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Estimating Water Depths of Upper Cretaceous Pilot Knob Volcanic-Related Strata: The McKown and Pflugerville Formations and Pyroclastic Ash at the Lower Falls Section, McKinney Falls State Park, Austin, Texas

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ABSTRACT

The McKown and Pflugerville formations and pyroclastic ash beds at McKinney Falls State Park in Austin, Texas, are closely associated with the Lower Campanian Pilot Knob volcano. This volcano is one of over 400 known Late Cretaceous volcanoes in the Balcones Igneous Province. The center of the Pilot Knob volcano is 1.5 mi (2.4 km) southeast of the McKinney Falls State Park. The McKown strata at the Lower McKinney Falls within the park have been interpreted as a beach complex deposited on the shallow-water north flank of the Pilot Knob volcano. Previous researchers based this interpretation on the presence of a shallow-water macrobiota and the coarse-grain texture of the limestones. However, a new investigation of the Lower McKinney Falls outcrops has developed evidence that the McKown limestones were deposited in deeper water (150 to 300 ft [50 to 100 m]) on the flank of the Pilot Knob volcano by gravity-flow processes that formed carbonate debrites and hyperconcentrated-density-flow deposits. The new evidence comes from micropetrography data that demonstrates the matrix of the packstones is dominated by coccolith hash and that there are calcispheres and planktic foraminifers in both the packstones and grainstones. The composition of the McKown limestone is a mixture of shallow- and deep-water biotas, indicating the shallow-water biota were resedimented into a deeper-water setting. Also, McKown bedding relationships with the pyroclastic ash beds below indicates deposition in a low-energy setting.

The pyroclastic volcanic beds contain coccoliths and are interpreted as being deposited in a deeper-water, lower-energy setting. Also, the Pflugerville limestone section is very similar to the McKown limestone section and evidence indicates Pflugerville limestones were not deposited in a shallow-water setting. The evidence produced by the present investigation substantiates that the carbonate strata at the Lower McKinney Falls were not deposited in a beach or shoaling complex but were deposited on the deeper flank of the Pilot Knob volcano. The concepts developed by this investigation of these deeper-water carbonates can be applied to interpreting the depositional setting of other carbonates associated with the Balcones Igneous Province volcanic mounds.

INTRODUCTION

McKinney Falls State Park in Austin, Texas, is located approximately 1.5 mi (~2.4 km) northwest of the center of the Late Cretaceous Pilot Knob volcano (Figs. 1–3). The volcano (Fig. 3) formed during late Austin Chalk time interval (early Campanian) on the Comanche Platform (e.g., Hill [1890], McKinlay [1940], Romberg and Barnes [1954], Young et al. [1975], Garner and Young [1976], Young [1976], Raney [1997], Ewing and Caran [1982], Caran et al. [2013], and Saribudak [2023]) approximately 81.5 to 84.1 million years ago (Griffin et al., 2010). This volcano was one of several hundred small volcanoes that formed the Balcones Igneous Province in South and Central Texas (Ewing, 1986; Barker and Young, 1979; Barker et al., 1987). Sedimentation at the time of volcanic activity on the Comanche Platform was deeper-water, open-marine chalk. The buildup of the volcanoes, at or above sea level, produced localized shallow-water areas where healthy carbonate factories (i.e., high-productivity zone of skeletal biota) could initiate and proliferate (i.e., generate coarser-grain biota such as mollusks, red algae, etc.) (Young et

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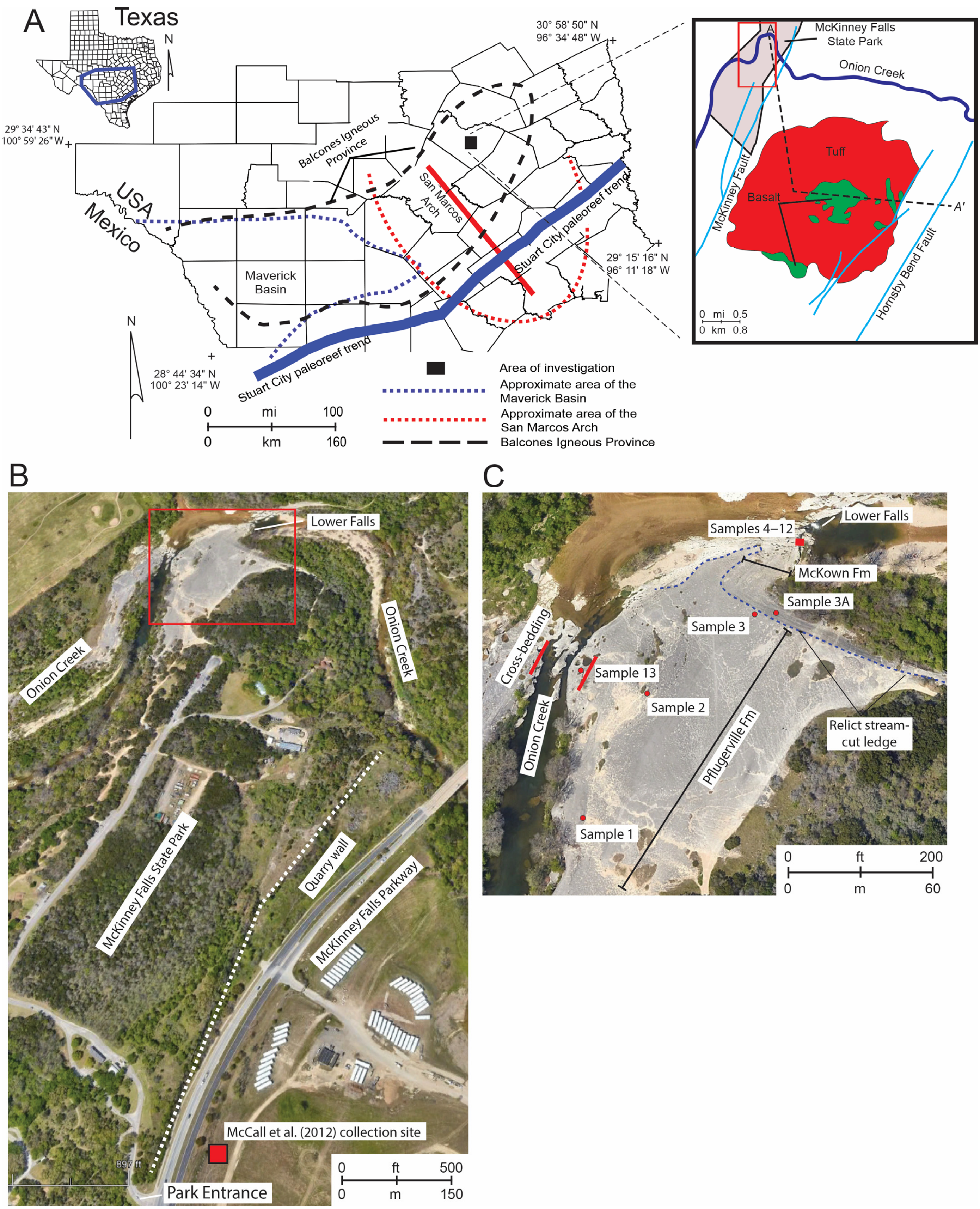

A
Texas
N
30° 58' 50" N
96° 34' 48" W
29° 34' 43" N
100° 59' 26" W
Balcones Igneous Province
San Marcos Arch
Stuart City paleoreef trend
USA
Mexico
Maverick Basin
29° 15' 16" N
96° 11' 18" W
28° 44' 34" N
100° 23' 14" W
Stuart City paleoreef trend
0 mi 100
0 km 160
Area of investigation
Approximate area of the Maverick Basin
Approximate area of the San Marcos Arch
Balcones Igneous Province
A
McKinney Falls State Park
Onion Creek
Tuff
Basalt
A'
McKinney Fault
Hornsby Bend Fault
0 mi 0.5
0 km 0.8
B
Lower Falls
Onion Creek
Onion Creek
McKinney Falls State Park
Quarry wall
McKinney Falls Parkway
McCall et al. (2012) collection site
897 ft
Park Entrance
0 ft 500
0 m 150
C
Lower Falls
Samples 4–12
McKown Fm
Sample 3A
Sample 3
Cross-bedding
Sample 13
Sample 2
Onion Creek
Pflugerville Fm
Relict stream-cut ledge
Sample 1
0 ft 200
0 m 60

(FACING PAGE) Figure 1. Regional to local maps of study area. (A) Map showing regional paleogeography for the Late Cretaceous Comanche Platform in South and Central Texas. The Balcones Igneous Province is outlined by the black dashed line. The location of McKinney Falls State Park is shown in the inset and its position relative to the Pilot Knob volcano is displayed. Line of cross-section A–A' in Figure 3 is shown. (B) Aerial view of the McKinney Falls State Park Lower McKinney Falls outcrop (red outline). Quarry wall exposure of the McKown Limestone is delineated by a white dashed line. McCall et al. (2012) fossil collection site in the pyroclastic ash beds is also located (solid red box). (C) Aerial view of the Lower McKinney Falls outcrop. The relict stream-cut ledge is marked with a blue-dashed line. Sample locations are shown by red dots. Black lines with bars at end denote measured section shown in Figure 5. Area of cross-bedded Pflugerville limestone shown in Figure 14B is labeled with red line.

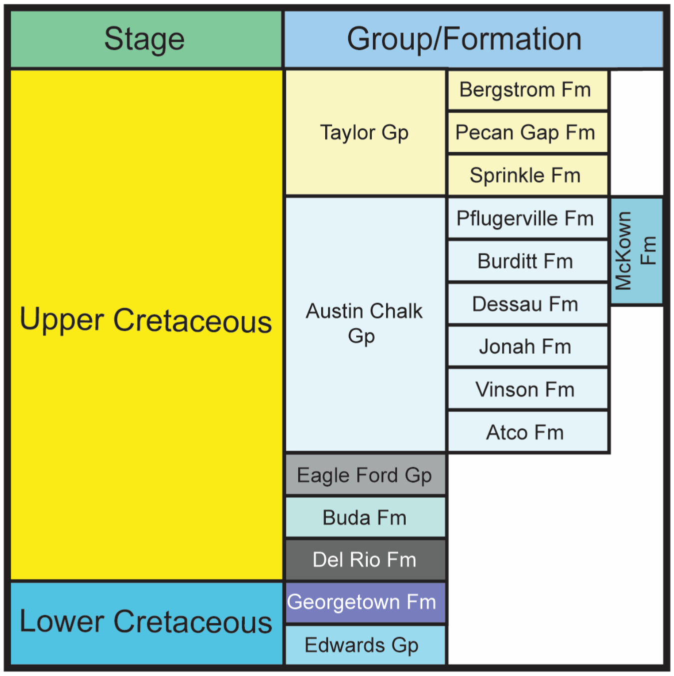


Figure 2. Stratigraphic section for the area of Pilot Knob and McKinney Falls State Park (modified after Young et al. [1975]).

al., 1975; Young, 1976; Luttrell, 1977; Loucks et al., 2023). McKinney Falls State Park is a location of pyroclastic beds and coarse-grained limestones of the McKown and Pflugerville formations, all associated with the Pilot Knob volcanic buildup (Figs. 1, 3, and 4).

