7. Overturned Rim Sequence ❖❖❖

Shock pressures overwhelm the material strength of rock in the immediate vicinity of an impact event. Thus, rock under the influence of shock does not behave in the immovable, brittle fashion that we normally assign to it. The excavation flow (Fig. 4.8 and 4.9) that generated the crater produced a nearly instantaneous folding of the bedrock in the rim of the crater, which is partly responsible for the height of the rim above the surrounding plain. Structural overturning of the strata was noted by Barringer (1910) in the northwest corner of the crater: "... the strata exposed in the walls of the crater gradually increase from 5 degrees up to vertical and in one place they are slightly overturned." In that same paper, he also characterizes the stratigraphic consequences, writing that a deeper sandstone is on top of shallower sandstone, which is on top of even shallower limestone. Shoemaker (1960) pointed out that similar overturned sequences are produced in the rims of nuclear explosion craters (*e.g.*, the crater produced by the ~1 kt Ess or Teapot Ess explosion in 1955). An overturned rim sequence is now recognized as one of the hallmarks of an impact crater.

Traditionally, students are introduced to this overturning in a study of the Moenkopi in the northeast rim of the crater, where cross-bedded laminae within the siltstone can be used to identify the overturned sequence. Additional details of those outcrops are provided in the trail guide for the east crater rim (Chapter 17). The overturned sequence can, however, be seen around the entire crater. For example, on the south rim of the crater, one finds the Wupatki and Moqui members of the Moenkopi repeated and overturned (Fig. 7.1).

Before examining another example of the overturned sequence, it is perhaps useful to first examine a schematic diagram that illustrates the structural and stratigraphic context of the overturned rim sequence. In structural terms, the overturned rim is a syncline with a circumferential axial trace or compound syncline, because there are actually two folds involved. The first is associated with the uplift and outward tilting of the beds in the crater walls (as described in the last chapter) and the second is with the complete overturning of those strata. With regard to the latter, there are actually two types of overturning evident in the crater rim (Fig. 7.2). Structural overturning occurs when the dips of the beds pass a vertical plane (and, thus, have dips exceeding 90°). Stratigraphic overturning occurs when the dips of the beds are rotated 90° beyond the outward dip of the lower limb of the fold. Thus, if the outward dips of the rim strata are, say, 35°, stratigraphic overturning occurs when the beds exceed dips of 125° (90° + 35°). Indeed, some strata will dip 215° (180° + 35°) on the overturned upper limb of that fold, relative to their pre-impact orientation.

Several locations exist on the east side of the crater where erosion reveals the fold hinge in the Kaibab and Moenkopi units. An example of a fold hinge in Moenkopi is shown in Fig. 7.3. The axial plane is within the fissile Moqui Member of the Moenkopi. In overturned sequences where the hinge is not exposed, it is often difficult to identify the axial plane because of the fissile nature of the Moqui. One often has to rely on the geopetal characteristics of the Wupatki Member to demonstrate the overturned stratigraphic context. This and other fold hinges are included in the trail guide for the east crater rim.

The Moenkopi is not everywhere exposed along the upper crater walls, because it is buried within the overturned Kaibab and Coconino. Access to the Moenkopi is facilitated by rim erosion, as illustrated in a series of time-steps in Fig. 7.4. As erosion cuts back into the crater walls, it removes fold hinges in the deeper layers (*e.g.*, Kaibab) and reveals overturned sequences in the shallower layers (*i.e.*, Moenkopi). Folds in both the Kaibab and Moenkopi are evident along the east crater rim. As discussed further in the next chapter, the amount of erosion is still being debated, but Shoemaker (1974) argued that 40 ft (12 m) occurred on the outer flank of the northeast corner of the crater, which suggests a cut back of the inner crater wall probably also occurred in that area.

The Moenkopi exposed in upper crater walls will not everywhere be the same thickness. This partly reflects pre-impact topographical relief that existed on the Moenkopi, because it was the eroding surface unit on the landscape. It also is partly the result of structural thinning that occurred during the overturning process, which is manifest in a series of small faults in the overturned rim sequence.

