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Third-day road log, from Grants to Milan, Homestake Mining Company, Dos Lomas, Haystack Mountain and El Tintero

Spencer G. Lucas, Andrew B. Heckert, William R. Berglof, Larry S. Crumpler, Jayne C. Aubele, Barry S. Kues, and Virginia T. McLemore

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Every fall since 1950, the New Mexico Geological Society (NMGS) has held an annual Fall Field Conference that explores some region of New Mexico (or surrounding states). Always well attended, these conferences provide a guidebook to participants. Besides detailed road logs, the guidebooks contain many well written, edited, and peer-reviewed geoscience papers. These books have set the national standard for geologic guidebooks and are an essential geologic reference for anyone working in or around New Mexico.

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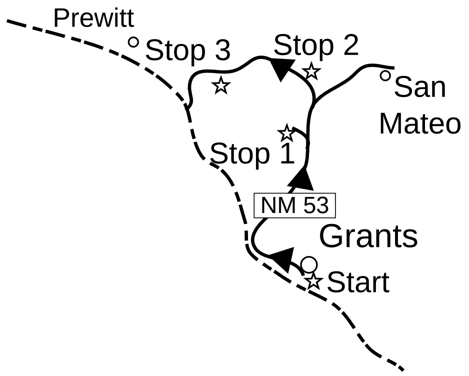
THIRD-DAY ROAD LOG, FROM GRANTS TO MILAN, HOMESTAKE MINING COMPANY, DOS LOMAS, HAYSTACK MOUNTAIN AND EL TINTERO

SPENCER G. LUCAS, ANDREW B. HECKERT, WILLIAM R. BERGLOF, LARRY S. CRUMPLER,
JAYNE C. AUBELE, BARRY S. KUES AND VIRGINIA T. MCLEMORE



Assembly Point: Best Western Inn and Suites, 1501 East Santa Fe Avenue, Grants
Departure Time: 8:00 AM
Distance: 29.6 miles (to old Highway 66 intersection); 36.1 miles to I-40 east on-ramp near Prewitt.
Stops: 3

SUMMARY

The field conference ends today, focusing on uranium mining, mill site and tailings reclamation and the late Cenozoic volcanic rocks to the northwest of Grants. Today's trip begins at Stop 1 with a tour and explanation of the Homestake Mining Company reclamation project near Grants. Homestake was a major producer of uranium ore from the Ambrosia Lake District to the north of today's route, milled the ore at this site, and has been reclaiming the mill tailings for more than two decades.

At Stop 2 near Dos Lomas (a topographic feature) we examine a well-exposed sandstone pipe in the Bluff Sandstone and discuss uranium deposits in the Todilto Formation, together with their mining history and the origin of the intraformational folds that localized the uranium mineralization in the Todilto.

We then move on to Stop 3, between El Tintero volcano and Haystack Mountain (also known as Haystack Butte). El Tintero, with an estimated age of 30-120 ka, was the source of an extensive series of lava flows (the "Bluewater flow"), some of which are crossed by I-40 west of Grants (see road log for Day 2). Uranium in the Todilto Formation was discovered for mining at Haystack Mountain, and one of the largest known Todilto deposits was mined there. Indeed, uranium mining in New Mexico began at Haystack Mountain.

Mileage

0.0 Start in parking lot of Best Western Inn and Suites on east side of Grants. **Turn left** and proceed west on Santa Fe Avenue. The view east as you leave the lot is directed toward Horace Mesa, a high, basalt-capped mesa that marks the southwestern edge of the Mount Taylor volcanic field. These basalts are dominantly nepheline hawaiites and are up to 30 m thick and locally columnar. Fault scarps cut the mesa surface in a northeast-striking orientation typical of most Quaternary structures throughout the volcanic field, as do several alignments and fissures of vents on the mesa (Fig. 3.1). Consequently, the flows covering Horace Mesa are incompletely mapped. Preliminary shallow geophysical studies for a planned (but never built) mesa-top astronomical observatory facility encountered several subsurface cavities within the basalt believed to be lava tubes. **0.4**

0.4 Bridge over Santa Fe railroad tracks. Directly ahead is West Grants Ridge (also called Black Mesa), with Chinle Group red beds capped by basalt of Black Mesa, prominent at 12:00 as the backdrop for

FIGURE 3.1. Aerial oblique view looking north centered on Grants area. Several fault scarps cut basalts of Horace Mesa on the right. Black Mesa, also known as West Grants Ridge, is the prominent symmetrical mesa to the left. East Grants Ridge is the upper ridge, where the half-sectioned scoria cone is highlighted by underlying bright pumice from the East Grants Ridge rhyolite dome. The terminus of the Zuni Canyon lava flow from the Paxton Springs vent on the south side of the Zuni Mountains fills the valley and is crossed by I-40. Diverging channels within the flow near its terminus are clearly visible. The moderately crenulated outline of the flow is typical of aa flows.

the town of Grants. Lava flows of Black Mesa may be traced to their source at the northeast end of East Grants Ridge, where the original scoria cone was half-sectioned during development of Lobo Canyon. A K-Ar age of the basalt lava flows capping Black Mesa is 2.57 ± 0.13 Ma (Laughlin et al., 1993), and there is a K/Ar age of 3.3 ± 0.3 Ma (Bassett et al., 1963a, b) for the rhyolite pumice underlying these flows. **0.2**

0.6 Enter Grants proper on old Highway 66. **1.0**

1.6 View ahead of U.S. Gypsum perlite processing plant. **0.2**

1.8 U. S. Gypsum Grants Plant. Perlite quarried from a dome-like volcanic mass at the northeast end of the East Grants Ridge was processed at this site and shipped by rail to other U. S. Gypsum plants. One of the more common uses of perlite is in the production of wallboard or "drywall." **0.2**

MINERAL RESOURCES OF EAST GRANTS RIDGE

Virginia T. McLemore and James M. Barker
New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801

East Grants Ridge is prominently visible from I-40 as a topographic ridge northeast of Grants, New Mexico, marked by a large basaltic plug projecting through light-colored pumice beds (Fig. 3.2). Up to 900 ft of Jurassic and Cretaceous rocks form the base of the ridge and include (oldest to youngest) the Entrada Sandstone, Todilto Limestone, Summerville Formation, Bluff Sandstone, Morrison Formation, Dakota Sandstone, Mancos Shale, Gallup Sandstone, and Crevasse Canyon Formation (Fig. 3.2; Thaden et al., 1967; Barker et al., 1989). Volcanic rocks consist of an older rhyolitic dome, ash-flow tuff, and rhyolite flows overlain by younger basalt flows and plugs. These rocks contain deposits of uranium, pumice, and perlite that were mined in the past. Occurrences of scoria, limestone, topaz, garnet, and obsidian also are found on East Grants Ridge.

Uranium, used mostly as fuel for nuclear reactors, was produced from the F-33 mine on the northwest side of East Grants Ridge by Anaconda and United Nuclear-Homestake Partners. From 1954 to 1959 and 1971 to 1977, 205,000 short tons of ore grading 0.21% U_3O_8 were produced (Barker et al., 1989; McLemore, 1983). Uranium was mined from a cluster of deposits along northeast-trending intraformational folds in the middle and upper parts of the Todilto Limestone (McLemore and Chenoweth, 1989, 1991). Uranium and vanadium minerals included uraninite, pitchblende, coffinite, paramontroseite, häggite, carnotite and grantsite, in a gangue of calcite, barite, fluorite, and pyrite. Reserves were depleted in 1977, and Homestake Minerals Corporation reclaimed the mine in the 1990s.