The McKown Formation (named by Garner and Young [1976]) at McKinney Falls State Park has been studied by previous researchers (e.g., Hill [1890], White [1960], Young et al. [1975], Garner and Young [1976], Young [1976], Raney [1997], Caran et al. [2013]) and has been the central theme of many geologic fieldtrips (e.g., Corpus Christi Geological Society [1955], Young et al. [1975], Young et al. [1982], Caran et al. [2013], and Cherepon and Saribudak [2021]). Therefore, the authors of this present investigation think it is important to provide an accurate interpretation that evaluates all data for the origin of pyroclastics and limestones at the Lower McKinney Falls in McKinney Falls State Park. Past interpretations for the limestones suggested that the McKown Formation at the Lower McKinney Falls was deposited in a high-energy beach complex around the rim of the Pilot Knob volcano (e.g., White [1960], Young et al. [1975], Garner and Young [1976], Raney [1997], Caran et al. [2013], and Cherepon and Saribudak [2021]) and that the Pflugerville Formation was deposited in deeper water as a marly chalk (Young et al., 1975; Garner and Young, 1976). Data developed during this present investigation raises questions about these previous interpretations. We propose that the origin of the McKown and Pflugerville limestones at the Lower McKinney Falls is related to deposition in deeper water on the flanks of the Pilot Knob volcano by gravity-flow deposits and the carbonate sediment was sourced from an updip shallow-water carbonate factory. Also, Young et al. (1975) and Garner and Young (1976) have interpreted the Pflugerville Formation above the McKown Formation in McKinney Falls State Park as a marly chalk, which does not fit the analysis of the samples collected from this formation by the present authors.

To document these new interpretations and conclusions about the deposition of limestones at the Lower McKinney Falls, the following objectives are addressed: (1) review of the general regional depositional setting and description of the Pilot Knob volcano, (2) description of the limestones and pyroclastic beds in outcrop at the Lower McKinney Falls, (3) analysis of the outcrop strata using micropetrography (thin-section petrography and scanning electron microscopy [SEM]), (4) identification and depositional significance of biotas, (5) discussion of depositional setting of the McKown and Pflugerville limestones and pyroclastic volcanic strata at the Lower McKinney Falls, and (6) discussion of the depositional model and history of the strata in the area northwest of the Pilot Knob volcano.

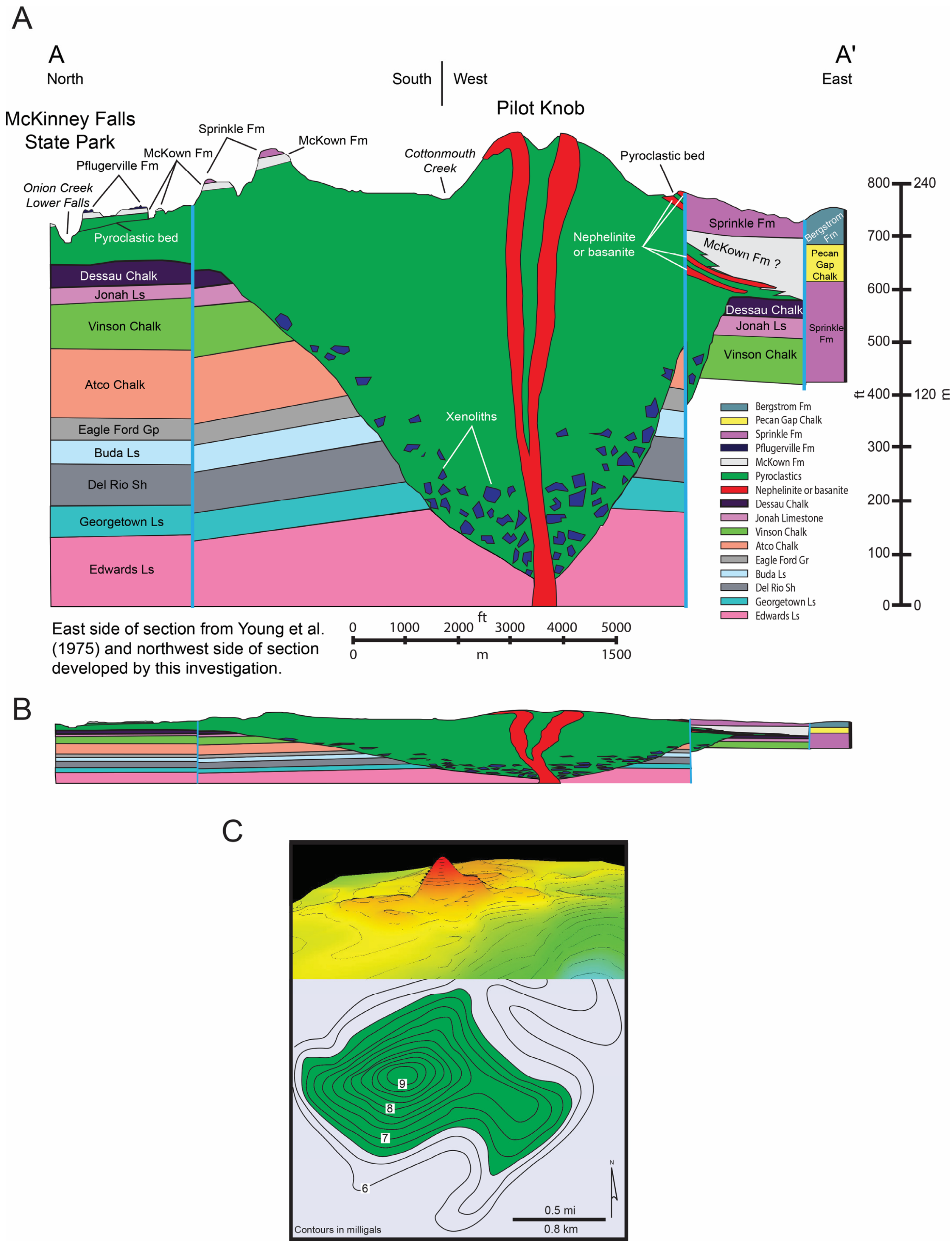
DATA AND METHODS

The outcrop at the Lower McKinney Falls (Figs. 1 and 4) was described for this investigation and hand samples were collected both for preparation of thin sections and for SEM samples (Fig. 5). The thin sections were impregnated with blue-dyed epoxy to emphasize macropores and blue-fluorescent dye to emphasize micropores. The thin sections were analyzed for texture, fabric, mineralogy, and biotas. SEM analysis was mainly done for the recognition of microscale coccoliths (plates of phytoplankton coccolithophores) and coccolith-element material. SEM was conducted on a FEI Nova NanoSEM 430 system at the Bureau of Economic Geology, University of Texas at Austin. Standard procedures used were an accelerating voltage of 10 to 15 kV with a working distance of 3 to 10 mm.

GENERAL REGIONAL GEOLOGY AND STRATIGRAPHY

General Regional Geology

In early Campanian time (upper Austin Chalk), the area of investigation was located on the drowned, deeper-water, open-marine Comanche Platform (Fig. 1). Marly chalks and chalky marls of the Austin Chalk Group were the predominant rock type being deposited on the deeper-water, drowned shelf (e.g., Loucks et al. [2020, 2022]). In the McKinney Falls State Park area, bottom sediment conditions were well oxygenated (i.e., oxic) and the sediments were highly bioturbated. Major biotas include planktic organisms composed of coccolithophores (during settling to the sea bottom they separated into individual coccolith elements or crystals), planktic foraminifers, calcispheres (floating algae), saccocomids (pelagic crinoids), and ammonites. Some


A
A
North
South
West
A'
East
Pilot Knob
McKinney Falls State Park
Sprinkle Fm
McKown Fm
McKown Fm
Pflugerville Fm
Onion Creek Lower Falls
Cottonmouth Creek
Pyroclastic bed
Pyroclastic bed
Nephelinite or basanite
Sprinkle Fm
McKown Fm ?
Bergstrom Fm
Pecan Gap Chalk
Sprinkle Fm
Dessau Chalk
Jonah Ls
Vinson Chalk
Atco Chalk
Eagle Ford Gp
Buda Ls
Del Rio Sh
Georgetown Ls
Edwards Ls
Xenoliths
Dessau Chalk
Jonah Ls
Vinson Chalk
Bergstrom Fm
Pecan Gap Chalk
Sprinkle Fm
Pflugerville Fm
McKown Fm
Pyroclastics
Nephelinite or basanite
Dessau Chalk
Jonah Limestone
Vinson Chalk
Atco Chalk
Eagle Ford Gr
Buda Ls
Del Rio Sh
Georgetown Ls
Edwards Ls
ft
800
700
600
500
400
300
200
100
0
m
240
120
0
East side of section from Young et al. (1975) and northwest side of section developed by this investigation.
ft
0
1000
2000
3000
4000
5000
0
m
1500
B
C
9
8
7
6
N
0.5 mi
0.8 km
Contours in milligals

(FACING PAGE) Figure 3. Pilot Knob volcano. (A) Idealized cross-section A–A' through the Pilot Knob volcano into the area of the McKinney Falls State Park. See location in Figure 1A. The west to east half (right side) of the diagram is from Young et al. (1975) and the north to south half (left side) is redrawn by this study to include the McKinney Falls State Park area. The diagram depicts the deep underlying crater and eroded volcanic mound of the Pilot Knob volcano. Vertical exaggeration is approximately 7x. (B) Same figure as A but the vertical exaggeration is removed. (C) Gravity map in three-dimensional rendition with regional gradient removed showing the general shape of the Pilot Knob volcanic body (modified after Romberg and Barnes [1954]).

benthic organisms were also present including inoceramids (large flat bivalves that could tolerate soft, muddy bottom conditions [Boucot, 1990]), echinoderms, and benthic foraminifers. The deeper-water, open-marine Austin Chalk strata do not crop out in McKinney Falls State Park, but the strata do commonly crop out in much of the Travis County area (Young et al., 1975; Garner and Young, 1976).

Stratigraphy

The Austin Chalk Group is composed of several formations (Young et al., 1975) (Figs. 2 and 5). The pyroclastic ash beds are a localized volcanic unit associated with the activity of the Pilot Knob volcano. The upper part has been interpreted by several authors (Durham, 1949; Young et al., 1975) as altered volcanics deposited as mud flows with large carbonate lithoclasts in some measured sections (Fig. 4B). The coarse-grained carbonate McKown Formation at Lower McKinney Falls is also associated with the development of the Pilot Knob volcano and lies between the pyroclastic ash beds below and the Pflugerville and Sprinkle formations above (Figs. 2–4B). The Pflugerville Formation regionally is a marly chalk (Young et al., 1975), but at the Lower McKinney Falls the rocks assigned to this unit are coarser skeletal packstone to grainstone.

The stratigraphy at the Lower McKinney Falls has been defined by Young et al. (1975) and is shown in Figures 4B and 5. The authors of this investigation follow the stratigraphy of Young et al. (1975) as their study depended on the details of the local paleontology. However, the Pflugerville Formation at the Lower McKinney Falls does not match the description of the Pflugerville Formation as a marly chalk provided by Garner and Young (1976) but is a coarse-grained carbonate similar to the McKown Formation.

Balcones Igneous Province and Pilot Knob Volcano

The Balcones Igneous Province extends across the Maverick Basin and the San Marcos Arch in South and Central Texas, covering an area of approximately 260 mi (418 km) long and 75 mi (121 km) wide (Simmons, 1967; this report) (Fig. 1A). Ewing (1986) and Barker et al. (1987) documented more than 200 volcanic features in the area and recent studies by the present authors indicate there may be more than 400 igneous bodies. A modern analog for these volcanoes is the Surtsey volcano offshore of Iceland (Fig. 6). The Surtsey and Pilot Knob volcanoes both developed in deep, open-marine waters and are dominated by pyroclastic debris.

The stages of volcanic development are presented in Figure 7. Magma rising along deep-seated faults and fractures from the mantle is the source of the volcanic material. The magma is estimated to be from 50 mi to 60 mi (80 to 100 km) in depth (Fig. 7A) (Barker et al., 1987; Ewing, 2004). When the hot magma interacted with the cooler sea water, a phreatomagmatic eruption occurred (i.e., explosive steam events) creating volcanic ash and lapilli (Figs. 6A and 7B). These volcanoes build to and above sea level by the deposition of the volcanic ash and lapilli (Fig. 7C). Some basaltic lava flows also helped form the mound (Romberg and Barnes, 1954; Barker and Young, 1979; Cherepon and Saribudak, 2021; Saribudak, 2023). The presence of non-pillow lava basalt flows is evidence that part of the volcano was above sea level (Barker and Young, 1979). During periods while the volcano was periodically dormant or ceased erupting, a carbonate factory was able to become established and generate an abundant supply of skeletal material (Figs. 7D and 8). Some of the shallow-water carbonate material was transported off the volcanic mound and formed debrite deposits on the flanks of the mound and at the toe of slope. Three three-dimensional block models are presented in Figure 8 to express selected stages of the development of a typical Balcones Igneous Province volcanic mound and associated carbonate sediments. The interpreted depositional setting of the Lower McKinney Falls is outlined on Figure 8A.

