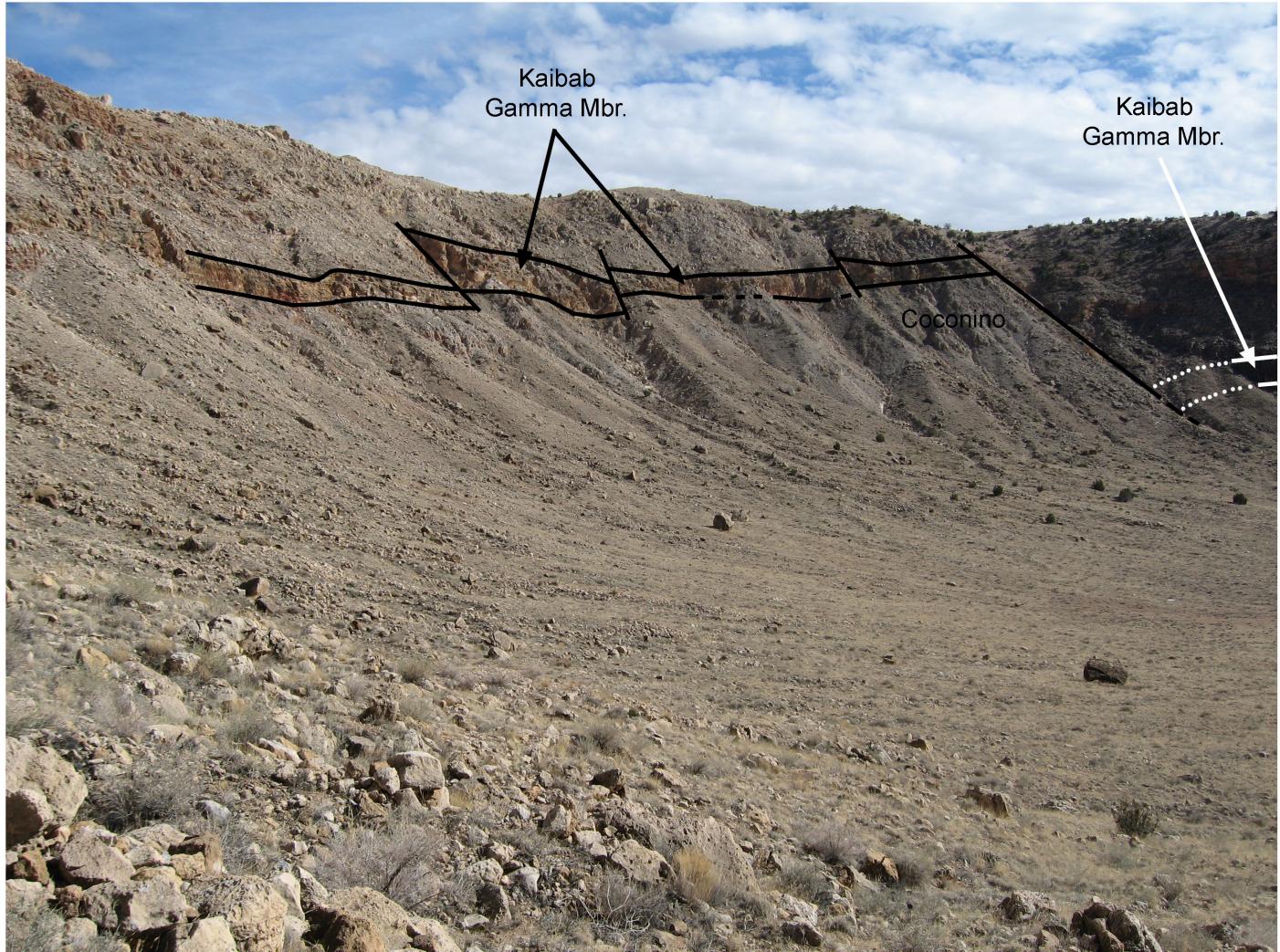


Fig. 15.5. From this vantage point we can trace the Gamma Mbr of the Kaibab Fm along the east crater wall, into the southeast corner of the crater, and part way across the south crater wall. The unit is off-set by several faults, including a large tear fault in the corner. The displacement along that tear fault is 45 m. On the north side of the tear fault, 90 m of Coconino sandstone is exposed. Coconino is not exposed on the southside of fault and only traces of Coconino and Toroweap can be found along the south crater wall. Those units along the south crater wall were buried by alloigenic and fall-out breccia (like the deposits examined in the previous figure) and Pleistocene talus (like that in the foreground of this photograph).



Fig. 15.6. The lower walls of the crater are covered by Pleistocene sediments. Talus derived from the upper crater walls was produced first (Qpt) and then dissected, so that only small remnants survive. A younger alluvium (Qp) spilled through the dissecting gullies and flowed towards the center of the crater. Two periods of wetter climatic conditions than we have today are implied. The margins of the younger alluvium deposit are now being dissected and overlapped by recent playa deposits. View is to the east from the crater floor.