Pumice is a lightweight, porous igneous rock that forms during explosive volcanic events. Pumice is used mainly as an aggregate in lightweight building blocks and assorted building products; other uses include industrial abrasive, absorbent, concrete aggregate and admixture, filter aid, filler, soap, horticulture (including landscaping), and the stonewashing of denim (Bolen, 2001). A pumice deposit on the south side of East Grants Ridge, near the prominent basaltic volcanic plug, was mined during World War II and from 1946 to 1952 (Barker et al., 1989). Pumice Corporation of America (PCA) produced 59,473 short tons of pumice from open pits from 1946 to 1952 (Weber, 1965); production during World War II is unknown.

Perlite is a weathered high-silica rhyolitic volcanic glass with 2.5% water. When sized perlite is rapidly softened in a commercial furnace, the water converts to steam bubbles that produce lightweight cellular foam when the perlite is cooled. This rock foam has many uses in construction, filtering, and horticulture. The U. S. Gypsum (USG) perlite deposit is about 9 mi northeast of Grants, mainly in sections 35, 36, T12N, R9W and sections 1, 2, T11N, R9W comprising 1144 acres (Fig. 3.2). The deposit is related to a local vent/plug in the Mount Taylor volcanic complex and is up to 177 ft thick in drill holes. The perlite is tan to gray,

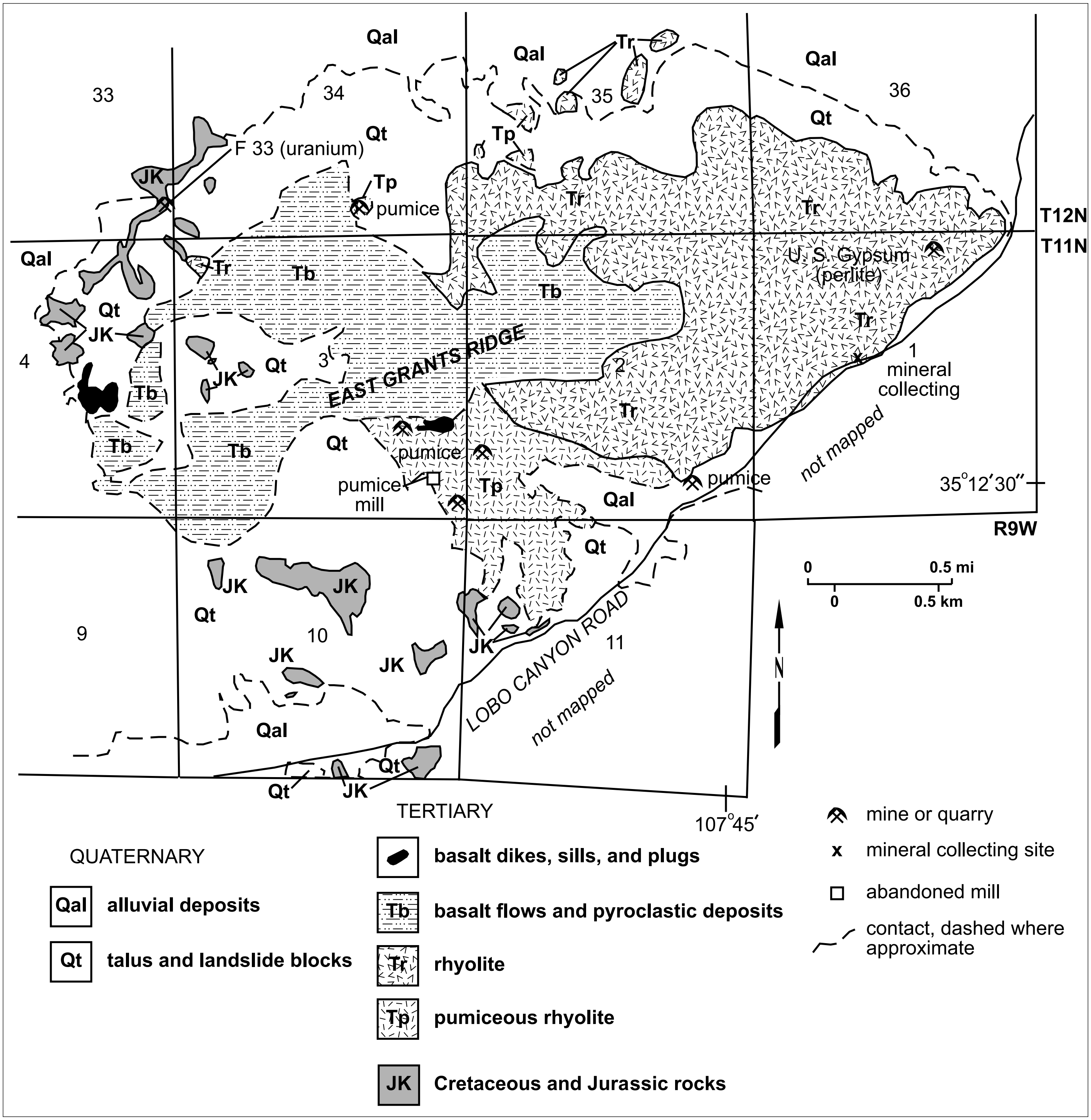


FIGURE 3.2. Geologic map of East Grants Ridge.

with flow banded and pumiceous portions and granular texture. USG operations began in 1953, after the company purchased the property from PCA and local claimholders, and terminated in the early 1990s. For many years, less than 10,000 tons were produced yearly by open pit methods, and a significant portion of the 6 to 10-million-ton reserve remains in place. Total production was a few hundred thousand tons. The mill is on a rail siding in Grants and has a permitted capacity of 20 tons per hour (116,000 tpy), but rarely operated at that level and needs a major overhaul. The property is currently for sale by USG.

Scoria and pumice are pyroclastic deposits formed as volcanic fragments ejected during explosive volcanic eruptions. Scoria (volcanic cinder) is red to black to gray, vesicular, basaltic (50–60% SiO_2) volcanic fragments. Most scoria deposits occur as loose, poorly consolidated, poor- to well-sorted cones or mounds of stratified fragments (Cima, 1978; Osburn, 1979, 1982; Peterson and Mason, 1983; Geitgey, 1994). The ejected material ranges in size from minor quantities of volcanic ash or cinder (<2 mm in diameter), scoria (2–100 mm in diameter), and volcanic bombs (smooth-sided) and blocks (angular fragments), which are greater than 100 mm in diameter. Most volcanic cinder cones contain approximately 75% scoria (Cima, 1978; Osburn, 1979, 1982). Scoria is not to be confused with pumice. Scoria is denser and more coarsely cellular or vesicular than most pumice (Peterson and Mason, 1983). Pumice is light in color, ranging from white to gray to pale yellow, pink, or brown and also is vesicular but of a dacitic to rhyolitic composition (60 to 70% SiO_2) (Geitgey, 1994). The vesicular nature of scoria results in lower density and higher porosity than most rock types. These properties result in commercial use as lightweight aggregates, insulators, absorbents, and abrasives (Geitgey, 1994). Most scoria in New Mexico is used to manufacture cinder block and concrete. Scoria is found along East Grants Ridge as part of the basaltic flows (Fig. 3.2). Although no production of scoria is reported from East Grants Ridge, scoria is a potential resource. Similarly, limestone has not been quarried from East Grants Ridge, but the limestone from the Todilto Formation could be crushed and used for construction purposes.

Mineral collecting at East Grants Ridge is well known for excellent micromounts of clear to amber topaz (6 mm or more long) and red-brown to red spessartine garnets (less than 1 cm in diameter) found in cavities and lithophysae in the rhyolite flow (Barker et al., 1989; DeMark, 1989; McLemore et al., 1989). In addition, quartz (less than 1 mm long), Apache tears (obsidian, 3 cm in diameter), and cassiterite (less than 4 mm in diameter) have been found.