The Pilot Knob volcano is eroded, but its dimensions can be estimated from magnetics (Saribudak, 2016, 2023), gravity (Romberg and Barnes, 1954), and outcrop patterns (Young et al., 1975; Garner and Young, 1976). An estimated present-day shape of the mound from gravity data is shown in Figure 3C. The diameter of the volcanic mound is estimated to be approximately 1.5 mi (~2.4 km) in diameter and the total thickness is 600 ft (180 m). Estimated height above the sea floor was 300 to 400 ft (90 to 120 ft) and the average slope is estimated to be 4.5°.

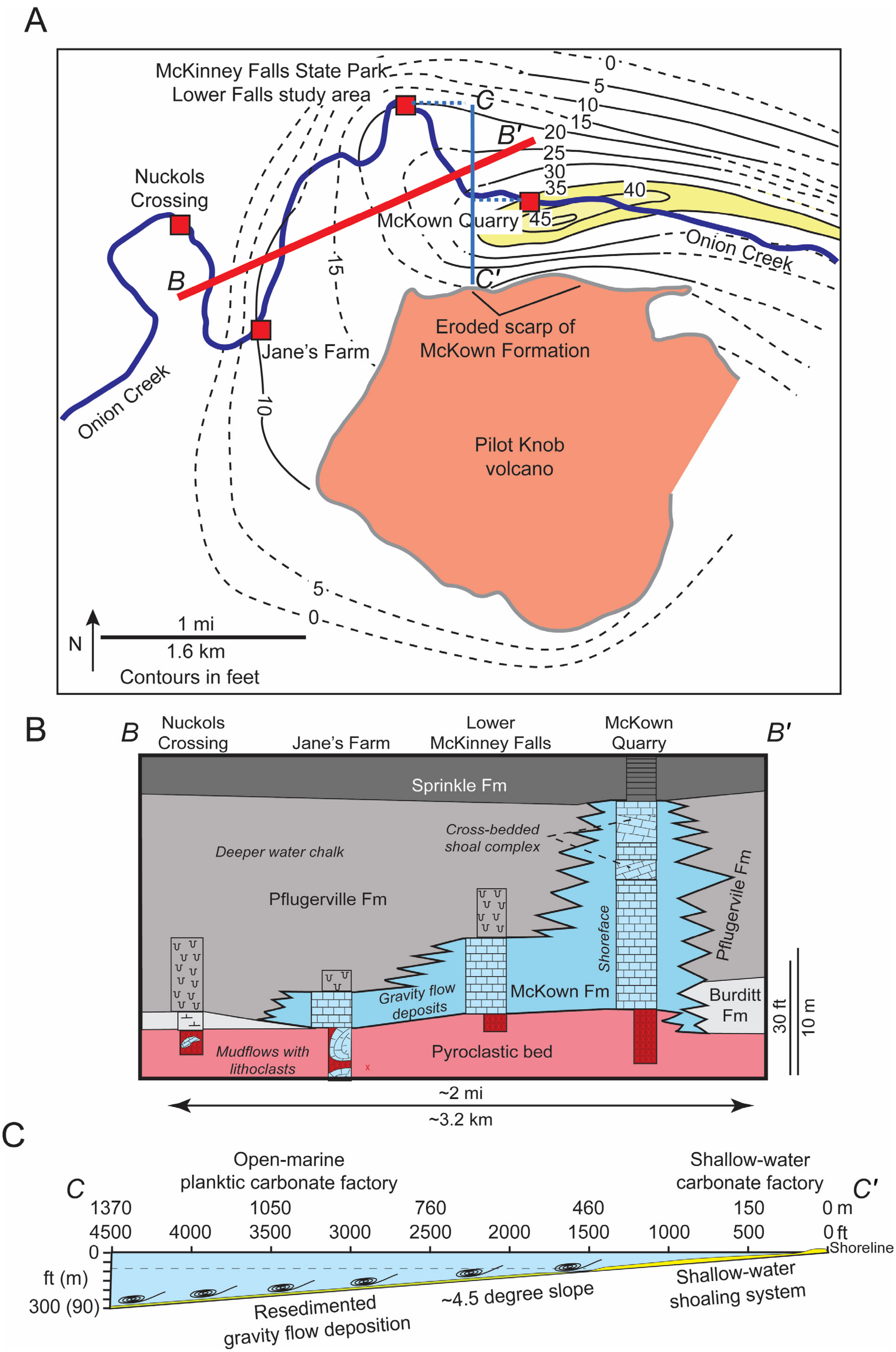
Volcanic rocks in the Balcones Igneous Province are silica undersaturated and predominantly mafic tuffs in composition (e.g., Barker et al. [1987]). Spencer (1969), Ewing and Caran (1982), Wittke and Lawrence (1993), Ewing (2004), Griffin et al. (2010), and Reed and Loucks (2022) present more detailed information on the composition of these igneous rocks.

DISCUSSION OF STRATA AT THE LOWER MCKINNEY FALLS

The present investigation concentrated on the rocks cropping out at the Lower McKinney Falls within McKinney Falls State Park (Figs. 1, 4, and 5). This is the principal area where geological field trips visit. The stratigraphic section at the Lower McKinney Falls is composed of three rock units that were assigned formation names by Young (1975) and Garner and Young (1976) (Fig. 4). The lowest unit is the pyroclastic ash beds, the middle unit is the McKown Formation, and the upper unit is the Pflugerville Formation (Fig. 5). Each of these units are described below as to their texture, fabric, sedimentary and biological structures, and biota composition. The interpretation of how these rocks were deposited is presented in a later section.

Pyroclastic Ash Beds

Only the upper 6 ft (1.8 m) of pyroclastic ash beds are exposed at the Lower McKinney Falls (Figs. 9A–9C and 10). There are two main lithofacies (i.e., rock types): the lower altered volcanic mudstone (Figs. 10 and 11) and the upper coarser-grained pyroclastic debris beds (Figs. 10, 12, and 13). Coccoliths of deeper-water origin were recognized in the pyroclastic samples collected by the present investigation (Figs. 11 and 13). A study by McCall et al. (2012), across the road from McKinney Falls State Park (Fig. 1B), described numerous shallow-water macrofossils in the uppermost clays (altered ash) of this unit and suggested that they were deposited in deeper water below storm-wave base by gravity-flow processes. Caran et al. (2013) also proposed that the pyroclastic ash beds and associated biotas in the McKinney Falls State Park area were deposited below storm-wave base in several hundred feet of water.


A
McKinney Falls State Park
Lower Falls study area
Nuckols Crossing
McKown Quarry
Jane's Farm
Onion Creek
Onion Creek
Eroded scarp of McKown Formation
Pilot Knob volcano
B
B′
C
C′
1 mi
1.6 km
Contours in feet
N
B
B
B′
Nuckols Crossing
Jane's Farm
Lower McKinney Falls
McKown Quarry
Sprinkle Fm
Cross-bedded shoal complex
Deeper water chalk
Pflugerville Fm
Pflugervile Fm
Shoreface
Gravity flow deposits
McKown Fm
Burditt Fm
Mudflows with lithoclasts
Pyroclastic bed
30 ft
10 m
~2 mi
~3.2 km
C
Open-marine planktic carbonate factory
Shallow-water carbonate factory
C
C′
1370 1050 760 460 150 0 m
4500 4000 3500 3000 2500 2000 1500 1000 500 0 ft
ft (m)
300 (90)
Shoreline
Resedimented gravity flow deposition
~4.5 degree slope
Shallow-water shoaling system

(FACING PAGE) Figure 4. McKown Formation. (A) Isopach map of the McKown Formation (modified after Young et al. [1975]). The isopach thick colored in yellow is interpreted as the likely shallow-water, shoaling area carbonate factory. In this scenario, the Lower McKinney Falls outcrop is approximately 2500 ft (1370 m) to the northwest of the carbonate thick. Line of the outcrop cross-section B–B' is show in B. Cross-section C–C' line refers to water-depth calculations in C. (B) Outcrop cross-section B–B' (modified after Young et al. [1975]) shows the transition from the thick, shallow-water (interpreted), cross-bedded McKown limestone updip into the deeper-water McKown limestone gravity-flow deposits downdip. (C) Estimation of water depth at the Lower McKinney Falls outcrop is calculated by assuming the slope on the flank of the volcano to be 4.5º. The calculated water depth is estimated to be as deep as 300 ft (~90 m). The horizontal dashed line in cross-section C–C' is depth above which the carbonate factory would be most productive.

Altered Volcanic Mudstone

This volcanic deposit appears as soft mudstone in outcrop (Figs. 9A–9C and 10). In thin section (Figs. 8A and 8B), it is characterized by altered volcanic grains containing volcanic glass shard relicts (Figs. 11A and 11B). Much of the ash is altered to clay minerals. SEM imaging documents pieces of altered glass shards (Fig. 11E). Also, evident from SEM imaging is the presence of whole coccoliths and coccolith hash (Figs. 11C–11E) indicating deposition of this unit in a deeper-water, open-marine environment. The relict ash bed shows decimeter-scale long, calcite-filled fractures in outcrop, which are interpreted as shrinkage cracks related to late alteration (Figs. 10A–10C).

Pyroclastic Debris Beds

The coarser-grained pyroclastic debris beds (Figs. 9B, 10A, 10B, and 10D–10F) in outcrop appear as thinly-laminated to thinly bedded coarser-grained volcanic rock fragments (i.e., ash and lapilli) (Fig. 12). The beds are continuous but uneven (Figs. 10A, 10B, 10D, and 10E). Grain size is very variable and limestone clasts of several inches in diameter are present (Figs. 10E and 10F) and sorting is poor. Pyroclastic grains are cemented by a rim of fibrous clay cement followed by coarser-crystalline calcite cement (Fig. 12). The rock fabric displays loose packing indicating cementation was early.

The contact with the limestones above displays load structures where the carbonate sediments sank into the soft volcanics and caused the volcanic material to flow upward (Fig. 10F). Pyroclastic debris is well-preserved in thin section (Fig. 12) and most grains show gas vesicles (Figs. 12, 13A, and 13B). Soft, irregular chalk intraclasts (Figs. 12C and 12D) are also present and these intraclasts are evidence of erosion by gravity-flow currents in a deeper-water setting where chalk was already deposited. The chalk clasts are not xenoliths as xenoliths would have to have been well lithified in order to have survived being ejective during volcanic activity. SEM imaging shows the preservation of coccoliths mixed within the pyroclastic material (Figs. 13D–13F), which supports deposition in deeper, open-marine waters. Figure 13A and 13B shows vesicles in ash partially filled with fibrous clay minerals.

McKown Formation

In outcrop, much of the lower McKown limestones at the Lower McKinney Falls section appear massive (Fig. 9), but minor evidence of cross-bedding is present (Figs. 5 and 14A). Mollusk skeletal lime packstones (Figs. 5 and 15) are the most common rock type, but some mollusk skeletal lime grainstones are present (Figs. 5 and 16).

Biota of Shallow-Water Origin

The macrofossils (i.e., larger carbonate grains) are similar throughout the 13 ft (4 m) of the McKown outcrop section. The larger grains are dominated by bivalve fragments (Figs. 15 and 16). Other common grains include red algae (Fig. 16B), echinoderm fragments, benthic foraminifers (Fig. 15C), and bryozoans (Figs. 16C, 12A, 12C, and 12D). Rare pyroclastic grains (Fig. 15C) were noted at the base of the limestone section where it is in contact with the pyroclastic strata. All these grains can be readily recognized in thin section.