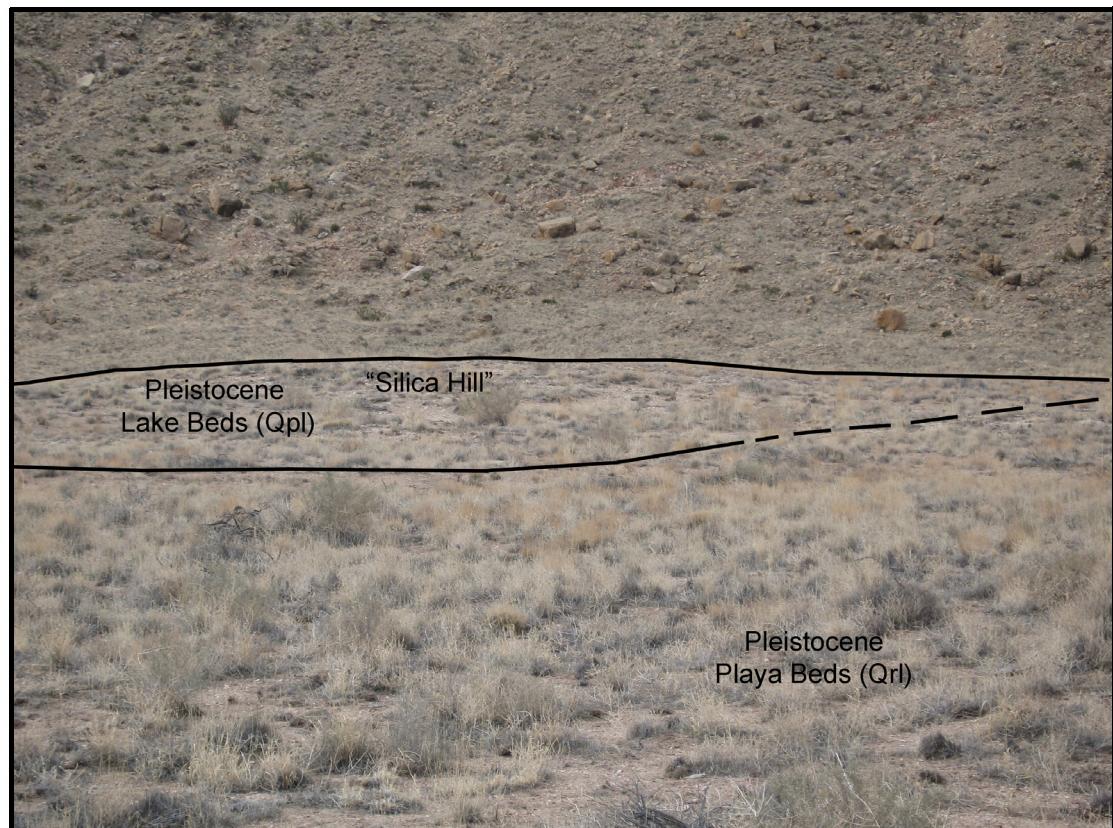


Fig. 15.7. A hill composed of Pleistocene lake sediments rises on the north side of the crater floor and is surrounded by recent playa sediments. The lake sediments imply at least one period of wetter climatic conditions, sufficient to raise the water table >69 m above its current level. The lake sediments are nearly 30 m thick and cover the original floor of the crater. View is looking west. The trail that descends from the northwest corner of the crater rim cuts across the slope in the background.



Fig. 15.8. Desiccation polygons or mud cracks occur on the crater floor, reflecting current arid conditions and intermittent rainfall. These features are found in playa sediment, new fine-grained alluvium, and remnants of drilling mud generated during mining operations. These recent, relatively soft-sediment features are similar to lithified features in the Triassic Moenkopi Fm in the upper crater walls (e.g., Fig. 2.4).