2.0 Traffic light at First Street. **0.1**

2.1 Traffic light at Second Street. **0.2**

2.3 Traffic light at Fifth Street. **0.1**

2.4 Grants Chamber of Commerce and Mining Museum on right. Hills beyond the museum forming the northwestern edge of the town of Grants and Milan are largely colluvial materials consisting of large blocks of basalt from Black Mesa in a surficial matrix of Chinle. The slopes of Black Mesa consist in part of several terraces or landslips in which the basalt cap is displaced down slope in disturbed sections. **0.1**

2.5 Grants Post Office on right. **0.4**

2.9 Chinle red beds to right. **0.4**

3.3 Traffic light; I-40 onramp to left (NM-53); **continue straight.** Chinle red beds on right. **0.2**

3.5 Malpais lava flows to left. The Precambrian-cored Zuni Mountains uplift is on the skyline at 10:00, and most of that skyline consists of Permian sedimentary units gently dipping to the north. At 9:00, near the western edge of Grants and the eastern edge of Milan, the relatively dark and rough Zuni Canyon lava flow fills the floor of the Rio San José valley along the course of I-40 (discussed in the road log for the end of Day 2). **0.4**

3.9 Red beds of Painted Desert Member of Petrified Forest Formation on right. **0.2**

4.1 Bridge over Santa Fe Railroad tracks. **0.2**

4.3 Welcome to Milan. **Get in right lane.** West Grants Ridge (Black Mesa) to right. **1.3**

5.6 I-40 access to left. Continue straight ahead. **Get to right and prepare to turn right**. **0.3**

5.9 **Junction 605; turn right** and cross railroad tracks to proceed north on NM-605. During the uranium boom this intersection merited a traffic light, but now, during the “bust,” the traffic light has been removed. The view east along this route is largely of the west flank of East Grants Ridge. **0.7**

6.6 Note extensive colluvium of basalt boulders to right. **0.7**

7.3 Haystack Mountain at 9:30; low, broad mound at 10:30 is Homestake Mining Company reclaimed tailings pile, where we will soon stop. **0.2**

7.5 Mesa at 12:00 is La Jara Mesa, a part of the Mount Taylor volcanic field that projects westward from the base of Mount Taylor. At 1:00, the west flank of Mount Taylor is visible. Immediately in front of Mount Taylor is East Grants Ridge. The prominent grassy slope on East Grants Ridge is the west flank of a large scoria cone that is half-sectioned in the side of Lobo Canyon and visible from the Lobo Canyon road. **0.5**

8.0 Mile marker 2; Mt. Taylor at 1:00. **1.0**

9.0 Mile marker 3; Lobo Canyon and Mount Taylor volcano at 2:00. **Get in left lane. 0.7**

9.7 Tailings pile at 9:30-10:30 (Fig. 3.3). East Grants Ridge at 3:00. Note zigzag pattern of drill roads dating from the early 1950s,

FIGURE 3.3. The Homestake tailings pile, site of Stop 1.

developed at about the time of the discovery of a large uranium deposit (F-33 Mine) in the Todilto Formation at the base of East Grants Ridge. Little additional uranium was discovered despite the extensive drilling. **0.9**

10.6 Pass tailings pile on left, get into left lane **0.5**

11.1 **Turn left** on unpaved road to Homestake Mining Company facility offices. **0.3**

11.4 **STOP 1.** Homestake Mining Company facility. Note dip slope of Permian San Andres Limestone on Yeso Formation ahead (west). The facility is discussed in the accompanying minipaper by McLemore, and the information in the following text was provided by Alan Cox of Barrick Management Corporation.

Homestake Mining Company was one of the original pioneers in the uranium business in the Grants Mineral Belt-Ambrosia Lake District (Fig. 3.4), with operations beginning in the mid-1950's. Homestake was involved in the operation of two separate milling facilities and several underground mines in the Ambrosia Lake area.

Two mills were constructed in 1956-57 in conjunction with the U.S. Atomic Energy Commission to supply uranium to meet U.S. government needs. Yellowcake production from milling operations commenced in 1958. The smaller of the two mills, with a capacity of 750 tons per day (tpd), was owned by the Homestake-New Mexico Partners, and started processing ore in April 1958. The second Homestake-Sapin Partners mill commenced operating in May 1958 at an optimal capacity of 1750 tpd. The Homestake-New Mexico Partners operation closed in 1961 due to uranium market deterioration. In 1961, a consolidation of uranium properties occurred that involved the combining of the Homestake-New Mexico Partners, Homestake-Sapin Partners and Sabre-Pinon Corporation interests. The milling complex at Grants subsequently went through a series of modifications, with optimal production capacity increased to 3400 tpd. Production at the operation continued from that time period until May 1990, when milling operations were shut down.

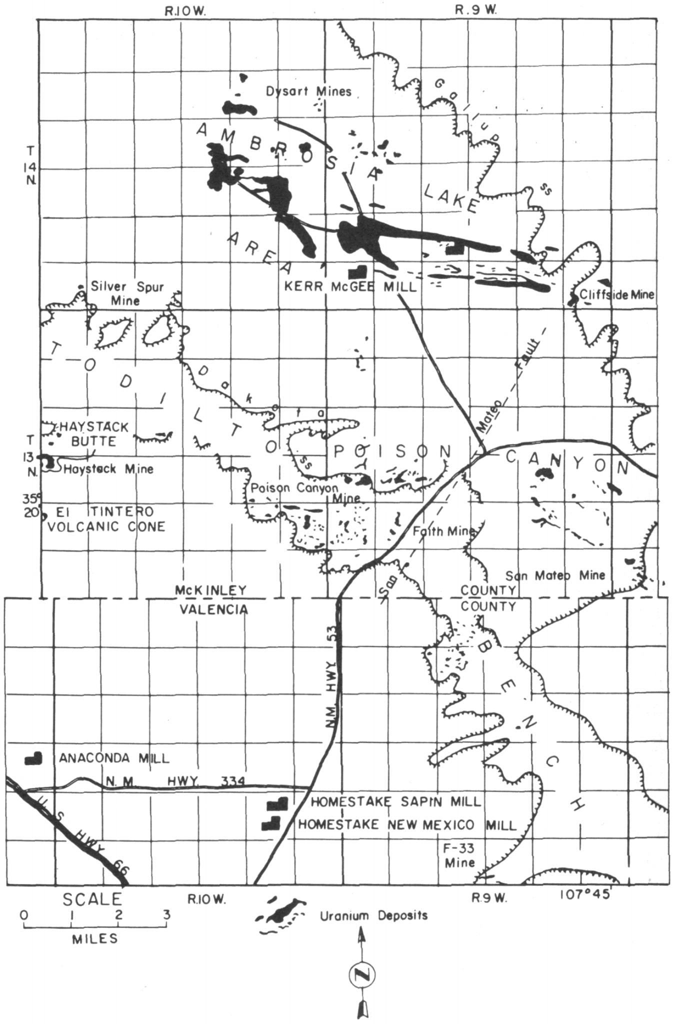


FIGURE 3.4. Map of uranium deposits in the Grants district (from Kittel et al., 1967).

Over the years, additional organization and ownership changes were made relating to the Homestake milling/processing operation. Homestake-Sapin Partners became the United Nuclear-Homestake Partners in 1968. This partnership was subsequently dissolved in February of 1981, and the operation became known as Homestake Mining Company-Grants.

The primary activities occurring at the site at present center around completion of a groundwater cleanup/restoration program that was commenced in the late 1970s and continues today. Seepage from the tailings piles at the milling site during operations introduced contamination into the water table underlying and downgradient of the pile locations. After final groundwater cleanup, final physical reclamation and closure of tailings piles and ancillary surface facilities related to the cleanup program will be completed with the site then scheduled to be turned over to the Department of Energy (DOE).