Biota of Open-Marine, Deep-Water Origin

Skeletal grains of known open-marine, deeper-water origin are present, especially nannofossils. Calcispheres (i.e., algal spherical bodies), planktic foraminifers, coccoliths, and large inoceramid fragments (up to 16 in (40 cm) across) are recorded (Figs. 15C–15E). At SEM scale, much of the mud (i.e., grains less than 10 μm) is coccoliths and coccolith elements (i.e., coccolith hash) (Fig. 17). Coccolith hash results from coccolithophores that were living in an open-marine, deeper-water environment dying and settling to the sea bottom. During settling through the deep-water column, the coccolithophores bodies are digested by animals, such as copepods, and the coccolithophores are broken down into coccoliths (i.e., plates) and coccolith elements (i.e., individual crystals that composed the coccolith) (Broerse et al., 2000; Ziveri et al., 2000a, 2000b). The coccolith fecal pellets and hash settled to the sea bottom and within the Austin Chalk Group the sea-bottom depth ranged from several hundreds of feet to 600+ ft (180+ m) (Loucks et al., 2020, 2023; Zheng et al., 2023). The coccolith-rich pellets are readily disaggregated by bioturbation.

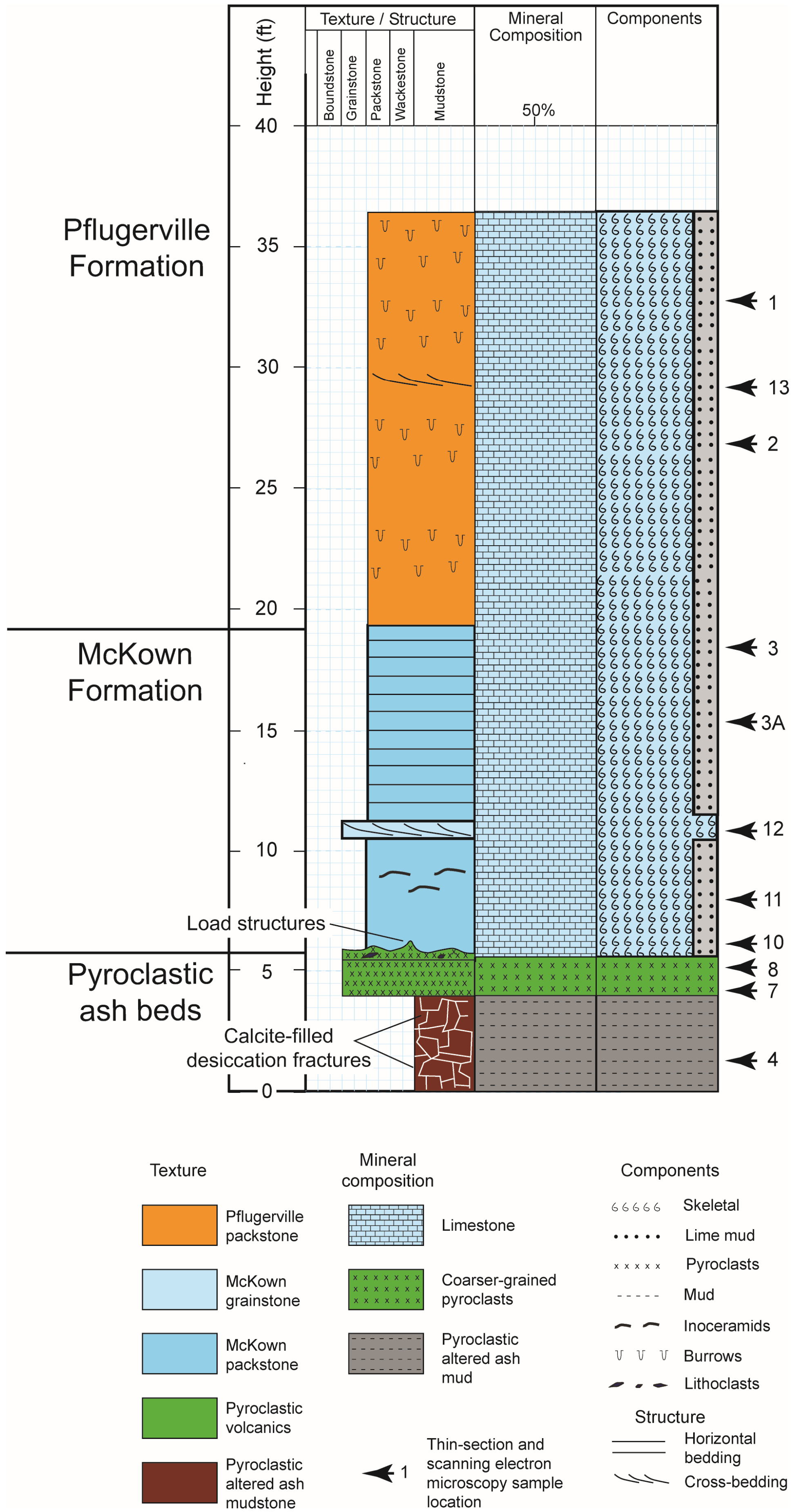
Limestone Rock Texture and Biota Composition

As mentioned above, the major rock-texture type at the Lower McKinney Falls is packstone along with some grainstone. The striking characteristic of these limestones is the mixture of deep- and shallow-water biotas (e.g., Figures 12 and 17). Shallow-water deposited carbonates should not contain significant deeper-water biota if they are in place. The presence of planktic foraminifers, calcispheres, and most importantly, coccolith hash indicates deposition in deeper water where the shallow-water biota was transported and mixed with the deeper-water biota. The mud matrix within the packstone is coccolith hash as shown by SEM imaging (Fig. 17). Therefore, the mixture of mollusks, red algae, echinoderm fragments, benthic foraminifers, and bryozoans with planktic foraminifers, calcispheres, coccolith hash, and inoceramid fragments is not supportive of shallow-water deposition but indicates deposition down the flank of the Pilot Knob volcanic mound.

Pflugerville Formation

Approximately 17 ft (5.2 m) of limestone from the Pflugerville Formation was measured and described at the Lower McKinney Falls (Figs. 5 and 9D). The designation as being Pflugerville Formation is by Young et al. (1975). The low erosional angle of the outcrop (Figs. 1C and 9D) makes it difficult to describe these strata without breaking the rock, which was not allowed under our collection permit by the Texas Parks and Wildlife Department. Several heavily-burrowed zones are dominated by *Thalassinoides* and *Planolities* burrows (Fig. 18). These burrows are subtidal in origin and the *Thalassinoides* burrows are

Figure 5. Outcrop measured section description at the Lower McKinney Falls in McKinney Falls State Park (see Figure 1 for location). Formation tops follow Young et al. (1975).



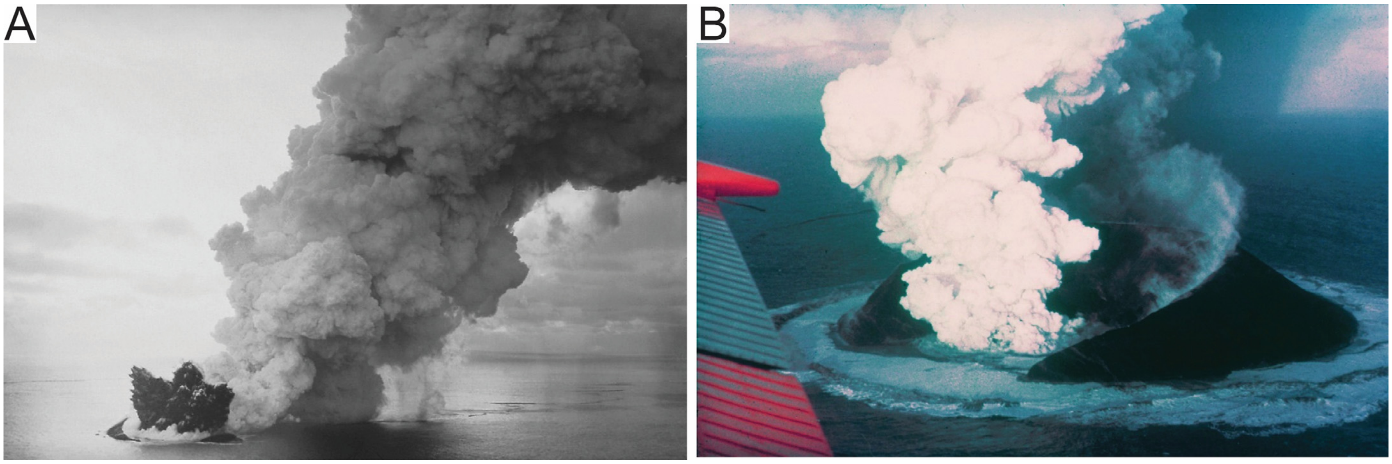


Figure 6. Modern analog for the Pilot Knob volcano. Surtsey is a deeper-water, open-marine volcano composed predominantly of pyroclastic material. (A) Phreatomagmatic eruption of the Surtsey volcano, offshore Iceland. When the hot magma interacts with the cooler sea water at the sea bottom, a flash-steam explosion occurs (courtesy of the National Oceanic and Atmospheric Administration). (B) Surtsey pyroclastic mound with an ash plume coming up through a flooded vent (courtesy of the National Oceanic and Atmospheric Administration).