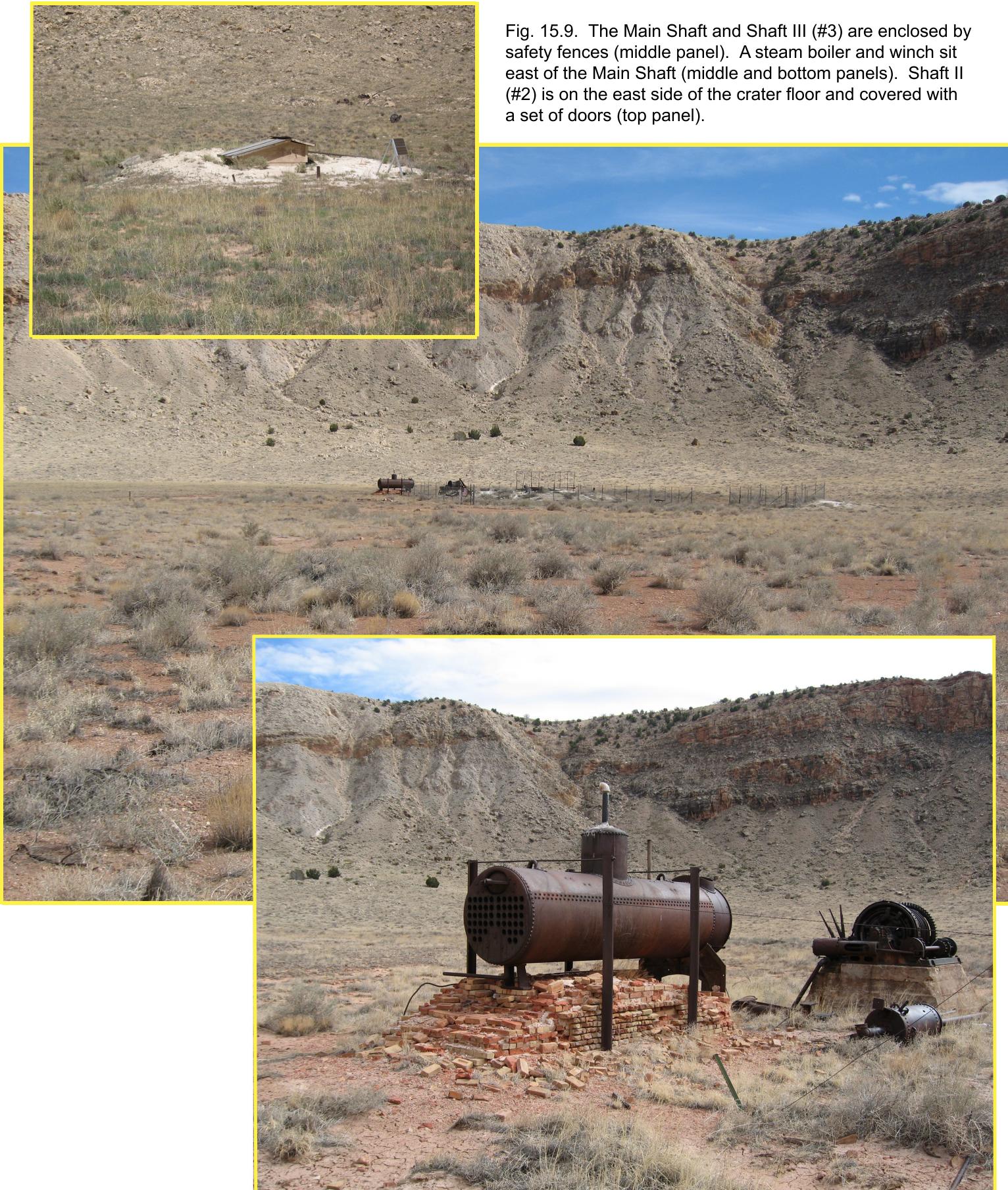


Fig. 15.9. The Main Shaft and Shaft III (#3) are enclosed by safety fences (middle panel). A steam boiler and winch sit east of the Main Shaft (middle and bottom panels). Shaft II (#2) is on the east side of the crater floor and covered with a set of doors (top panel).