Initial groundwater investigations of the alluvial aquifer system underlying the United Nuclear-Homestake Partners tailings site started in 1975 with the drilling of approximately 40 wells. An initial report was developed in 1976 on the groundwater hydrology of the San Mateo alluvium at the Partnership site. Subsequent to 1976, numerous other wells in the area were also developed for use in further defining the groundwater system. Contaminants were found in two different aquifer systems. The primary aquifer is the alluvial system, which averages approximately 100 ft deep, and encompasses both the Lobo Creek and San Mateo alluvial aquifers. The alluvial aquifer flow gradient in the site area generally runs in a north to south direction. The second aquifer system is the Chinle Group. It is comprised of three separate aquifers, the Upper, Middle and Lower Chinle aquifers. The Upper and Middle Chinle sub-crop under the alluvial system near the project site. Low-level concentrations of some contaminants have been observed in the Upper and Middle Chinle aquifers near these sub-crops.

The present aquifer cleanup/restoration program underway at the Grants site consists of several freshwater and reverse osmosis (RO) product water injection systems utilized to develop a hydraulic barrier to the groundwater flow downgradient of the tailings pile areas. The injection system impedes the migration of contaminants in the aquifer system and enables the use of upgradient collection wells to retrieve contaminated aquifer water. The collected water is either sent to the RO treatment plant for processing and subsequent use in the ground water injection systems or to the on-site evaporation pond system.

The initial evaporation pond and spray system was commissioned in 1990 as part of the groundwater restoration program to provide a means of reducing the volume of collected contaminated water at the site. Toe drains were installed around the edge of the large tailings pile during 1993 to assist in collection of water from the tailings and reduce future contamination contributions to the alluvial aquifer system underlying the site. At present there are two main evaporation ponds in use in conjunction with two smaller collection ponds for ongoing management of water associated with the cleanup program.

Grants Reclamation Project Chronology/ Milestones:

- Mill Site and Tailings Pile reclamation activities began in 1993.
- Mill Site demolition and reclamation started in September 1993.
- The milling complex buildings and plant were dismantled and buried in deep pits, with demolition materials stabilized in place by addition of concrete slurry in the disposal pits. Demolition and disposal/burial activities were completed in 5 months.

- The outer slopes of the large tailings pile were recontoured to 3-to-1 slopes for stability, then covered with a 3 ft compacted radon barrier clay cap. An 8-inch rock cap was then placed to protect the clay cap against erosion. This work was completed over a 24-month period.
- A groundwater restoration program started in 1977, continues at present, and is estimated to be completed around 2010-12.
- Final site reclamation is estimated to be completed by 2013. Upon completion of post-reclamation site monitoring, the site will be turned over to the Department of Energy (DOE) for long-term care.

After stop return to NM-605. The view as we drive back to NM-605 is directed towards the Mount Taylor composite volcano and East Grants Ridge. **0.3**

HOMESTAKE MILL

Virginia T. McLemore
New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801

The Homestake mill, 5.5 mi north of Milan, was the first uranium mill to process ores from the Ambrosia Lake area (Chenoweth, 1989) and actually consisted of two mills. The southern mill was known as the Homestake-New Mexico Partners mill. Homestake Company partnered with six additional companies and built the southern mill in 1957 and began production in February 1958, primarily from the Dysart, Hogan, and Section 32 mines in Ambrosia Lake to the north (Fig. 3.4). The mill used a carbonate-leaching process with caustic soda to recover uranium and had a capacity of 750 tons per day (tpd) (United Nuclear-Homestake Partners, 1968). In 1961, Homestake-Sapin Partners acquired the mill from Homestake-New Mexico Partners. That mill was closed in 1962.

A second, larger mill was built north of the first facility, also in 1957, by the Homestake-Sapin Partners, a partnership between Homestake and Sabre-piñon Corporation. Ore from the Sections 15, 23, and 25 mines was processed at this mill. This mill used a carbonate-leaching, caustic-precipitation process to recover uranium and had an initial capacity of 1650 tpd (United Nuclear-Homestake Partners, 1968). After acquiring the southern mill, Homestake-Sapin Partners expanded this mill to 3500 tpd.

In 1962, United Nuclear Corporation merged with Sabre-piñon Corporation but maintained the United Nuclear Corporation name. United Nuclear Corporation became the limited partner with Homestake, forming the United Nuclear-Homestake Partners, and continued operating the mill.

In March 1981, the United Nuclear-Homestake Partnership was dissolved, and Homestake became the sole owner. The partnership included five mines (Sections 13, 15, 23, 25, and 32) and the mill. The mill ceased production in 1981, but reopened in 1988 to process ore from the Section 23 mine and Chevron's Mount Taylor mine. The mill closed soon after and was decommissioned in 1990 and demolished in 1993. In 2001, Homestake Corporation merged with Barrick Gold Corporation.

The Homestake mill recovered 6,000,000 lbs of V_2O from 1973 to 1981 as a by-product (Chenoweth, 1989). Vanadium was removed to avoid contamination of the uranium concentrate.

Today, the mill site includes a large tailings pile covering 200 acres that is 100 ft in height, and contains 21 million short tons of tailings. The site also includes a small impoundment covering 40 acres that is 25 ft in height and contains 1.225 million short tons of tailings (U. S. Environmental Protection Agency, 2002). The tailings are built on alluvium that overlies Chinle and San Andres aquifers.

Between 1993 and 1995, under the direction and oversight of the Nuclear Regulatory Commission (pursuant to Source Materials License No. SUA-1471), the mill was demolished, and the surrounding area was reclaimed, including construction of radon barriers on the tailings piles. Surface reclamation activities included the excavation and disposal of contaminated soils and the construction of radon barrier (soil) covers and erosion protection covers (rock layers) on the perimeters of the tailings piles. Homestake continues to operate a groundwater extraction/injection system at the former mill site to dewater the large tailings impoundment and clean up groundwater contaminated by tailings seepage. It is estimated that cleanup will cost $23,292,000.

THE MOUNT TAYLOR VOLCANIC FIELD

Larry S. Crumpler
New Mexico Museum of Natural History, 1801 Mountain Road N. W., Albuquerque, NM 87104

The Mount Taylor volcanic field (late Pliocene, 3.9 Ma to 1.7 Ma) (Fig. 3.5) is one of the many late Cenozoic volcanic fields located around the margins of the Colorado Plateau. Mount Taylor is typical of many composite cones; from a distance it appears to be a relatively simple accumulation of lava and ash around a vent. However, the symmetry of exterior form is not a good indicator of the geologic complexity. In reality, Mount Taylor, like many composite volcanoes, consists of a conglomeration of several volcanic centers of many different magma compositions, all more or less clustered around a small area. The large scale symmetry is principally a result of the accumulation of fairly thick and viscous trachydacitic and trachyandesitic lavas later in the history of the volcano and an outward-radiating apron of debris shed off of these domes mixed with late pyroclastic materials.

Early alkali basaltic eruptions initiated volcanism in the field. This was followed closely in time by eruptions of rhyolitic domes and ash. The ash in many road cuts includes large chunks of pumice that frequently bear fragments of the granitic deep crust. Basaltic volcanism occurred from isolated vents together with domes of trachyte and intermediate trachytic rocks. These