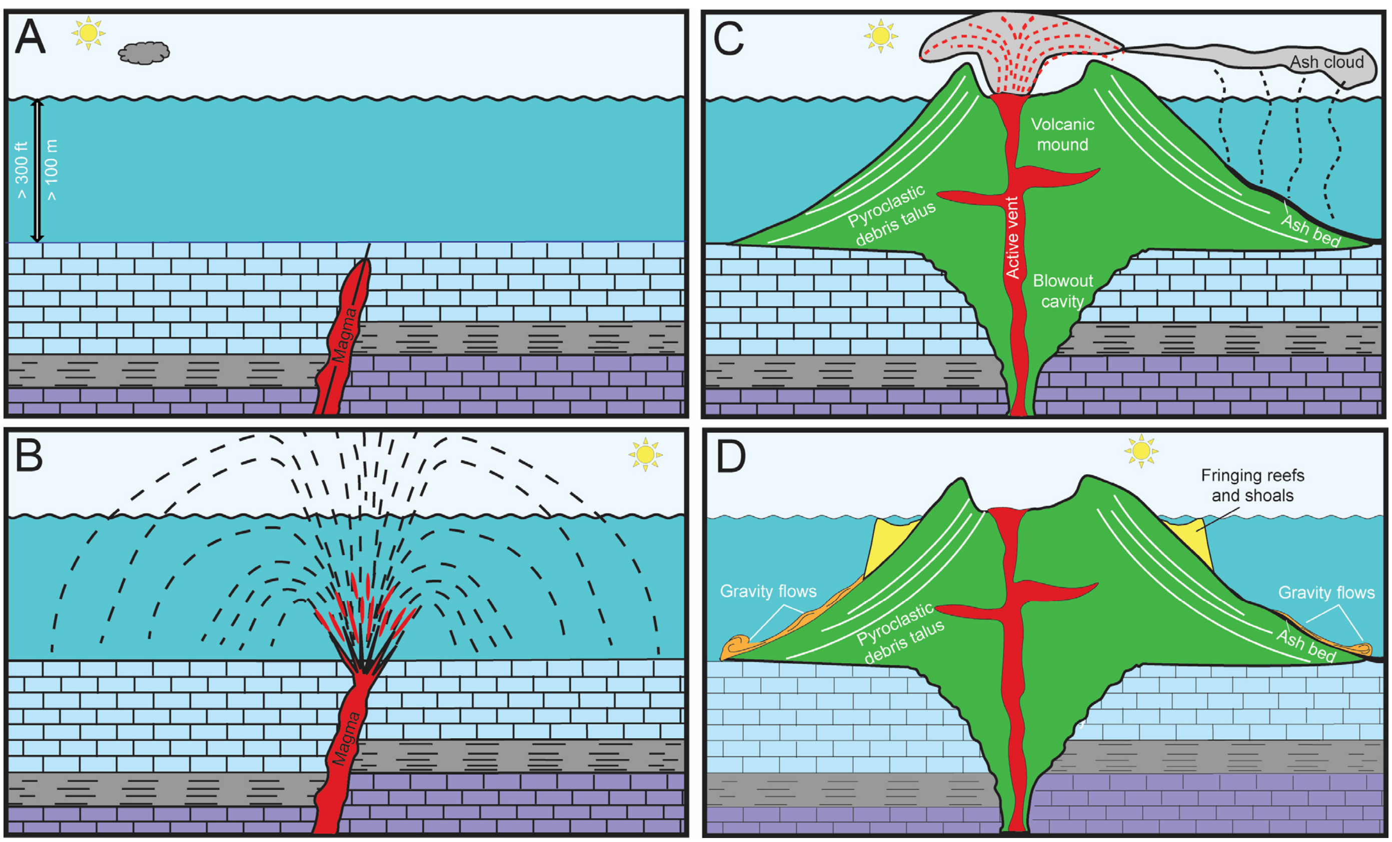
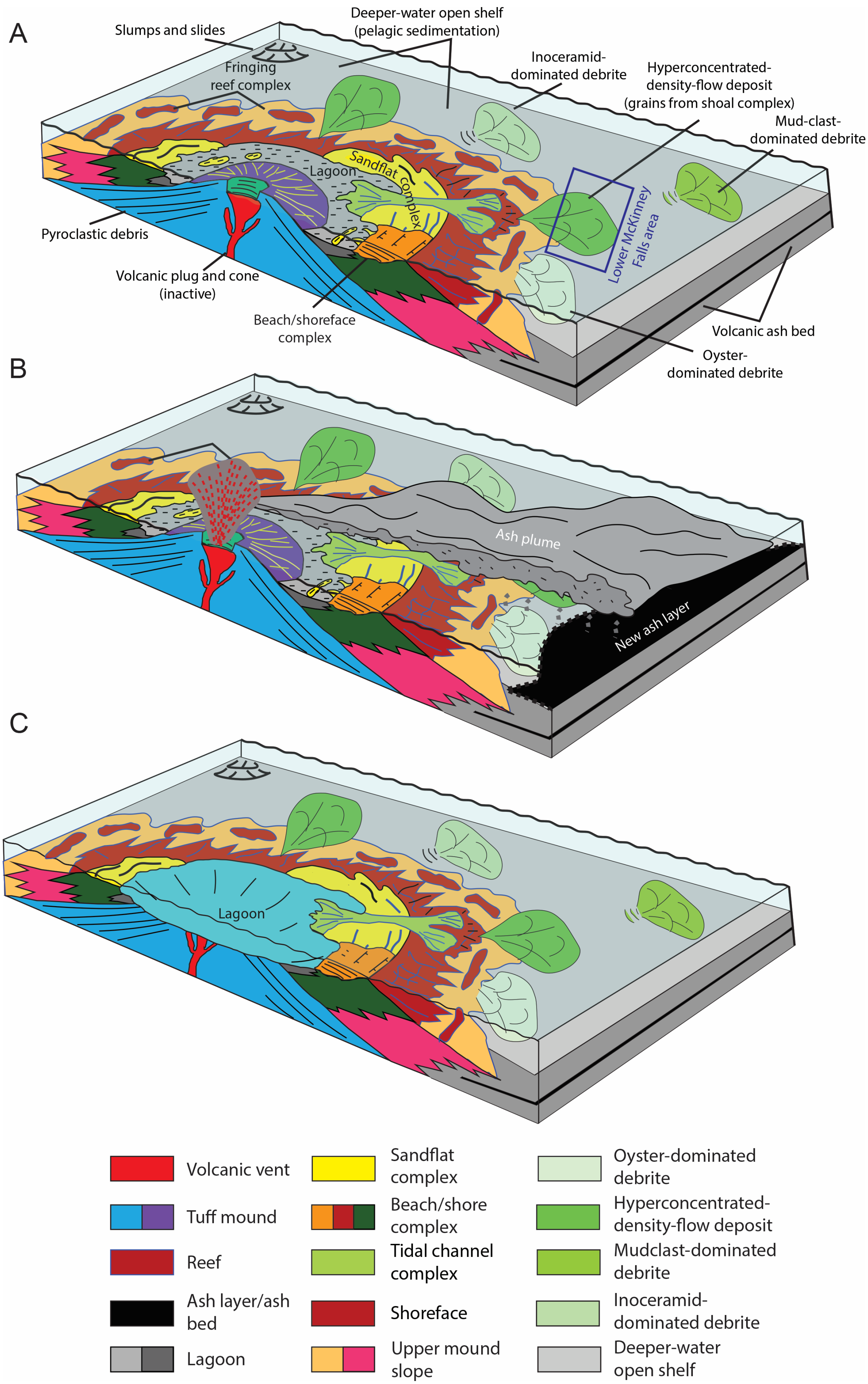


Figure 7. Developmental stages of a Pilot Knob type volcano in the Balcones Igneous Province (modified after Loucks and Reed [2022]). (A) Magma rises along fractures and faults from up to 60 mi (96 km) down in the Earth's crust. (B) When the hot magma reaches the seafloor and interacts with the cold sea water, a phreatomagmatic eruption occurs. (C) Overtime, pyroclastic debris builds a volcanic mound that may reach above sea level. (D) When the volcano goes dormant, a carbonate atoll system may build up around the volcanic vent creating a highly-productive carbonate factory. Abundant carbonate sediment is transported off the mound and resedimented by gravity-flow processes down the flanks of the mound, forming debrites.


A
Slumps and slides
Deeper-water open shelf
(pelagic sedimentation)
Fringing
reef complex
Inoceramid-
dominated debrite
Hyperconcentrated-
density-flow deposit
(grains from shoal complex)
Mud-clast-
dominated debrite
Lagoon
Sandflat complex
Lower McKinney
Falls area
Pyroclastic debris
Volcanic plug and cone
(inactive)
Beach/shoreface
complex
Volcanic ash bed
Oyster-
dominated debrite
B
Ash plume
New ash layer
C
Lagoon
Volcanic vent
Tuff mound
Reef
Ash layer/ash
bed
Lagoon
Sandflat
complex
Beach/shore
complex
Tidal channel
complex
Shoreface
Upper mound
slope
Oyster-dominated
debrite
Hyperconcentrated-
density-flow deposit
Mudclast-dominated
debrite
Inoceramid-
dominated debrite
Deeper-water
open shelf

(FACING PAGE) Figure 8. Schematic three-dimensional depositional models. Models are modified after Luttrell (1977), Loucks and Reed (2022), and Loucks et al. (2023). (A) Well-developed carbonate system associated with a dormant volcano that has built above sea level. Development of a lagoon is limited. Dominant components of debrites depend on the shallower water facies that is tapped as the sediment source. See Loucks and Reed (2022) for details concerning Balcones Igneous Province volcanic debrite deposits. (B) Volcanic activity can occur periodically and deposit new ash (i.e., pyroclastic) beds. During these periods of activity, the carbonate factory may be highly stressed or shut down. (C) Well-developed carbonate system associated with a highly-eroded extinct volcano. A prominent enclosed lagoon developed.

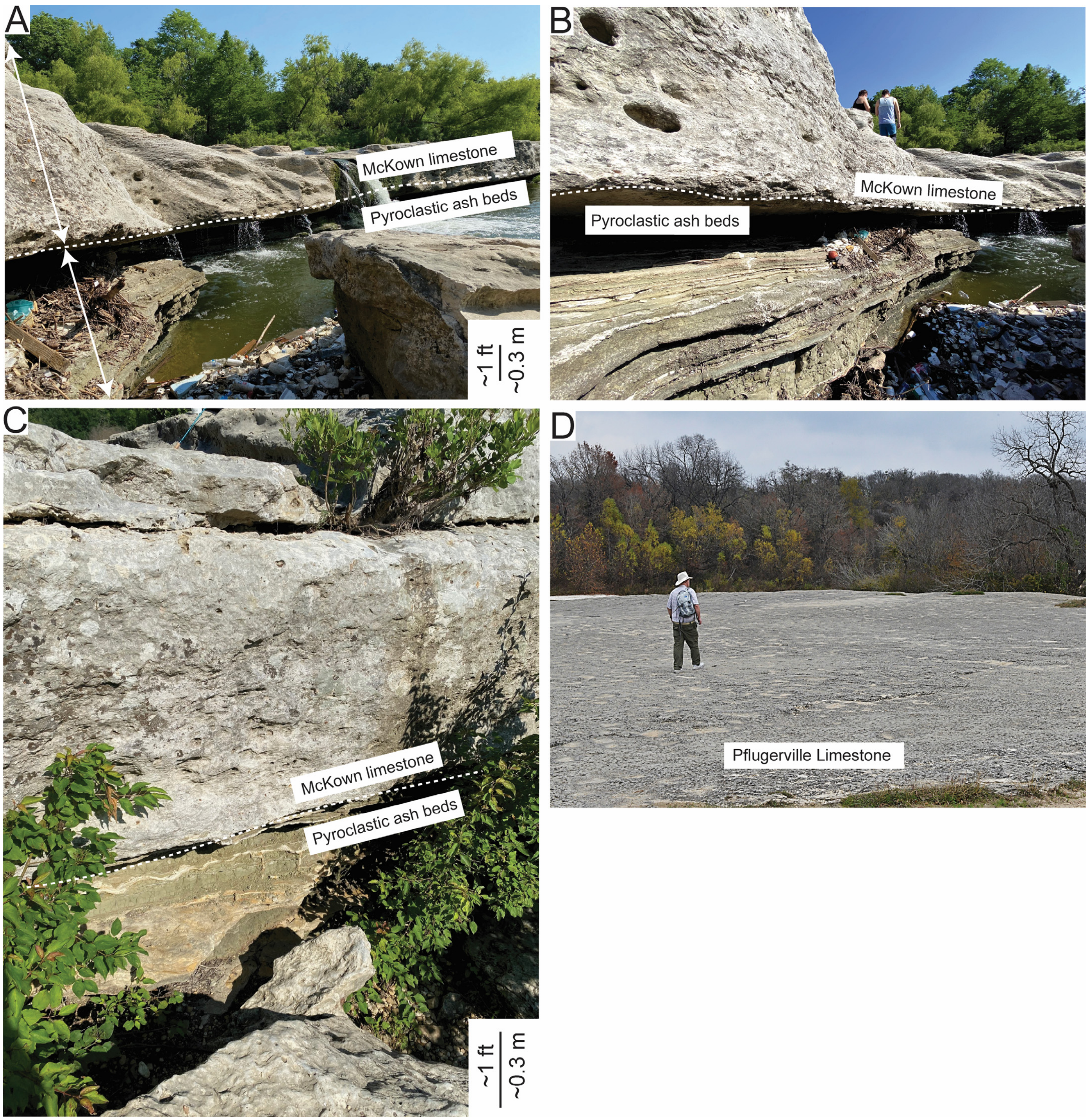


Figure 9. Lower McKinney Falls outcrop at McKinney Falls State Park. (A) View looking north from the Lower McKinney Falls where the McKown limestone overlies the pyroclastic ash beds. (B) Close up of the pyroclastic ash beds below and the McKown limestone above. (C) Close up of contact of the pyroclastic ash beds with the McKown Formation. (D) View looking northeast across the gently-dipping erosional surface of the Pflugerville Formation at the Lower McKinney Falls.