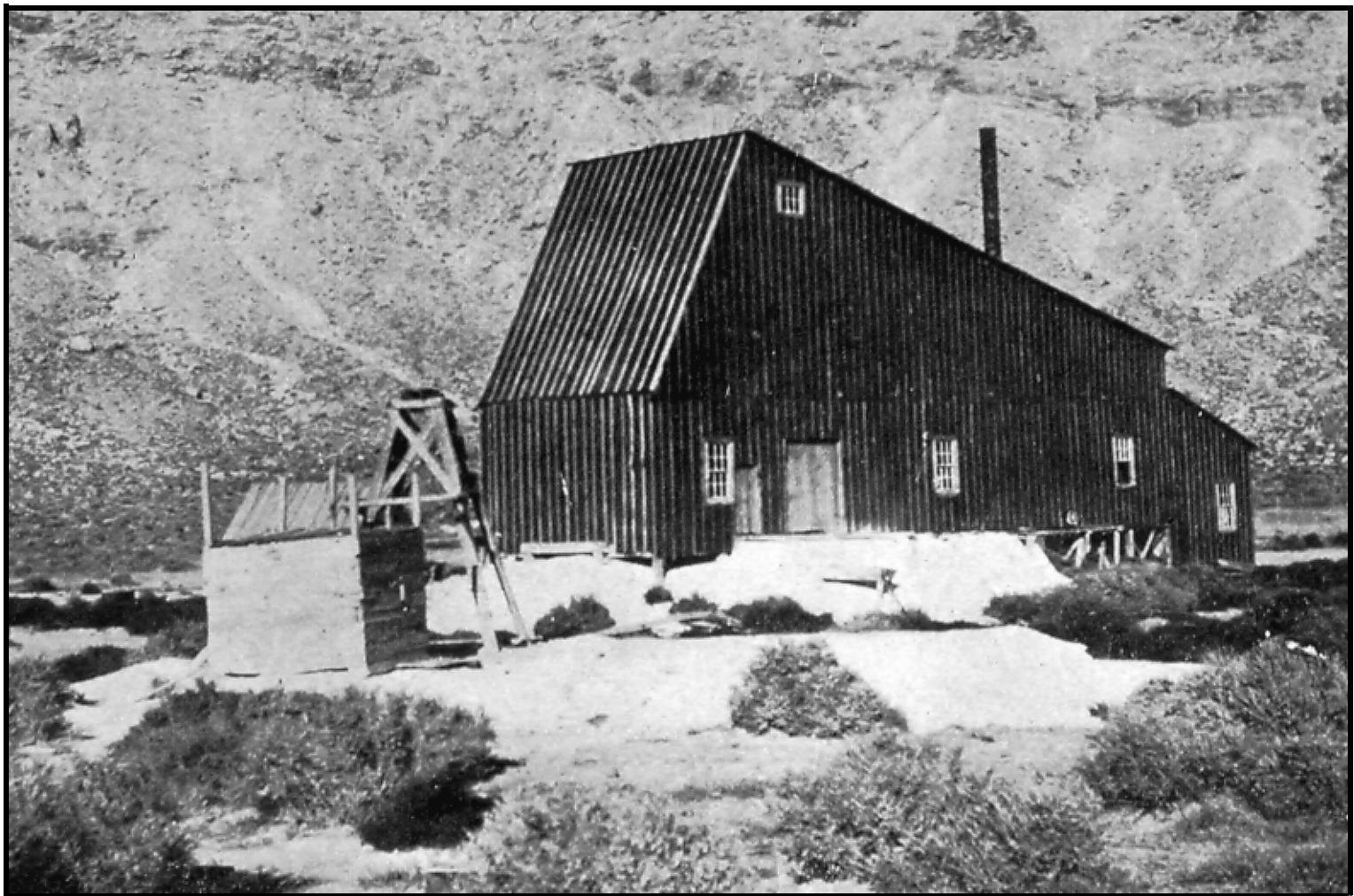


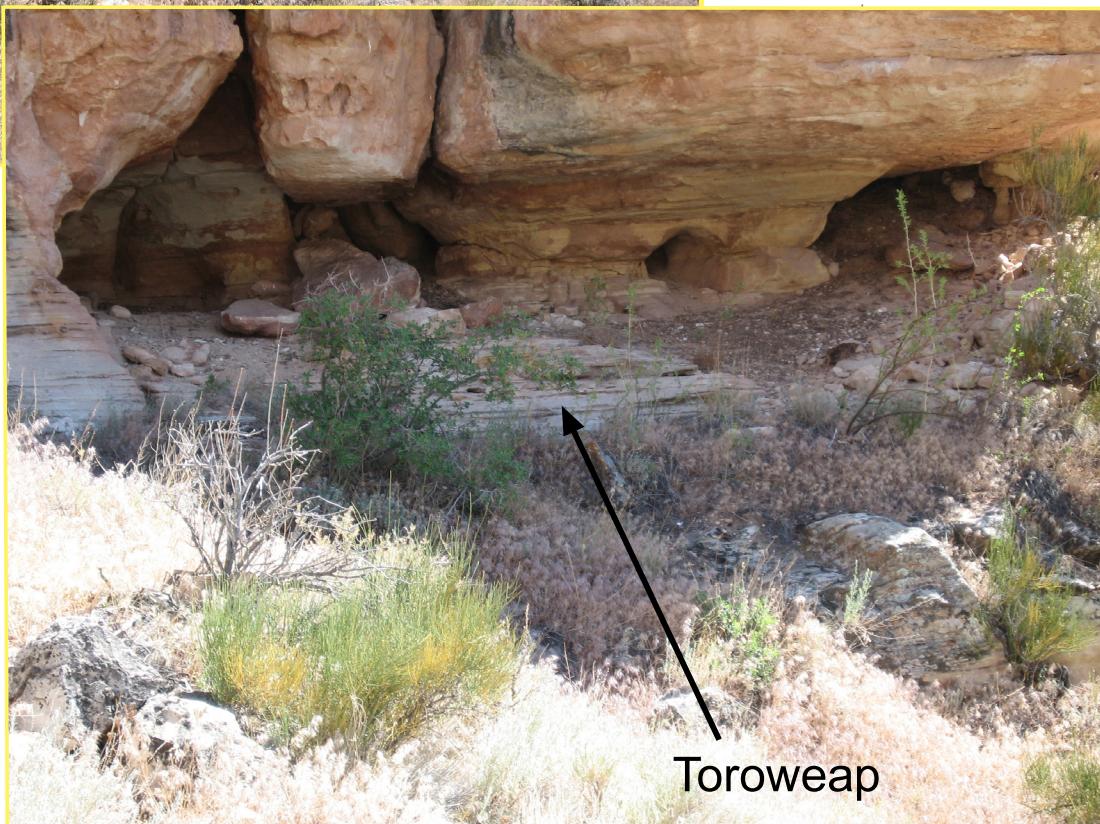
Fig. 15.10. Main Shaft house in the center of the crater floor. The shaft is very wide so that it would be suitable for two compartments. Excavation in the shaft reached a depth of ~230 ft, which was ~20 ft beneath the water table. Pumps were installed, but the bottom of the shaft collapsed and the effort to descend farther was abandoned. (Bottom panel of Plate XI in Barringer, 1910.)

Fig. 15.11. A cave in the Toroweap Formation is visible from the trail while hiking out of the crater (right). Water flows from the rim of the crater down through vertical fractures in the crater wall (middle and bottom panels). Water is then flushed into the crater at the Kaibab-Toroweap contact and through the Toroweap, causing preferential erosion of Toroweap sand. This sequence is a potential analogue for some local hydrological and erosional features on Mars.



Kaibab  
Gamma Mbr.

Note: This and other niches around the crater contain pack-rat middens. Please do not disturb the middens, because they will be analyzed to better determine the age of the crater and how climate has changed since the crater formed. The middens may also harbour the deadly Hanta-virus Pulmonary Syndrome.