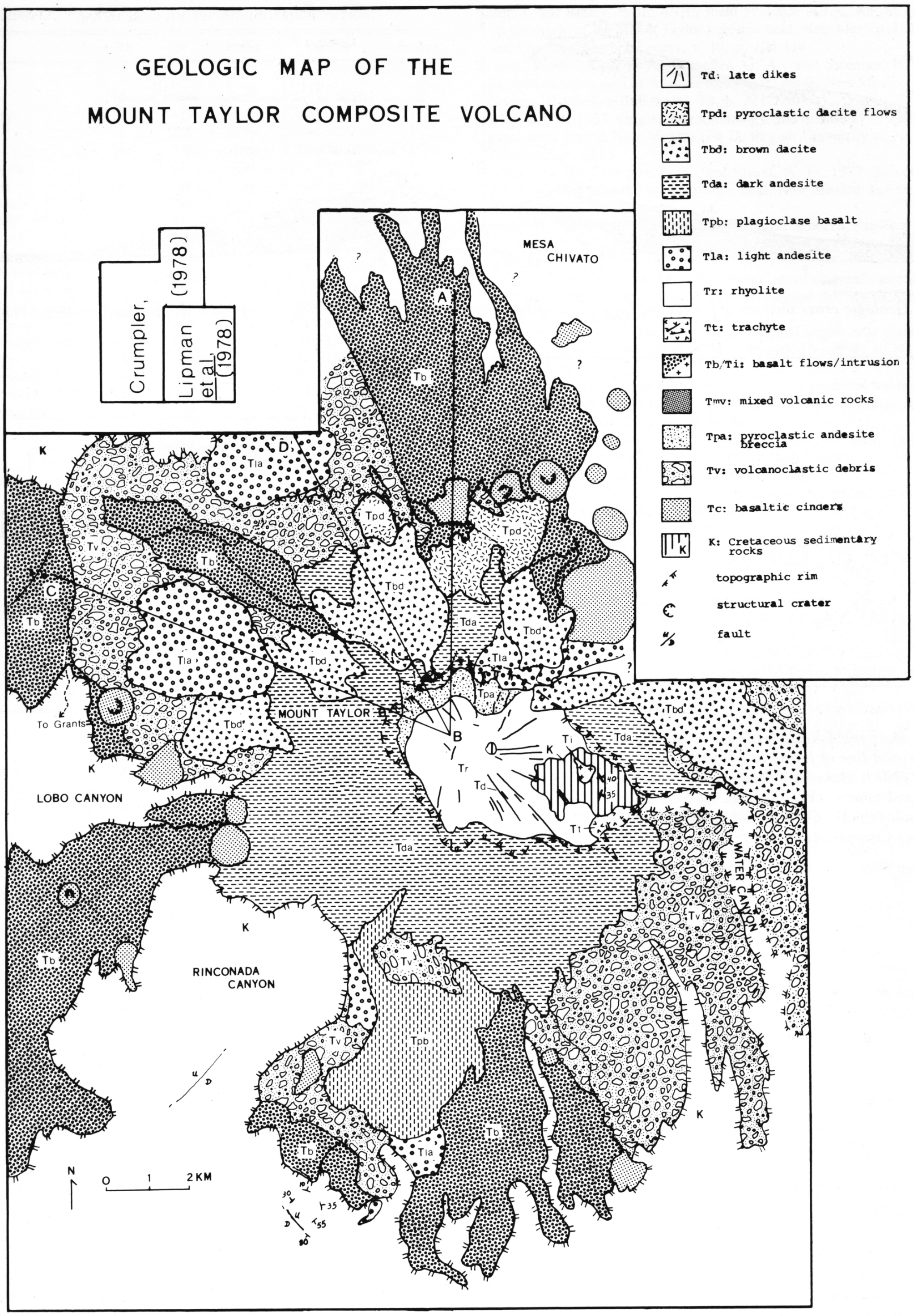


FIGURE 3.5. Geologic map of the Mount Taylor volcano, from Crumpler (1982).

began to accumulate as separate eruption centers distributed in time, but clustered near the site of the current main volcano of Mount Taylor. Continued eruption of isolated basaltic lava flows and scoria cones occurred even as the main cone of Mount Taylor had begun to take shape. As a result, thick trachydacitic lavas are interbedded on the outer slopes of the cones with aphyric and porphyritic alkali basalts bearing mantle nodules (Crumpler, 1982; Perry et al., 1990).

After the initial rhyolite eruptions, domes and thick viscous flows of trachyandesite and trachydacite began to erupt from various centers. Much of the late history involved emplacement of thick, viscous flows, and debris flows from flow domes of trachydacite near the summit. The extent to which a summit pyroclastic cone occupied the center of the volcano is undetermined. However, outcrops of intermediate composition ash and scoria on the amphitheater walls suggest that a pyroclastic cone may have occupied the summit originally. Both erosion and late explosive modification could have played a role in its destruction.

The more viscous trachydacitic domes tended to be extruded high up on the accumulated volcanic mass. Consequently, their precarious perch on the higher elevations, together with the abundance of snow or water in the upper volcano, led to frequent collapse and avalanching of the hot and/or muddy debris down the flanks of the growing pile of volcanic material. There may have been a recurring pyroclastic cone near the center of this extrusive activity that also contributed to the abundant loose materials that now litter the lower flanks of the volcano with fine light-colored ash and large, house-size blocks of trachydacite. Radial dikes of trachydacite in the summit amphitheater were probably feeder dikes for many of the viscous extrusions. Collapse and extrusion of viscous flows, along with occasional basaltic lava flows, contributed to the final external accumulations to the volcano.

The current morphology of Mount Taylor is that of a truncated cone, centered on a point located at the head of Water Canyon within the large, summit, amphitheater-shaped valley and just east of Mount Taylor peak and La Mosca peak. This amphitheater has the shape of a large crater, although the relative contributions of erosion versus late-stage (Mount St. Helens-like) lateral collapse are debated.

The original height of the volcano is a question frequently asked by laymen. Estimates of the original height are fraught with all sorts of potential error, largely resulting from the extreme individuality of most volcanoes. Long-lived volcanoes similar to Mount Taylor experience erosion in many cases that continually worries away the steep and loosely consolidated summits even while the volcano is active. As a result, not all the material erupted succeeds in adding to the summit before limited erosion removes it prior to the next eruption. If the summit pyroclastic cone was well developed, an original cone topping out at 13,000 to 14,000 ft is within reason. Many cones evolve through several stages of growth and collapse, as well as multiple summits, rather than a single conical mass, resulting in a more rounded and “lumpy” summit. If the near-terminal morphology attained this form, then 12,000 to 13,000 ft may be a better estimate of the original height.

The San Francisco Peaks near Flagstaff Arizona, some 0.5 million years younger, are probably a good analogue for the appearance of Mount Taylor as late as 0.5 to 1 Ma. It is notable that there is good evidence that late collapse of the east flank occurred at San Francisco Mountain. A similar event could well have been involved at Mount Taylor volcano.

Mount Taylor is a part of a much larger field of volcanism (Crumpler, 1980, 1982, 1990). Mesa Chivato extends for 60 km north and east of Mount Taylor. Volcanism in the northern volcanic field consists mostly of individual scoria cones, numerous maar craters, alkali basalt lava flows, and exotic viscous lava flows of alkali compositions (hawaiite, mugearite, benmoreite, and aphyric trachyte) typically seen in oceanic islands and in the major rifts and hot spots of Earth. These include domes of silvery white trachyte, benmorite, and mugearite. Faulting was concurrent with much of the volcanism, and several long fault scarps are parallel to fissures and cut across individual cones. Fissure eruptions are better developed in the northern Mount Taylor field than in many other fields, perhaps because of the contemporaneous strong extensional environment during eruptions. Several cones are distinctly elongated along the general northeast-southwest trend of faulting and fissures. Maar craters and collapse crater overlapping along this same trend are common.