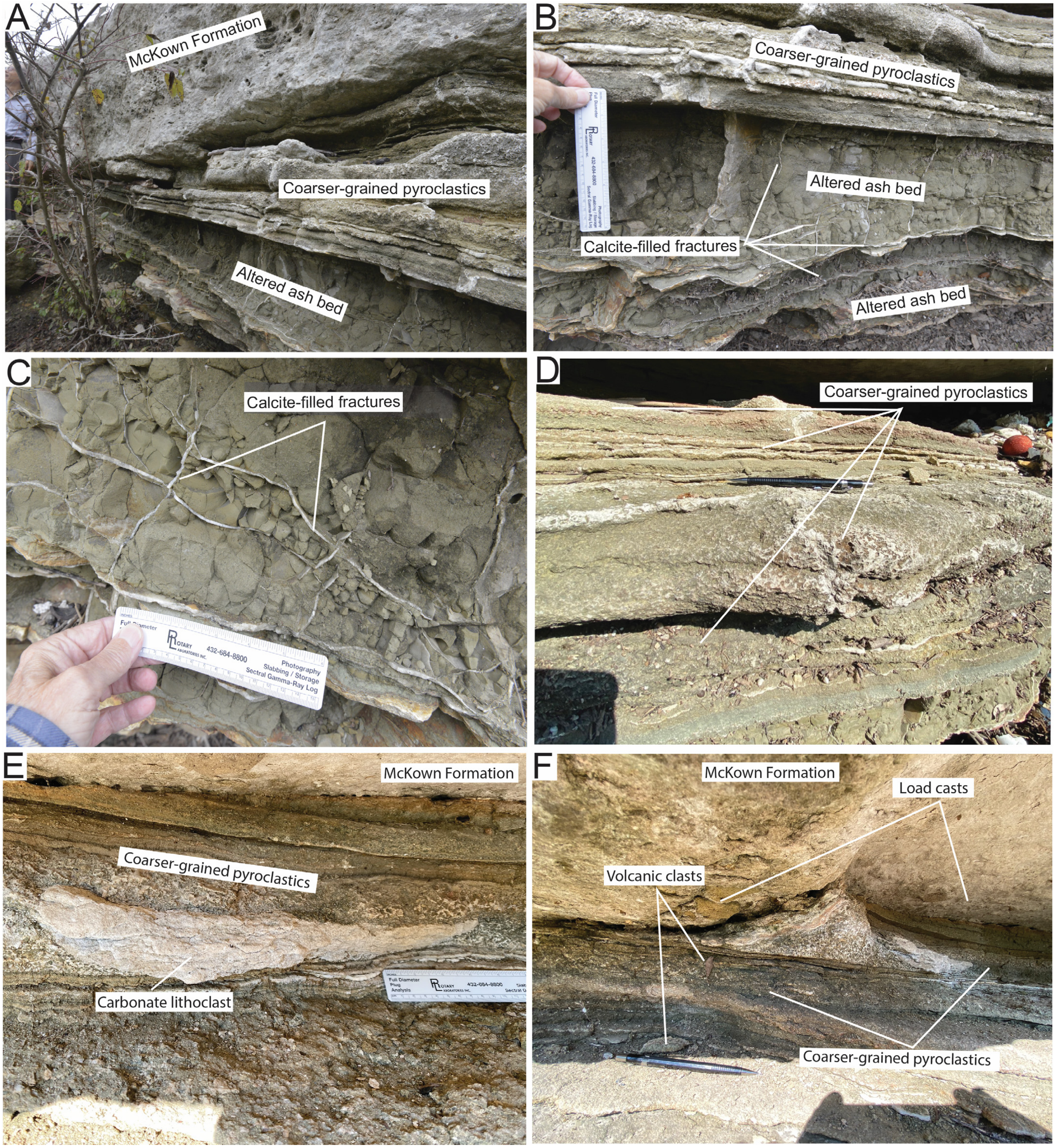


Figure 10. Pyroclastic ash beds. (A) Succession from bottom to top is altered ash bed (volcanic mudstone), coarser-grained pyroclastic beds, and McKown limestone. Person on left for general scale. (B) Close up of altered ash layer showing calcite-filled fractures. The ash has altered to clay. (C) Close up of the calcite-filled fractures in the volcanic mudstone layer. (D) Coarser-grained pyroclastic layers showing irregularities in bedding. (E) Coarser-grained, thin pyroclastic beds containing a carbonate lithoclast. (F) Sediment loading created a load structure where the massive carbonate sediments above were rapidly deposited on unlithified pyroclastics below injecting some of the pyroclastics into the carbonate sediment.

attributed to burrowing shrimp. Some low-angle cross-bedding is present (Fig. 14B). The major rock textures are bivalve packstones with some layers of bivalve grainstones (Figs. 19A and 19B). The rock texture is similar to the McKown limestone below. The Pflugerville limestone also shows a mixed composition of shallow-water and open-marine, deep-water biotas (Fig. 16). Coccolith hash dominates the lime mud matrix (Figs. 19C and 19D).

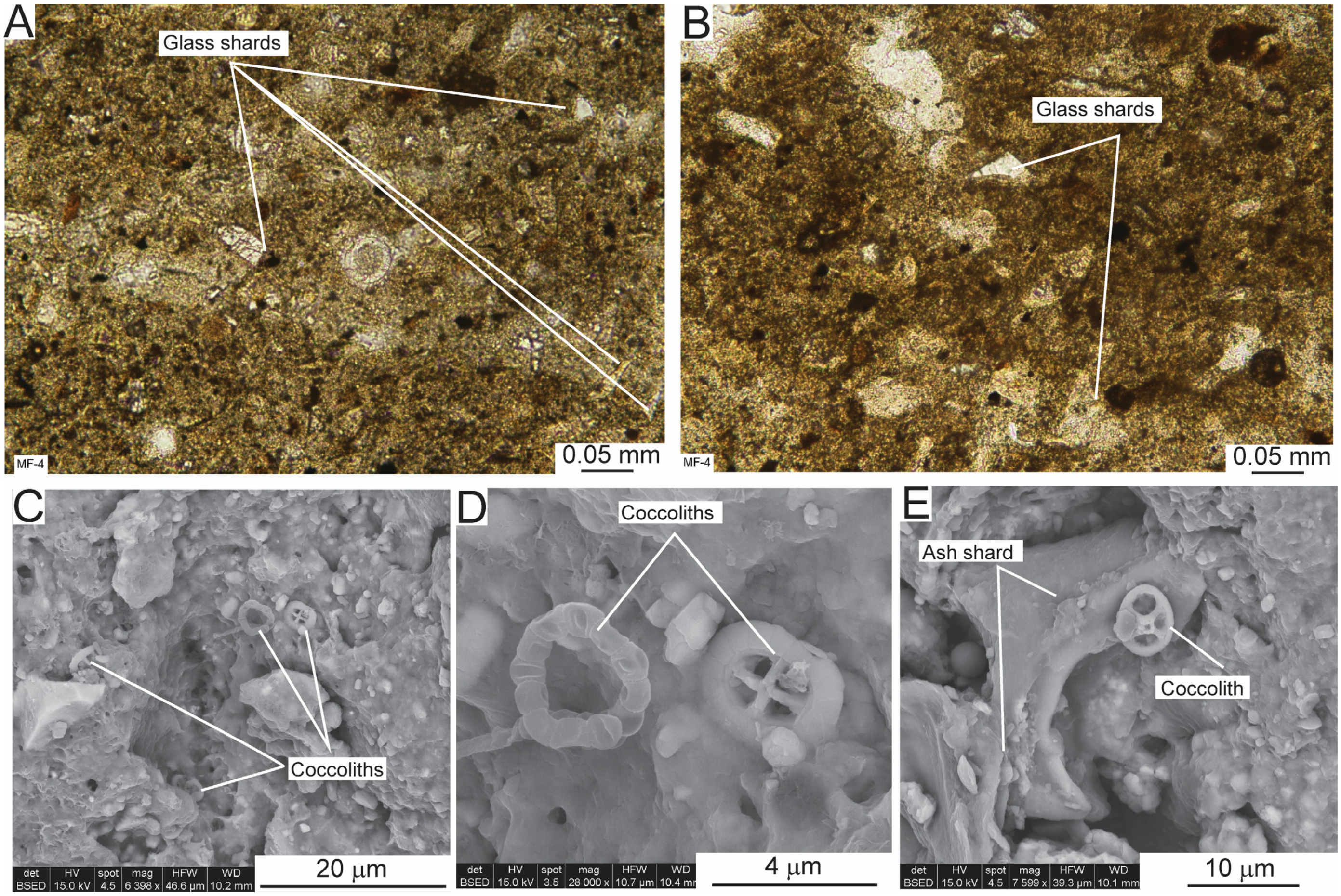


Figure 11. Volcanic mudstone. (A) Thin section of altered volcanic ash to clay that contains glass shards. (B) Another thin-section example of the altered volcanic ash with relict shards. The upper shard has a partial vesicular rim. (C) SEM image of volcanic ash containing coccoliths. (D) Close up of C. (E) SEM image of the volcanic ash mudstone with a well-preserved ash shard and a coccolith.

DISCUSSION OF ORIGIN OF STRATA AT THE LOWER MCKINNEY FALLS

A major question about the origin of the limestones at the well-exposed outcrops at Lower McKinney Falls is whether the limestones are shallow-water beach deposits as proposed by several authors (e.g., White [1960], Young et al. [1975], Garner and Young [1976], Raney [1997], Caran et al. [2013], and Cherepon and Saribudak [2021]) or are the limestones gravity-flow deposits transported down the volcanic mound flanks and deposited in deeper water as interpreted by the present authors. White (1960) and Young et al. (1975) were some of the first to suggest that the shallow-water biota and coarse-grained texture of the limestones indicated a beach-complex origin. They also proposed that a sharp change of slope (i.e., ledge) within these deposits at the Lower McKinney Falls may have been a beach berm (Fig. 20). They did not analyze the nannofossils in the packstones and grainstones or consider the slope of the volcano and the likely water depths in the area of the Lower McKinney Falls outcrop. In the following discussion, a variety of data is integrated to define the deposition setting of the Lower McKinney Falls pyroclastic ash, McKown, and Pflugerville strata.

Pyroclastic Ash Strata

The pyroclastic rocks immediately underlying the McKown limestone provide important insights about the depositional setting of the area. The pyroclastic clay bed (Figs. 10A–10C) was considered to be a mud flow by Young et al. (1975). The presence of coccoliths and soft, irregular chalk intraclasts in the mud flow indicates it is a marine deposit that formed in deeper water. It is unlikely that fine-grained ash beds, such as these, could have been deposited in a relatively high-energy, shallow-water surf zone (i.e., foreshore area of a beach complex) without being reworked. Therefore, this pyroclastic clay bed is likely a deeper-water mud flow deposited down the flank of the Pilot Knob volcanic mound.