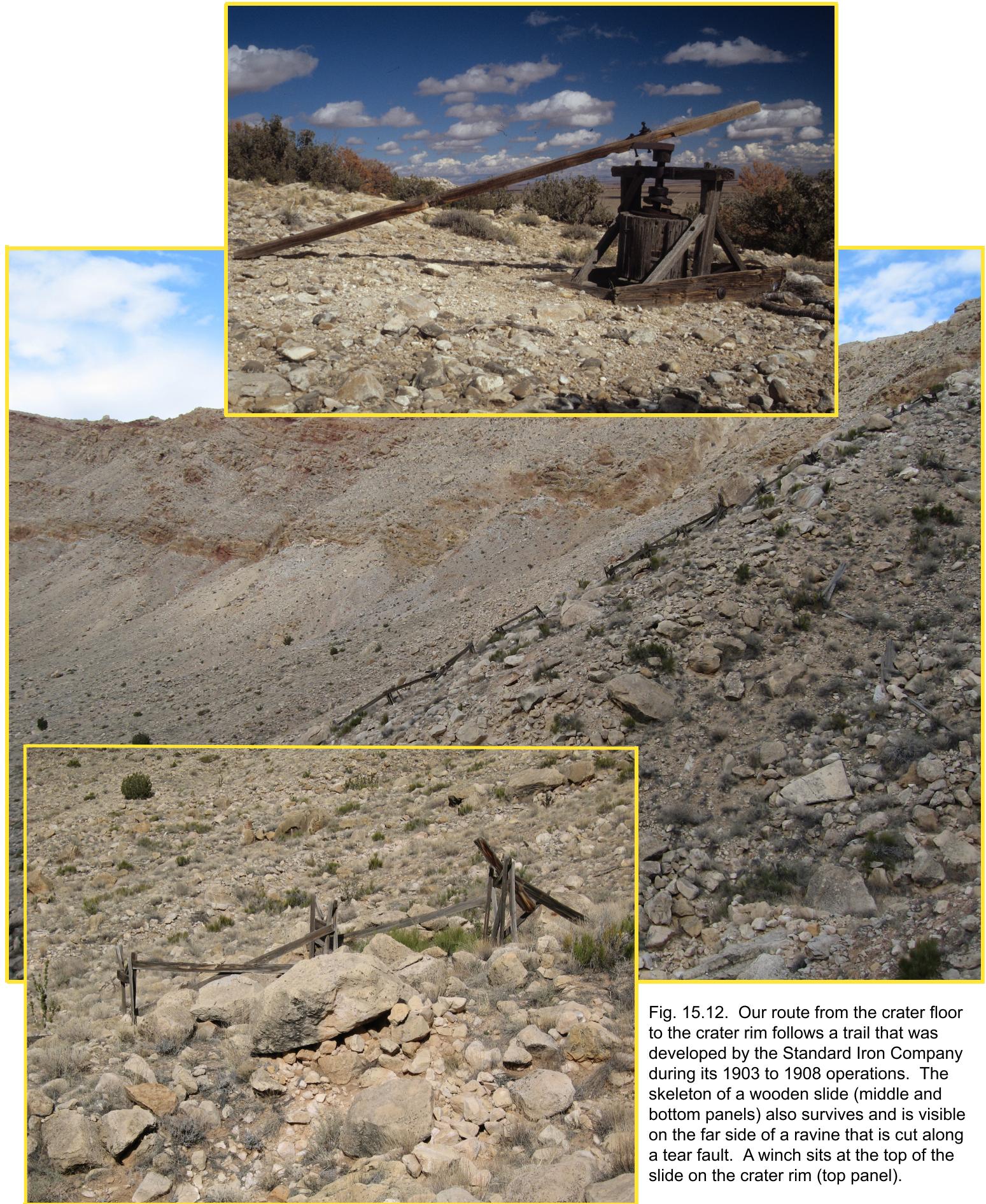


Fig. 15.12. Our route from the crater floor to the crater rim follows a trail that was developed by the Standard Iron Company during its 1903 to 1908 operations. The skeleton of a wooden slide (middle and bottom panels) also survives and is visible on the far side of a ravine that is cut along a tear fault. A winch sits at the top of the slide on the crater rim (top panel).