11.7 **Stop sign; turn left**. Mount Taylor at 12:00. **0.9**

12.6 Mile marker 6. At 9:30-11:00 note Jurassic section dipping northeast with lower red rock cliffs of Entrada Sandstone and cuesta beyond capped by Dakota Sandstone. The Todilto Formation forms a white cap on top of the Entrada. **0.3**

12.9 Low cuesta at 1:00 to 3:00 between the highway and La Jara Mesa is developed along the Grants monocline. The Grants monocline dips NNE and may be traced through the low gap in East Grants Ridge (southwest of the grassy scoria cone flanks) across Lobo Canyon, and across the base of Horace Mesa near the northeastern edge of Grants where it merges gently with the generally north and eastward-dipping sedimentary units sloping away from the Zuni Mountains. **0.4**

13.3 Road curves left. **0.3**

13.6 Mile marker 7. **1.0**

14.6 Mile marker 8. On low mesas to right, Entrada Sandstone is capped by limestone in the Todilto, and uranium ore was produced from numerous open pit and shallow underground mines in the Todilto Formation. El Tintero at 9:30. Haystack Mountain at 10:00 was the site of the famous discovery of uranium in the Todilto Limestone by Paddy Martinez in 1950. **0.7**

15.3 View of El Tintero at 9:30. From a distance El Tintero has the appearance of a small knob on top of a broad swell. The odd box shape of the small scoria cone, which is perched near the summit of a much broader shield volcano, is the result of quarrying for cinders that has disturbed the otherwise well-preserved flanks of a typical cone. This will be the site of the last stop of the day. **0.6**

15.9 McKinley County line. Note cuesta to left

(Fig. 3.6) at 10:00 to 11:00 with Jurassic Entrada Sandstone capped by the Todilto. **1.0**

16.9 Highway intersects the Entrada-Todilto cuesta and outcrop. **Slow down and prepare to turn left** ahead. **0.3**

17.2 **Turn left** and cross cattleguard. View is directed toward cliffs of Entrada Sandstone capped by Todilto Formation. Road proceeds on Todilto dip slope. **0.2**

17.4 Mine rubble visible on left for approximately next 2 mi is from numerous open pit and shallow underground uranium mines in the Todilto Formation. The area has been extensively reclaimed, and the open pit mines are no longer accessible. After reclamation in the early 1990s, signs in English, Navajo, and Spanish were placed in the area warning of potential radiological hazard (Fig. 3.7). Not long afterward, the signs disappeared, presumably vandalized. Additional Todilto mines, mostly underground at depths up to 500 ft, were operated to the right (north) of the road.

Uranium was also produced from deposits in sandstone at several surface and underground mines in the Poison Canyon Tongue (of economic usage) within the Brushy Basin Member of the Morrison Formation. Access to these mines was from below or just above (north) of the Dakota rims above the Morrison Formation to the north and east of this point.

FIGURE 3.6. Crossbedded eolian sandstone of the Jurassic Entrada Sandstone overlain by a thin interval of limestone of the Todilto Formation at mile 15.9.

FIGURE 3.7. Warning sign in three languages, long since removed.

Monolith at 2:00 is the eroded remnant of a large sandstone pipe in the Bluff Sandstone. **0.9**

18.3 Road curves right. Mesa ahead exposes the Jurassic-Cretaceous section at Stop 2. **0.1**

18.4 Site (to right) of Barbara J #2 underground uranium mine in the Todilto (Fig. 3.8). Production began in the 200-ft-deep mine in 1959 and continued through 1968, producing 46,495 tons of ore that yielded 191,199 pounds of U_3O_8. **0.4**

18.8 Limestone quarry in Todilto Formation on left. **0.2**

19.0 Road forks, continue left. **0.4**

19.4 Crest of hill in Quaternary dune sands. **0.3**

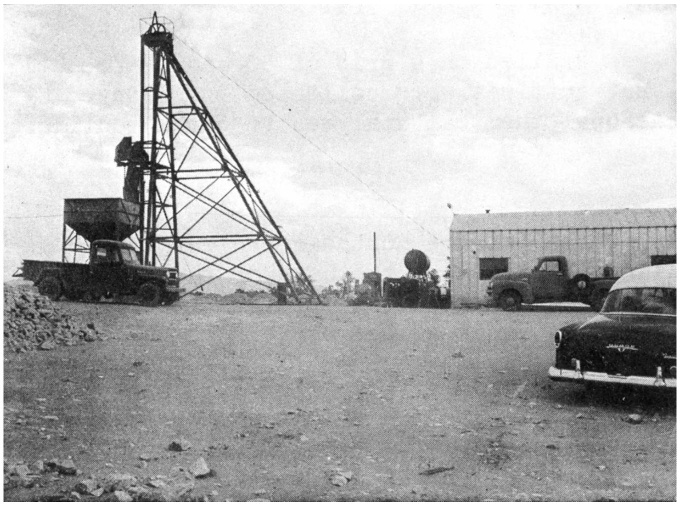


FIGURE 3.8. The headframe of the Barbara J # 2 Mine as seen in 1959 (source: Atomic Energy Commission, 1959).

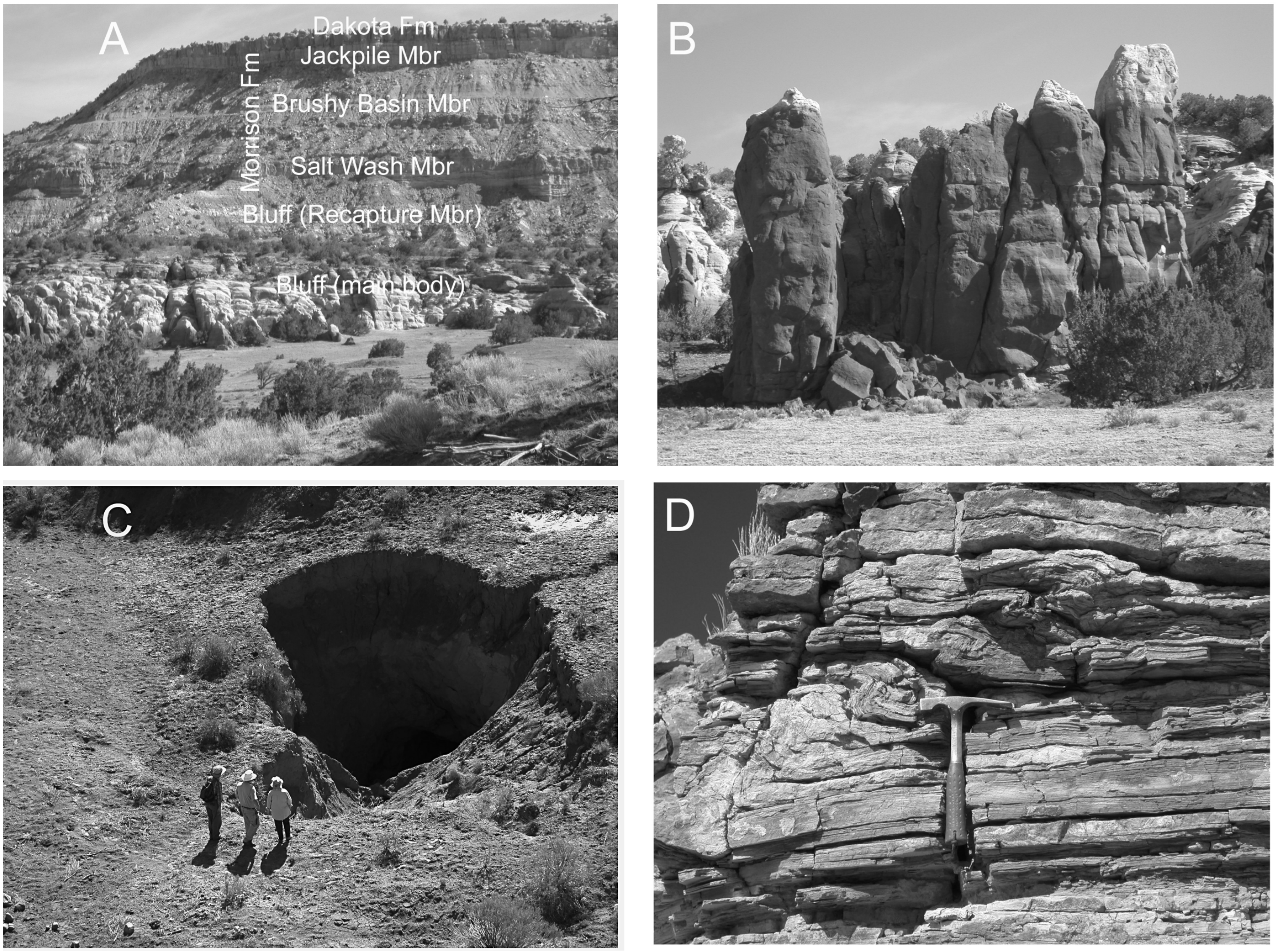


FIGURE 3.9. Four views of the Jurassic rocks at Stop 2. A. View of mesa with Bluff Sandstone (main body and Recapture members), overlain by Salt Wash, Brushy Basin, and Jackpile members of Morrison Formation capped by Cretaceous Dakota Formation. B. Closeup of main body of Bluff Sandstone. C. Post-mining collapse in Todilto Formation. D. Small scale folding in limestone of Todilto Formation.