The laminated to thin-bedded, coarse-grained pyroclastic unit overlying the pyroclastic clay bed shows no evidence of being deposited in a higher-energy beach-foreshore area. The pyroclastic beds show no cross-bedding that would indicate reworking by wave-generated currents. The beds are irregular in thickness and show bed-by-bed variation in grain size (Figs. 10D–10F). There is no transition in composition between the pyroclastic ash beds and McKown Formation (see next paragraph). In a higher-energy beach-complex setting, some of the pyroclastic sediments would have been reworked into the carbonate sediment above. Only rare pyroclastic grains are found at the base of the McKown limestone (Fig. 15C). The pyroclastic beds are not reworked, which is uncharacteristic of a higher-energy foreshore setting. The pyroclastic bedding is reminiscent of event beds emplaced by periodic flow events down a slope. These beds are interpreted as being deposited by gravity-flow processes down the flank of the volcanic mound into deeper wa-

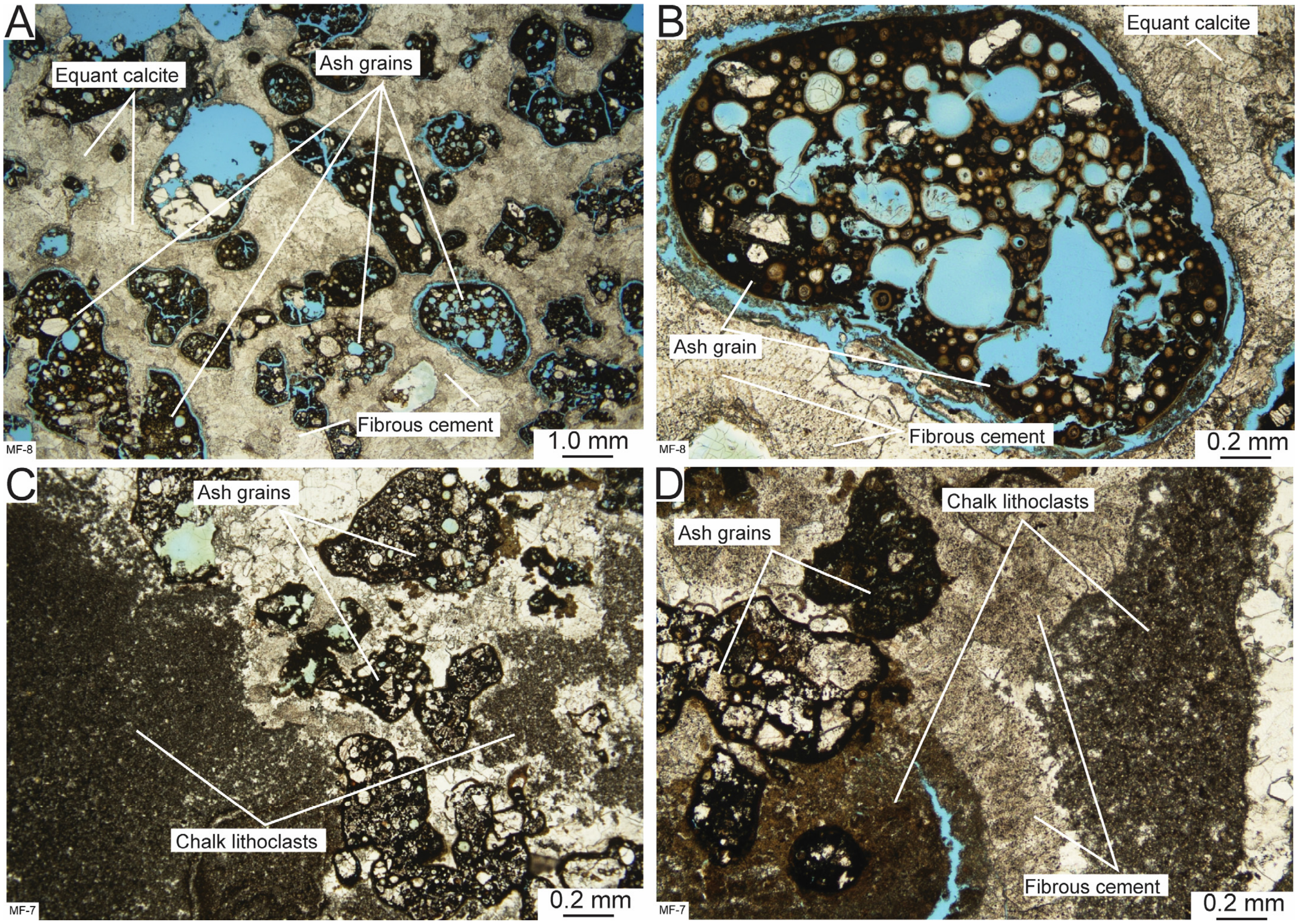


Figure 12. Thin-section photomicrographs of coarser-grained pyroclastics. (A) Volcanic ash grains with vesicles. Two stages of cement are present. First-stage cement is altered fibrous clay cement. Second-stage of cement is equant calcite. (B) Close up of A showing the two stages of cementation. (C) Volcanic ash and chalk lithoclasts. (D) Thin section with ash grains and chalk lithoclasts. Fibrous clay cement is well developed.

ter. The inclusion of coccoliths, planktic foraminifers, and chalk intraclasts support this conclusion.

At the time of deposition of the carbonate sediments above (McKown Formation), the coarser-grained pyroclastic sediments were unlithified. This is evident by load features at the top of the pyroclastics (Fig. 10F). The loading by the carbonate sediment caused the pyroclastics to squeeze upwards into the carbonate sediment. This loading suggests rapid deposition over the pyroclastics triggering them to become unstable (e.g., Owen [2003]). This process is not characteristic of a beach-complex environment but is common in gravity-flow deposits (e.g., Owen [2003]). Also, the abrupt deposition of the carbonate sediments over the pyroclastic sediments indicates there was no continuous transition in sedimentation between the two units. In a beach-foreshore setting, there should have been reworking of the pyroclastic sediments into the carbonate sediments as noted earlier. This is solid evidence that the carbonate sediments were imported by a rapid depositional event that dumped the carbonate sediments onto the unlithified pyroclastic sediments.

Limestone Strata

If the carbonate sediments were deposited in a beach-complex setting, then the bedding should show planar wedge sets dipping seaward with some trough cross-bedding in the upper shoreface. The basal limestone does display some poorly preserved cross-bedding (Fig. 14), but these cross-beds can be attributed to accretionary deposition related to gravity-flow processes. A beach complex is a moderate- to high-energy setting where waves and tidal currents winnow out any mud-sized particles resulting in carbonate sands without mud (i.e., grainstones). This is not what is observed in the Lower McKinney Falls McKown or Pflugerville limestones except in a few beds (Fig. 5).

The texture of the limestones is dominantly packstone with a coccolith-hash mud matrix. This is not the rock texture of beach or shoal sediments. The mixture of deep- and shallow-water biotas does not support a beach complex but indicates deposition in a deeper-water setting such as down the flank of the volcanic mound. The deeper-water biota of coccoliths, calcispheres, planktic foraminifers, and inoceramid fragments are absent or extremely rare in modern atoll settings (e.g., Rogers [1957] and Parker and Gischler [2011]).

In the open-marine, deeper-water column, the coccolithophores are whole and generally disaggregate settling through the deeper-water column (Broerse et al., 2000; Ziveri et al., 2000a, 2000b). If the coccolithophore material was washed in from the open-marine setting, then some portion of the coccolithophores would have likely been preserved as intact specimens, not as coccolith hash. The extremely-fine size of coccolithophores would preclude them from abrasion. Also, large inoceramid frag-

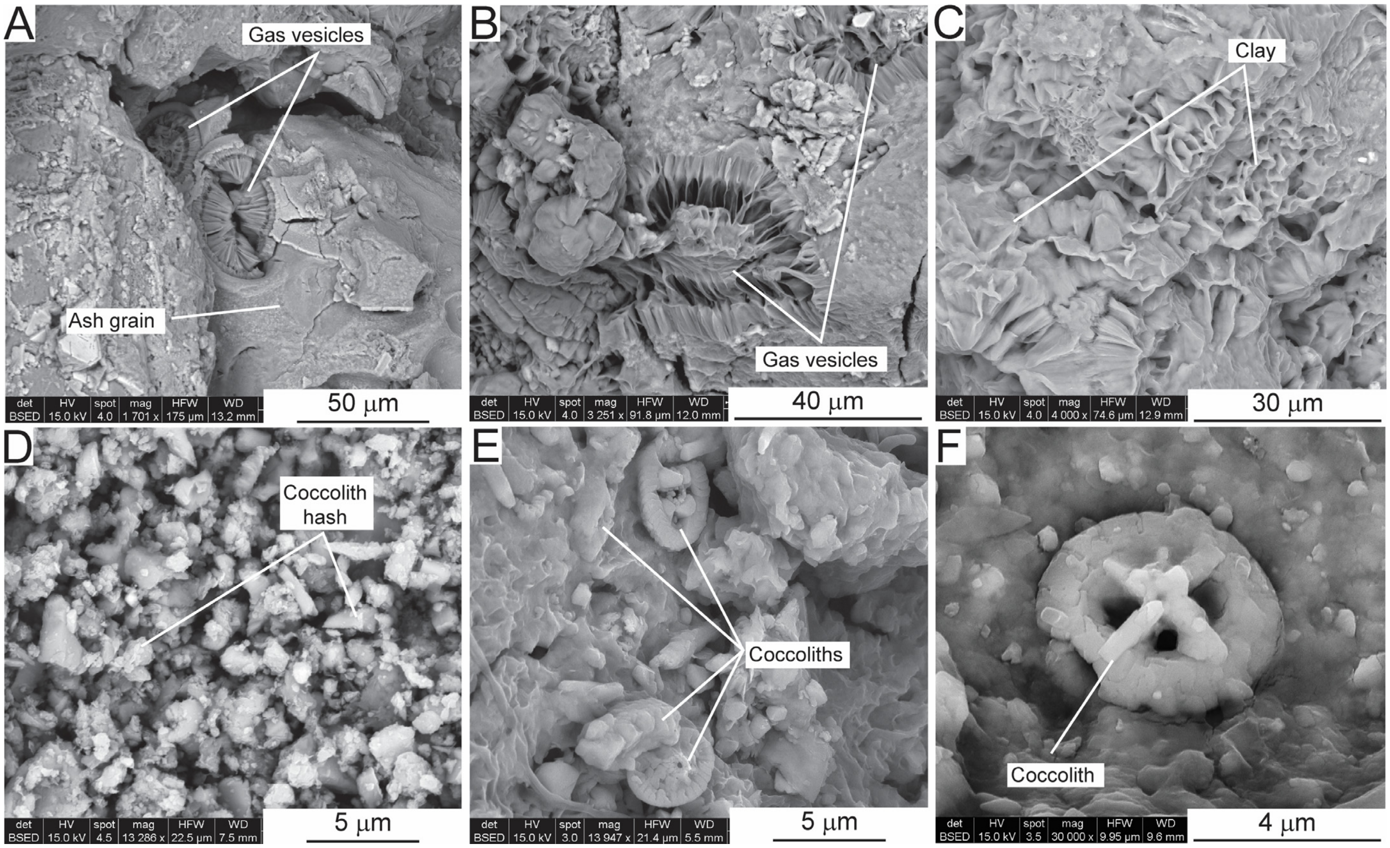


Figure 13. SEM images of coarse-grained pyroclastics. (A) Ash grain with vesicles filled with clay cement. (B) Vesicles filled with clay cement in ash grain. (C) Clay is a product of ash alteration. (D) Coccolith hash in matrix. (E) Coccoliths in coarser-grained ash beds. (F) Coccolith spine plate in coarser-grained ash beds.