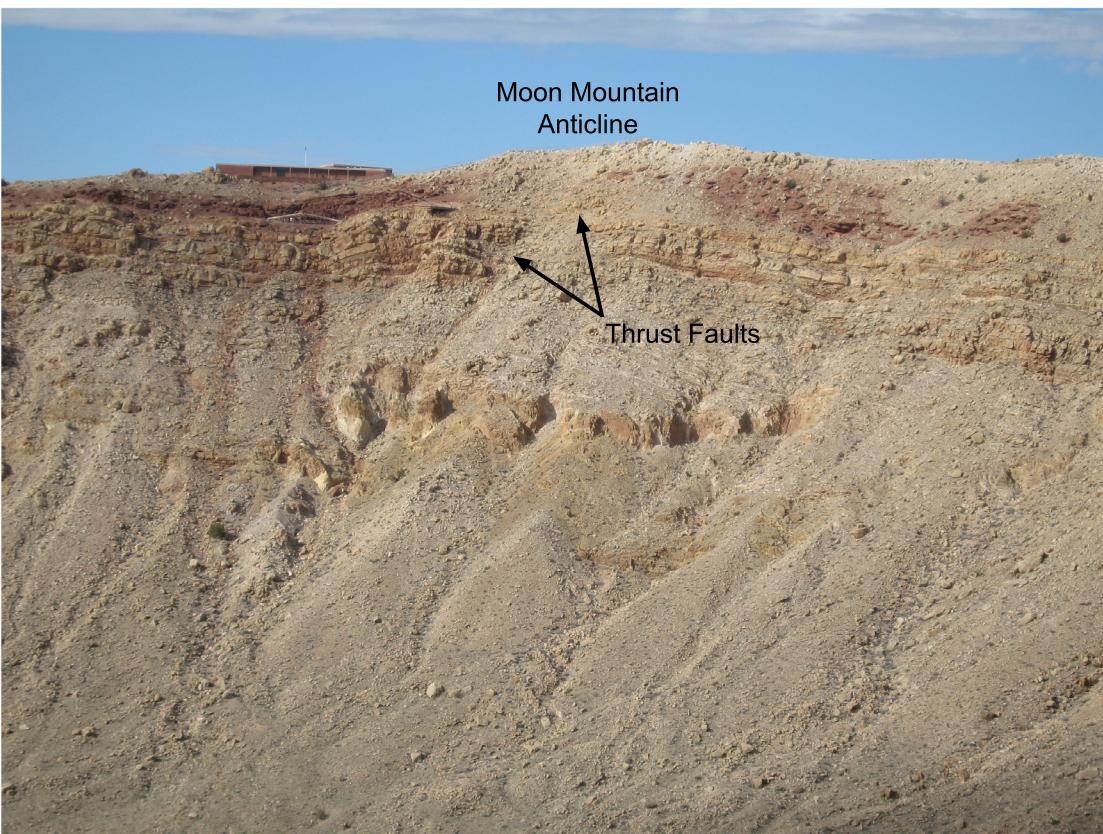
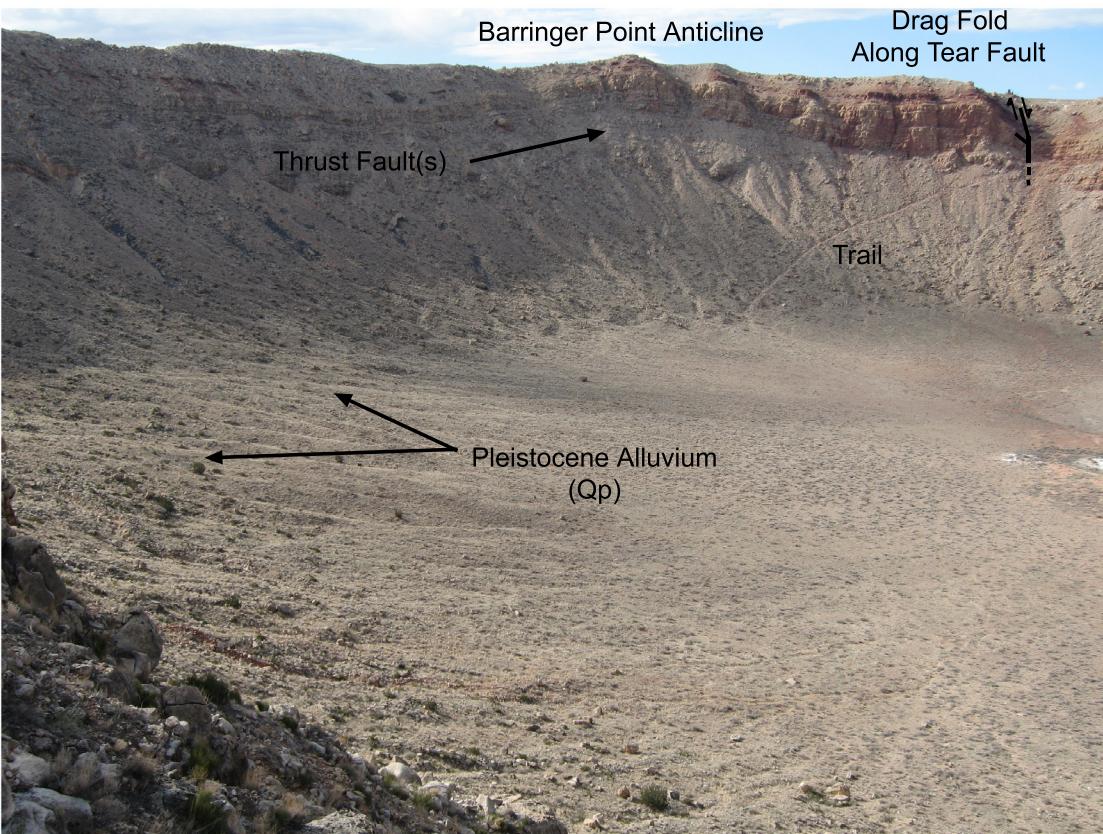


Fig. 15.13. Structural features associated with crater rim uplift are visible in distant crater walls. To the west-northwest (top panel) the Barringer Point anticline is visible; it is uplifted by one or more thrusts in the Beta Mbr of the Kaibab Fm. Moving clockwise around the crater rim, a complex tear fault is visible in the northwest “corner” of the crater. Drag along that fault is apparent to the left of the fault, near the trail we descended. Pleistocene alluvium that was shed from the crater walls is also visible in that same view. To the north, adjacent to the museum complex (bottom panel), the Moon Mountain anticline is visible. It is uplifted by thrust faults within the Alpha Mbr of the Kaibab Fm.



Fig. 15.14. The trail rises through Moenkopi (upper left). Slightly below trail level is the Kaibab-Moenkopi boundary (left center). Here, and at a few other locations around the crater, a breccia occurs at this boundary. Portions of the breccia are dominated by Kaibab clasts (lower right), although some portions contain Moenkopi clasts (upper right), including blocks with pre-existing desiccation cracks.