19.7 **Stop 2**. **Pull off to right** at curve before culvert. Here, we examine large sandstone pipes in the Bluff Sandstone, and we discuss Todilto uranium deposits and mining and the intraformational folds that were the locus of uranium mineralization in the limestone (Fig. 3.9).

Numerous large and small uranium deposits in the Todilto Formation were mined from within an area of some three square miles beginning near this stop and extending back to Highway 605. This was one of the most important mining areas in the Todilto. Some of the workings of one underground mine, the Section 25 shaft, are probably directly beneath us here.

The Todilto dips up to five degrees toward the northeast in this general area. Southwest of the road (to the right, if we look back) we have been driving on the Todilto was at shallow depth and there was extensive mining from open pits and shallow underground mines. Downdip, to the northeast of the road, the mines were mostly underground at depths sometimes exceeding 400 ft.

The primary uranium deposits consist mainly of uraninite and subsidiary coffinite, with small quantities of blue-black vanadium minerals, replacing limestone along intraformational folds and at times filling fractures. Where the deposits are extensively oxidized, as in those found close to the surface, brightly colored, yellow tyuyamunite and uranophane are important ore minerals. Tyuyamunite is the calcium analogue of carnotite, containing both uranium and vanadium.

Intraformational folds in the Todilto (Fig. 3.9D) have a wide range of sizes and geometries. Some folds that were not obviously mineralized are exposed on Todilto outcrops, especially near the former mining areas. None of the larger folds are close to this stop, but smaller examples are accessible in the Todilto outcrops south of the road.

The origin of the intraformational folds has been controversial and remains unclear. Many folds show characteristics of soft-sediment deformation of the limestone not long after its deposition. This is consistent with estimated lead-uranium ages of 150-155 Ma for the uranium deposits that are localized by the folds (Berglof and McLemore, this volume), an age close to that of the Todilto itself. One hypothesis for the formation of the folds involves slumping of limestone mud on gentle slopes in response to earthquake shaking. Such shaking might also be a factor in the formation of sandstone pipes in the Summerville and Bluff above the Todilto; pipes are most prominent in areas where the intraformational folds are best developed and the limestone is mineralized with uranium. However, analysis of the trends of intraformational fold axes does not uniquely support this concept or other alternative hypotheses, and the origin of the folds remains uncertain.

Numerous sandstone pipes occur here and in Jurassic rocks in northwestern New Mexico, especially in the Grants, Laguna, and Gallup areas. The pipes are cylindrical or sub-cylindrical and range in diameter from less than a meter to tens of meters. They commonly contain material derived from overlying rock units, sometimes retaining recognizable original stratification, or they may be composed mostly of breccia. Many are bounded by ring faults, where the material within the pipes has moved downward with respect to the country rock outside the faults. Pipes are likely to be recognized where the enclosing strata are well exposed on cliffs or slopes on the sides of mesas. Some are more resistant to erosion than the surrounding rocks and appear as distinctive erosional remnants.

Most known pipes are in the Bluff Sandstone and the Summerville Formation, and were first recognized and described in the early 1950s when the Jurassic rocks received intensive study following uranium discoveries near Grants and Laguna. Attention was also drawn at the same time to the smaller number of pipes occurring in the Morrison Formation, as some of these are mineralized with uranium, most notably the Woodrow deposit near Laguna (Wylie, 1963), along with a few additional ones in the Laguna and Grants districts. None of the many pipes in the Bluff and Summerville are known to be mineralized. Exposed pipes in these formations in the Grants district are clustered near the area of most intense uranium mineralization in the Todilto Formation, and not far from the larger deposits in the Morrison, but there is no known connection between the Bluff/Summerville pipes and the uranium deposits.

The origin of the pipes has been the subject of considerable debate and remains unclear. The most likely origin seems to be related to foundering of sand into underlying water-saturated mud not long after the sediments were deposited (Schlee, 1963; Moench and Schlee, 1967). Several authors have suggested that solution of the underlying Todilto limestone and gypsum may have been a contributing factor, but have not cited direct evidence in support of this hypothesis. However, no outcropping pipes are known to extend downward into the Todilto, nor is the formation known for extensive karst or cave development. Extensive underground mining of Todilto uranium deposits in the Grants district similarly did not encounter sandstone pipes penetrating the limestone host rocks. One intriguing hypothesis, first hinted at in one of the earliest studies (Rapaport et al., 1952) and mentioned more specifically by Schlee (1963), is that earthquakes could have contributed to the formation of sandstone pipes. A voluminous literature now exists on "seismites" (seismogenically produced or altered structures) in numerous geological environments (e.g., Ettensohn et al., 2002). Under this hypothesis sandstone pipes could have affinities with sand boils and other water-escape structures observed to form during modern earthquakes.

After stop, continue west on unpaved road. 0.4

20.1 **Cattleguard. 0.4**

20.5 Crest of hill; after rounding a curve, the view at 12:00 is of the crest of the Zuni Mountains along the skyline and the mesa-like shape of Mount Sedgwick (9256 ft elevation); cross and descend through the Todilto Formation. Good view of the Jurassic section on Dos Lomas on the right. **0.3**

20.8 **Cattleguard;** Black Mesa (West Grants Ridge) is on the skyline at 11:00. Note Todilto exposures on left. **0.4**

21.2 Cross **one-lane metal bridge** (weight limit 10 tons). **Cross carefully!** On right are unusual mounds in the Todilto Formation (Fig. 3.10). These enigmatic, vaguely fold-like features, not known with this geometry elsewhere in the Todilto, may have formed in soft lime mud as a result of sediment loading from encroaching overlying dune sands (Green, 1982). **0.1**

21.3 Crest of hill; cross and descend through the Todilto Formation. Good view of the Zuni Mountains ahead. **0.2**

21.5 **Cattleguard. 0.2**

FIGURE 3.10. Mound in Todilto Formation limestone at mile 21.2.

21.7 Note Entrada Sandstone to right; Wingate Sandstone ("Iyanbito Member") visible at base of exposure is at one of its westernmost outcrops. **0.6**

22.3 Pass under power lines. **0.5**

22.8 Crest of hill; road to left. At 10:00, note the dip slope of the Permian San Andres Limestone over Yeso red beds on the north flank of the Zuni Mountains. El Tintero volcanic cone is at 11:00, an exposure of Todilto Formation above the Entrada Sandstone at 12:00, and Haystack Mountain at 1:00 with a section above the Todilto including Summerville, Bluff, and Morrison formations, with a Dakota Formation cap. **0.5**

23.3 Summit of El Tintero volcano at 10:30. Haystack Mountain (Fig. 3.11) at 12:30**. 0.8**

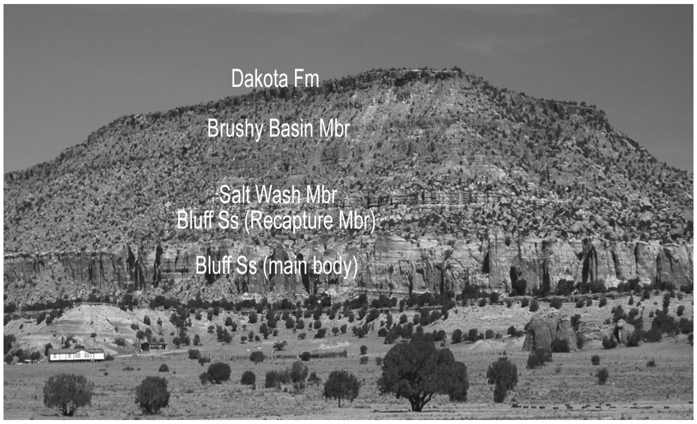


FIGURE 3.11. Photograph of Haystack Mountain (Butte).