The views in Fig. 7.4 are idealized. Hummocky ejecta and crater rays will modify the distribution, which will be discussed further in the next chapter. The amount of erosion that occurs is also variable. Consequently, as one circumnavigates the crater rim, one might be walking on Coconino (as in top panel of Fig. 7.4) or on Kaibab (as in bottom panel of Fig. 7.4). The amount of overturned debris on the rim crest varies accordingly. Roddy (1978) estimated the original rim was covered with ~20 ± 5 m of debris, which is a structurally-thinned remnant of an excavated stratigraphic thickness of at least 88 m (corresponding to Kaibab and Moenkopi, which dominate the exposed rim sequence) and also much less than a total excavated stratigraphic thickness of 300 to 310 m (corresponding to Coconino, Toroweap, Kaibab, and Moenkopi). Currently, 0 to ~20 m of ejected debris survives on the current rim crest, depending on location around the crater. A greater fraction of the uplifted rim is the result of the uplifted strata beneath the overturned debris sequence, which is responsible for ~47 m of the uplift (Roddy, 1978).

Deviations from the idealized view of Fig. 7.4 are evident in the south rim of the crater (Kring *et al.*, 2011a,b). A portion of the Kaibab has been sheared radially outward, so that it is mostly missing from a portion of the rim. Radially outward shearing also carried a hinge in the overturned Coconino towards the south. Key outcrops revealing that motion are discussed further in Chapter 18, one of the trail guides. That motion may also provide a clue about impact trajectory (Kring *et al.*, 2011b), as discussed further in Chapter 10.