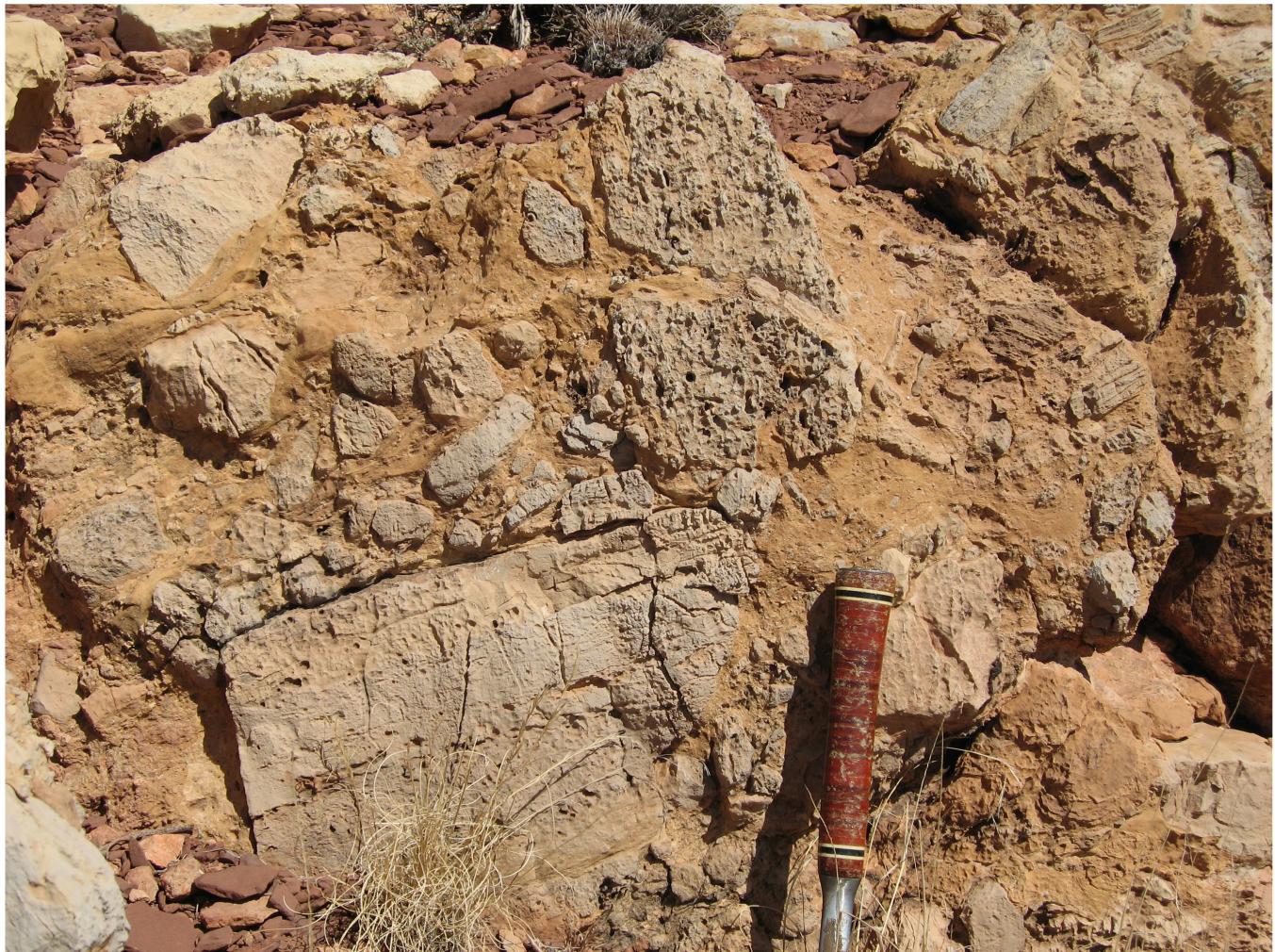


Fig. 15.15. Outcrop of breccia at the Kaibab-Moenkopi boundary. Clasts of dolomite are being etched by acidic water. The matrix is sandy and probably calcareous. The matrix appears to flow through a fracture separating a Kaibab cobble (upper center). Differential weathering of the sandy matrix and carbonate clasts accentuate the texture of the breccia. This outcrop is part of an extensive bed that can be traced along the north wall of the crater.

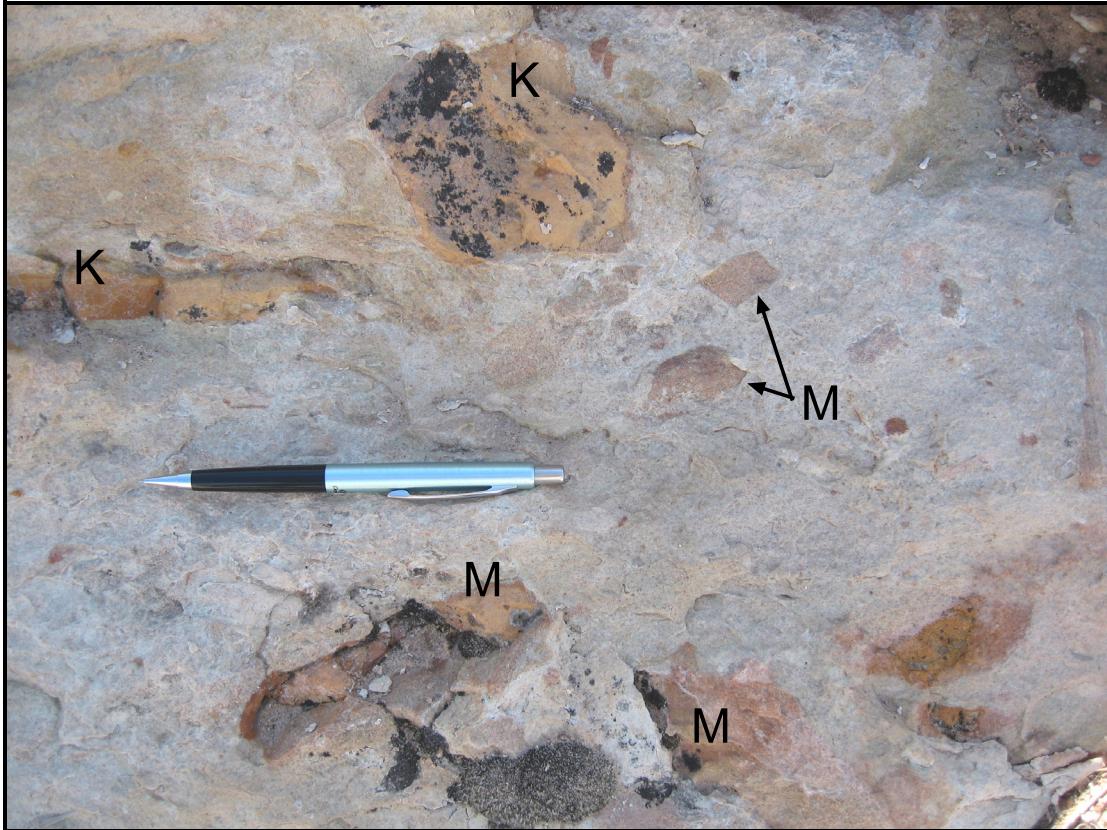


Fig. 15.16. Breccia along Kaibab-Moenkopi boundary that contains clasts from both units. Kaibab clasts are yellow and Moenkopi clasts are red. In case color reproduction is poor, they are labeled K and M, respectively. This outcrop is located in the southeast corner of the crater.