24.1 Culvert. View of El Tintero. **0.6**

24.7 Cattleguard. Todilto caps Entrada mesa ahead. **0.6**

25.3 Road enters at an angle from right; bluff to right is Entrada capped by Todilto. Good view to left of El Tintero and cinder quarry on it (Fig. 3.12); continue straight ahead. **0.2**

25.5 **Stop 3** at crest of hill. Road crest crosses basalt of El Tintero. Lunch stop. Examine El Tintero volcanic cone and review local mining history. El Tintero ("the inkwell") is a small shield volcano (elevation, 7222 ft) at the northwest end of the Bluewater basalt flow (Fig. 3.12). The Bluewater flow from El Tintero is isolated from the other relatively young flows of the Grants area, and extends more than 10 mi along and to the north of I-40, from a little south of Prewitt, past Bluewater, to NM Highway 605, a short distance northwest of Milan. The flow is tholeiitic in composition and preserves many primary flow structures (Crumpler, 1982).

The vent area (Fig. 3.12) is characterized by a summit scoria cone that contains a small bowl-shapped crater. Although much damaged now from cinder quarrying operations, the flanks of the cone are relatively undissected. An unusual lobe-shaped feature at the southwest base of the cone has the characteristics typical of perched lava ponds. Similar, but much larger examples of this feature occur at the source area of the Jornada del Muerto volcano in southern New Mexico.

Laughlin et al. (1993) and Laughlin and WoldeGabriel (1997) summarized the ages obtained for the Bluewater flow from three different dating methods: ^{3}He yielded 57 ± 6 ka; ^{36}Cl gave 35.6 ± 3.4 ka (probably too young), and uranium series work produced an age of 79 ± 40 ka.

The volcanic flows of the Mount Taylor area were of special interest to Captain Clarence E. Dutton, who surveyed the geology of the Zuni Plateau and Mount Taylor region, and produced one of the classic works in the history of American geology (Dutton, 1885). Dutton recognized for the first time that these flows were of different ages, and that the younger flows had nothing to do with the eruptions of Mount Taylor. Dutton's (1885, p. 180-181) comments on El Tintero (Fig. 3.13) convey well his exceptional powers of observation and interpretation:

"The lavas from the north of Bluewater [flowed from] the Tintero (inkstand), a low lava cone so inconspicuous that no geologist or other traveler who has written of this country appears to have noticed it hitherto.

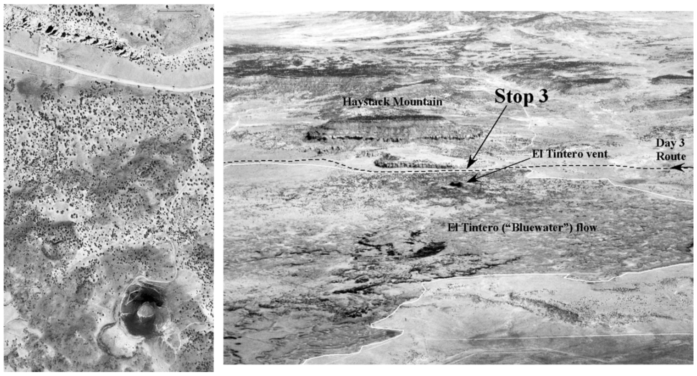


FIGURE 3.12. Vertical air photo (left) of the vent area for El Tintero volcano and surrounding lava flows (also known as the Bluewater flow). Note the lobe-shaped lava pond surface at the southwest base of the cone. Oblique air photo (right) of El Tintero, Haystack Mountain, and most of the area encompased in the Day 3 road log.

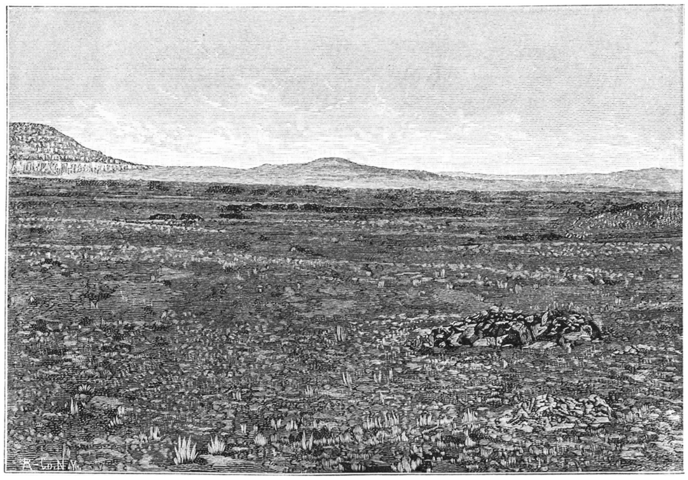


FIGURE 3.13. Dutton's (1885, fig. 25) woodcut illustration of El Tintero.

It has always been supposed that these fields of “malpais” emanated from Mount Taylor, and the supposition is a most natural one. Any one who crosses them or skirts along their edges without taking the pains to follow them to their sources would jump at once to that conclusion. From every point on the surface of the malpais Mount Taylor rises grandly as the most commanding object of the landscape; its volcanic nature is betrayed in every line and feature, and there is nothing else in sight to suggest a volcanic vent. But it is quite certain that they did not come from Mount Taylor, nor from any of its appendages; and the origin which I have stated has been verified with absolute certainty.

The Tintero vent is a low mound, rising by feeble slopes to a height which is difficult to state for want of any definite plane to refer it to. It may be represented rather as the maximum point of thickness in the sheets of lava, which are piled one on another or which spread out from it in every direction except the north. A well developed crater is found at the summit. It is not composed of fragmental ejecta but of massive lavas….It is evident that many streams have flowed from it, spreading out east and west to a width of five miles and flowing southerly into the trough of the [Rio] San Jose. Midway between Bluewater and Grant [sic] the streams narrow to the width of a mile or less. In many places the sheets are very fresh, but the older ones have been drifted over with blown sand and soil, through which the rough clinkers still project. Some of these streams may be many hundreds of years old, but others betoken such recency that we are tempted to attach some credence to the traditions of the Mexicans that when their Spanish ancestors first came to these regions they were still hot and steaming.”

One of the largest uranium deposits in the Todilto, and one of the first to be developed and mined, was immediately behind the Todilto rims above this point, mainly in sec. 19, T13N, R10W. It has been reclaimed. The legendary discovery (or rediscovery) in 1950 of uranium in the Todilto by Paddy Martinez, a Navajo sheepherder, which initiated the uranium boom in the Grants district, was at Haystack Mountain (also referred to frequently as Haystack Butte.) There were additional uranium mines in the Todilto to the right (north) of the road west of Stop 3. **To return to I-40 continue straight west. 1.9**

27.4 Paved road begins. Crest of Zuni Mountains between 9:00-12:00. **2.1**

29.5 Pass under railroad tracks, dirt road. **0.1**

29.6 Stop sign. **Turn left** on old Highway 66 to return to Grants. **0.2**

29.8 View of El Tintero and Mount Taylor at 10:00. **2.6**

32.4 Edge of lava flows from El Tintero. **0.3**

32.7 Road cut in El Tintero lava flows revealing the upper vesicular zone of the flows. **0.7**

33.4 Road descends margin of lava flows that continue to the left of the road. Numerous topographic rises here are relief features typical of lava flows variously referred to as “pressure ridges.” **1.2**

34.6 The road crosses another toe of the lava flow. **1.1**

35.7 **Turn right** onto NM Highway 606. **0.4**

36.1 **Turn left** (east) onto I-40 on ramp. Mount Taylor is at 10:00.

End of Third-day Road Log.