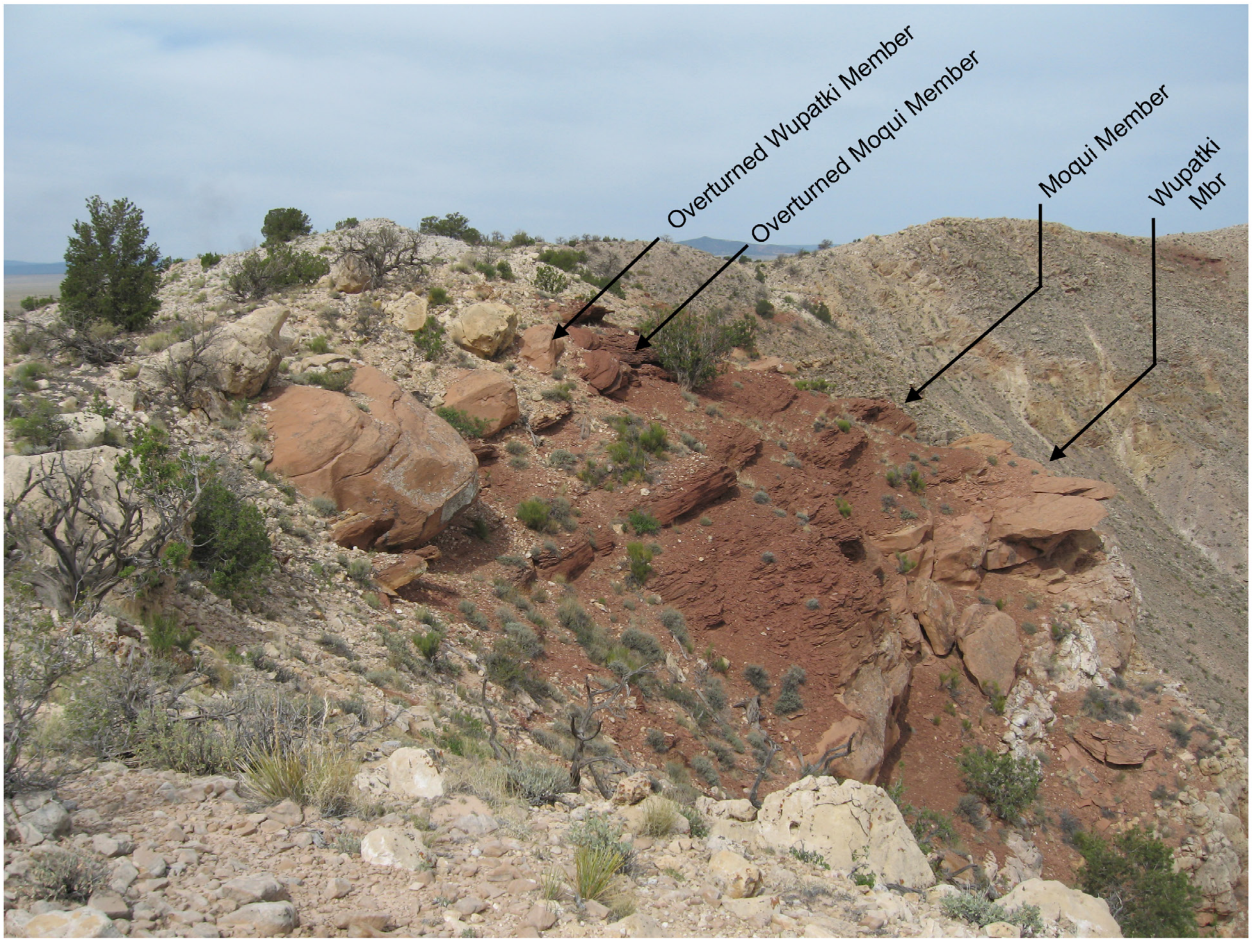

Fig. 7.1. Stratigraphic overturning of the Moenkopi Formation in the upper crater wall. The characteristic orbicular outcroping of the Wupatki Member sits on top of the Kaibab Formation (lower far right). Above the Wupatki is the fissile Moqui Member. The Wupatki-Moqui sequence is repeated, but overturned (center). Kaibab debris (upper far left) sits on top of the overturned Wupatki Member. Outcrop is on the south side of the crater. View is looking west.