Fig. 15.17. Beds along the Kaibab-Moenkopi boundary have been compressed, forming folds whose limbs are sometimes sheared along small off-set faults. This outcrop is located in the southeast corner of the crater.



Fig. 15.18. Clasts or remnant beds within the breccia at the Kaibab-Moenkopi boundary have been fractured, displaced, and rotated. This outcrop is along the north wall of the crater.



Fig. 15.19. Large clast or remnant bed that has been fractured and displaced. Smaller clasts populate the breccia above and to the right of the large sheared clast. Intermediate-size clasts are at the top of the view (upper right). This outcrop is along the north wall of the crater.

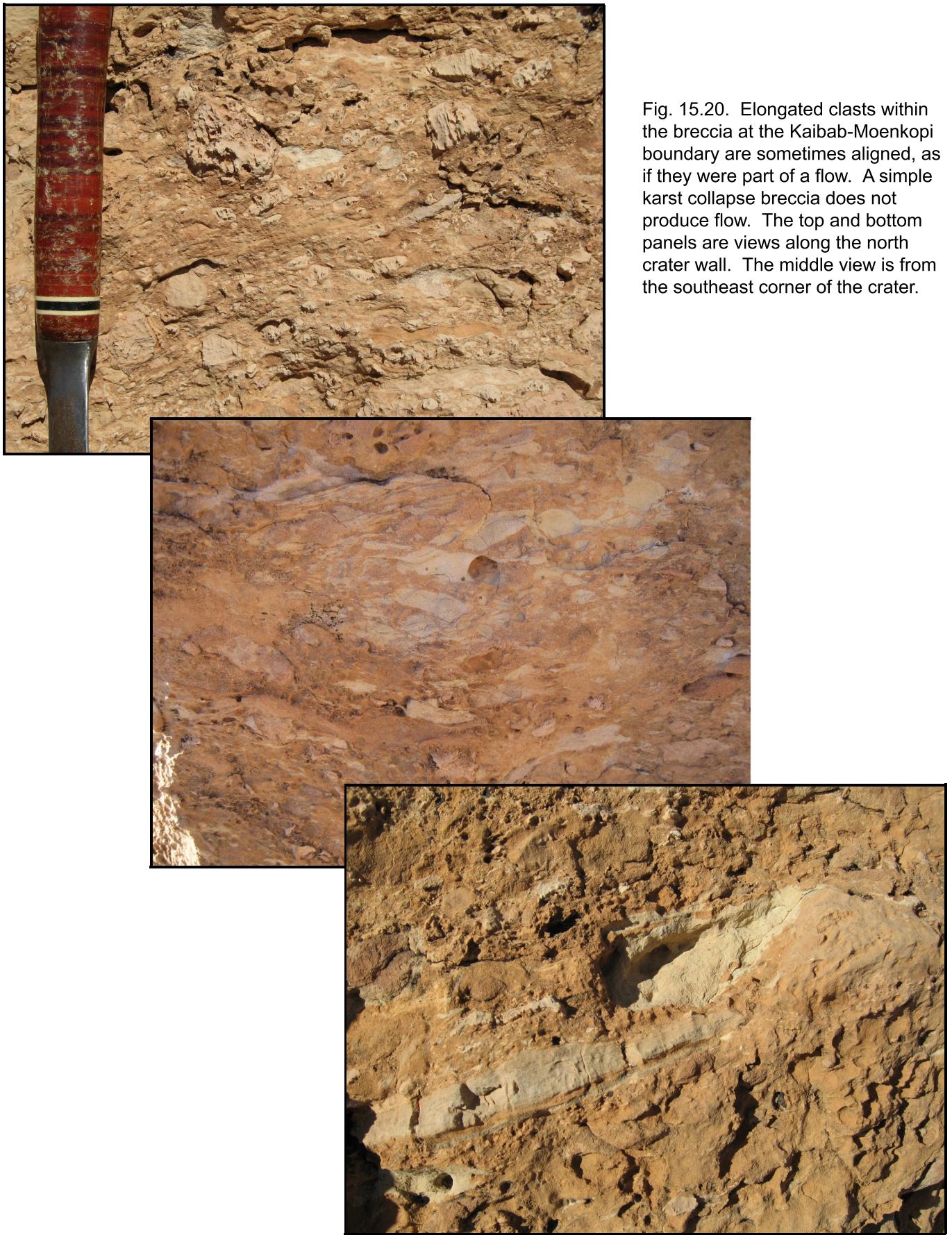


Fig. 15.20. Elongated clasts within the breccia at the Kaibab-Moenkopi boundary are sometimes aligned, as if they were part of a flow. A simple karst collapse breccia does not produce flow. The top and bottom panels are views along the north crater wall. The middle view is from the southeast corner of the crater.



Fig. 15.21. Most of the south rim of the crater is covered with debris from the Toroweap and Coconino formations. The aeolian Coconino sandstone is being eroded to produce a second generation of aeolian sands that now blanket portions of the south rim. Most blocks appear to have fractured along cross-bed contacts, because there are very few blocks with any hint of cross-bedding. An exception is shown above.