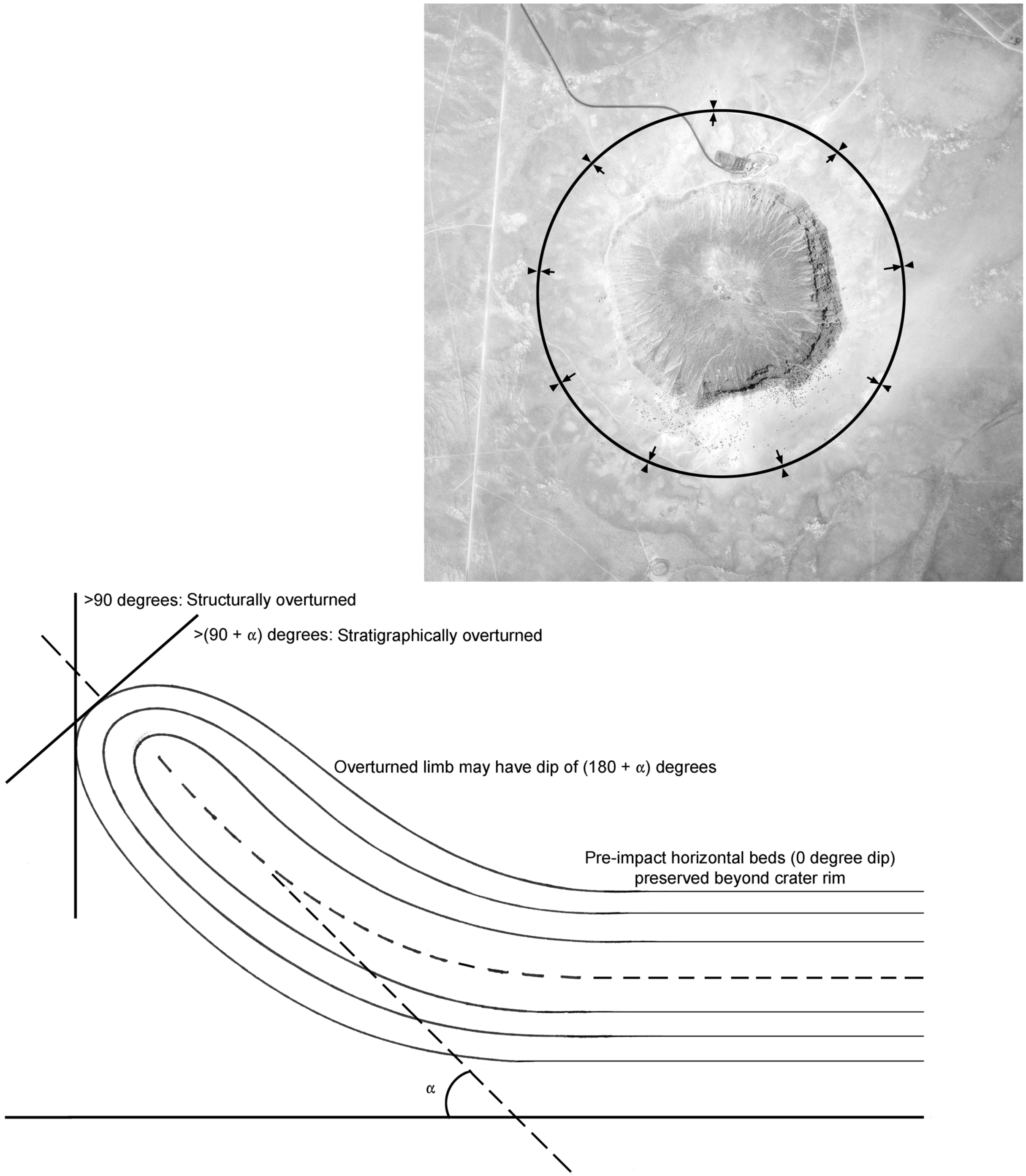

Fig. 7.2. Schematic diagram of the structural and stratigraphic overturning that occurs in the ring syncline of an impact crater rim (bottom). The axis of the ring syncline is not shown in the schematic diagram; it is perpendicular to the page and would trace a circle around the crater in a plan or map view. At Barringer Crater, the amount of uplift in the crater walls typically corresponds to an α of 35 to 40 degrees. The axial trace of the ring syncline at Barringer Crater is ~900 m from crater center or slightly more than 300 m beyond the crater rim (inset, upper right), based on the results of an intense drilling program (Roddy *et al.*, 1975) that penetrated the ejecta blanket and determined the elevation of subsurface bedrock. An independent measurement using ground-penetrating radar (Pilon *et al.*, 1991) suggests the axial trace may be slightly farther, ~400 m beyond the crater rim.

Fig. 7.3. 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. This outcrop is located on the east side of the crater, slightly north of Monument or House Rock.

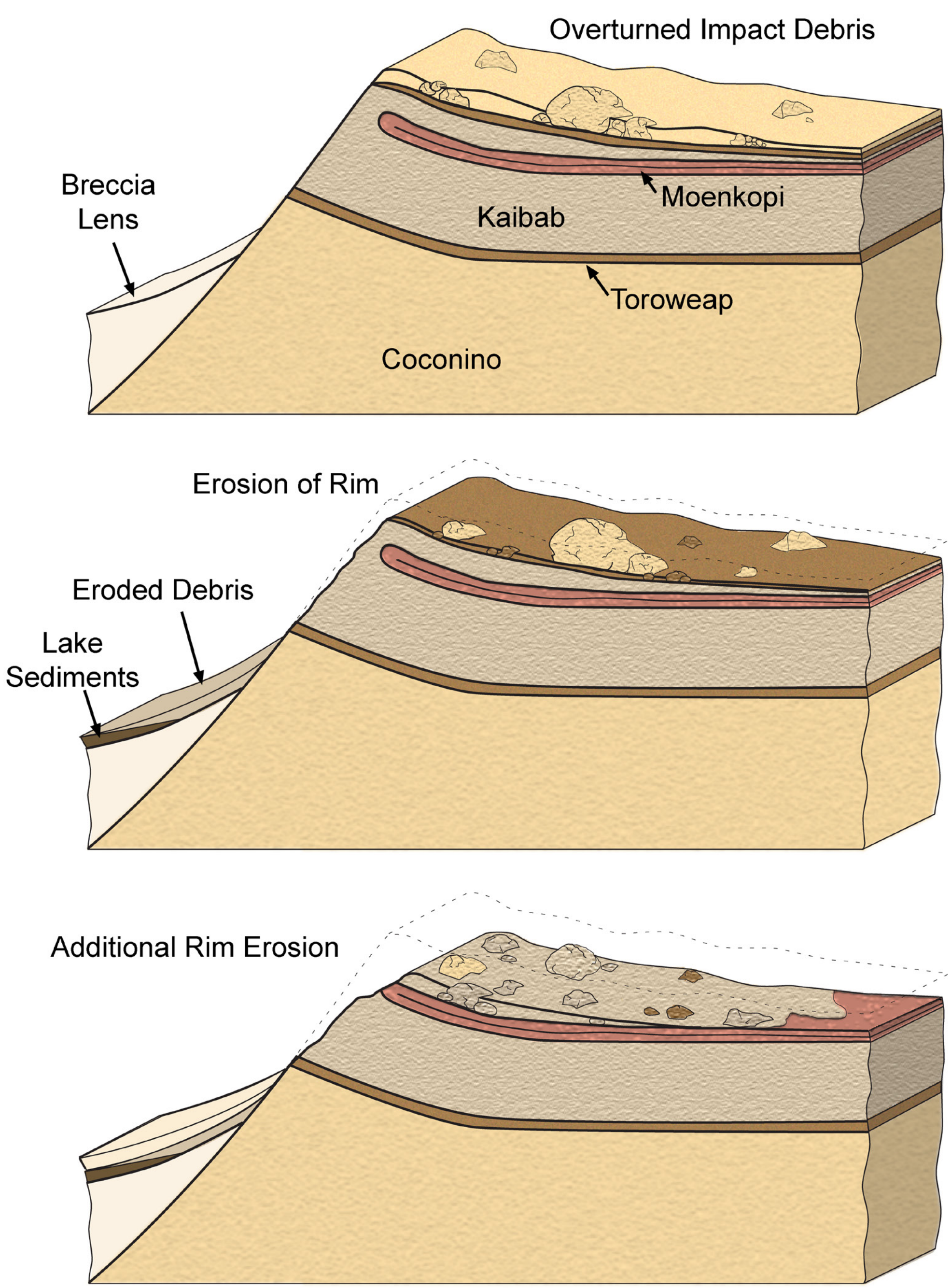

Fig. 7.4. Schematic illustration of the overturned rim sequence and its evolution during subsequent erosion. Immediately after impact, the rim is at its maximum height. The rim and ejecta blanket contain a complete overturned sequence of Moenkopi, Kaibab, Toroweap, and Coconino (top panel). This is an idealized view. Hummocky ejecta distribution and crater rays will modify this distribution. A breccia lens partially fills the crater. Over time, erosion of the rim exposes deeper levels in the upper crater wall and impact ejecta blanket (middle panel). Eroded debris falls to the crater floor. Coarse talus deposits interfinger with finer-grained lake sediments being deposited at the same time. Additional debris is washed down the flanks of the ejecta blanket towards the surrounding plain, where it collects in alluvium terraces (not shown). Additional erosion (bottom panel) exposes a Moenkopi fold hinge in the upper crater wall. It also creates an eroded pavement on the flank of the crater that is dominated by Kaibab. Erosion on the crater rim is not everywhere the same. Consequently, along the trail that circumnavigates the crater rim, one might be walking on Coconino (top panel) or on Kaibab that sits above an exposed Moenkopi hinge (bottom panel).