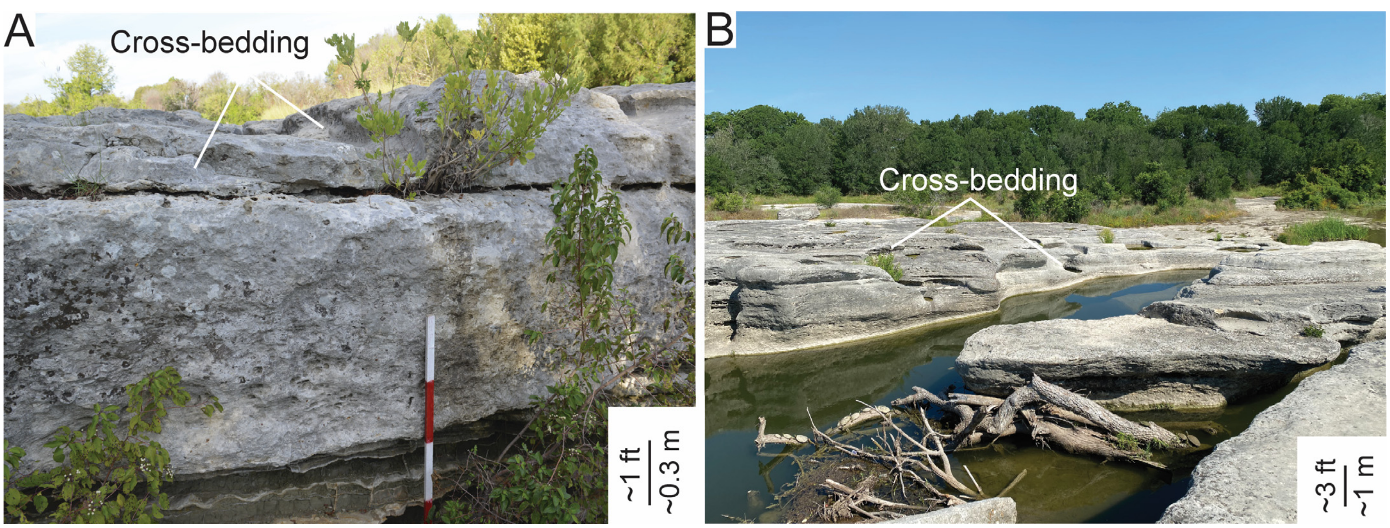


Figure 14. Cross-bedding in McKown and Pflugerville formations. (A) Crude cross-bedding in the massive McKown limestone is interpreted to be formed by debris-flow processes on the steep flank of the volcanic mound. (B) Low-angle cross-beds in Pflugerville Formation, also interpreted to be formed by debris-flow processes. Location of this outcrop shown in Figure 1B by red lines.

ments up to 16 in (40 cm) across (Raney, 1997) (Fig. 15E) are noted in the McKown outcrop. Inoceramids are known to live in deeper muddy substrate conditions and would not be present in shoaling environments (Boucot, 1990). If they were washed into a beach environment, they would not remain articulated in the higher-energy beach setting; they would be disaggregated into individual prisms. Therefore, the mixed biotas support a deeper-water setting down the flanks of the volcanic mound. The zones of *Thalassinoides* and *Planolities* burrows (Fig. 18) indicate deposition in a subaqueous environment offshore from a shoaling

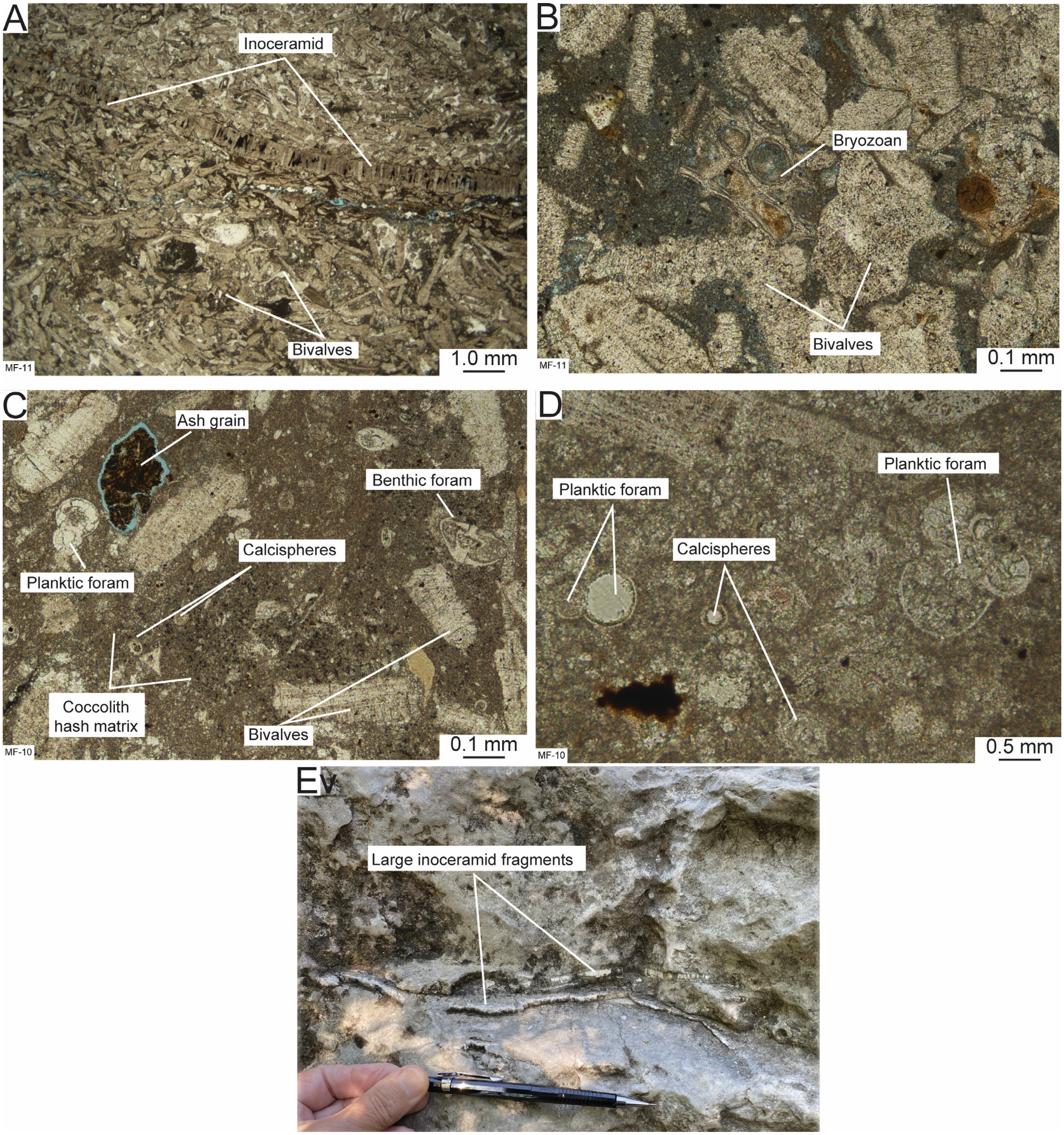


Figure 15. McKown packstone thin-section photomicrographs and outcrop photograph. (A) Poorly-sorted bivalve packstone containing a thin-walled inoceramid fragment. (B) Bivalve packstone with bryozoan fragment. (C) Skeletal wackestone to packstone with a volcanic ash fragment, benthic foraminifers, planktic foraminifers, and calcispheres. (D) Bivalve packstone with planktic foraminifers and calcispheres. (E) Large inoceramid fragments in bivalve packstone. Fragments this large indicate no reworking of the sediment after deposition.

complex. The bioturbated zones suggest depositional events where the top of the event deposits was burrowed.

Also, there is an abrupt change in outcrop-slope angle in the downdip direction of the outcrop that forms a steeper ledge which is approximately 8 to 9 ft (~2.4 to 2.7 m) high (Fig. 20). This feature was interpreted as a paleo-beach berm by Young et al. (1975). We suggest that if this was a beach berm then there should be no matrix (especially a coccolith-hash matrix) in the berm as berms are preserved as grainstones. Much of the limestone in this feature is packstone containing a coccolith hash matrix. Also, beach berms generally have a landward slope toward the back beach area. This reverse slope is not seen in this feature

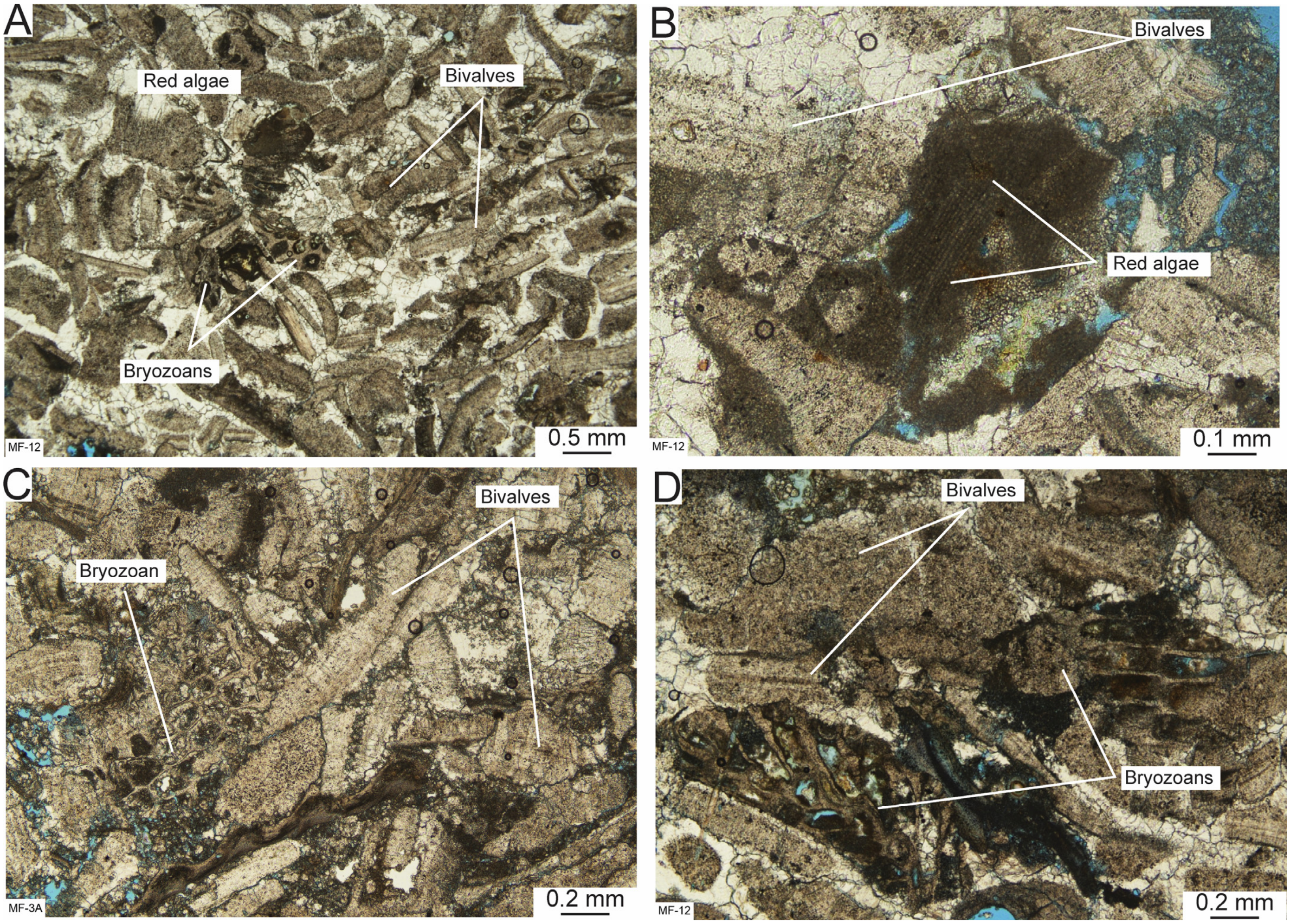


Figure 16. McKown grainstone thin-section photomicrographs. (A) Bivalve grainstone with bryozoan fragments cemented by equant calcite. (B) Red-algae grain in grainstone. (C) Bivalve grainstone with bryozoan fragments showing grain-to-grain pressure-solution contacts. (D) Close up of bivalve grainstone with bryozoan fragments.

Young et al. (1975) interpreted as a paleo-beach berm (Fig. 20). This ledge can be traced along the outcrop (Fig. 1C) to where it is at approximately 90° to the downdip ledge (Figs. 1C and 20D). We interpret Young et al.'s (1975) paleo-beach berm as a modern erosional feature carved by Onion Creek.

Water-Depth Estimate

Analysis of water depth as it increased down the flank of the emergent volcanic mound can be done by estimating the slope of the mound flanks and the distance from the estimated shoreline. The estimated slope of Pilot Knob is approximately 4.5° as calculated by the present investigation. Two scenarios can be applied to estimated water depths at the Lower McKinney Falls. The first scenario is based on an isopach map of the McKown limestone by Garner and Young (1976) that shows a thick cross-bedded limestone section of 45 ft (13.7 m) (McKown Quarry) on the north side of the mound and then the limestone thins northward towards the Lower McKinney Falls outcrop (Fig. 4A). Assuming the thick limestone section is the likely shallow-water beach complex area (i.e., near estimated shoreline), then applying a slope of 4.5° and a distance of approximately 2500 ft (~760 m) to the Lower McKinney Falls outcrop, a water depth of approximately 150 ft (~45 m) is calculated (Fig. 4C). The second scenario is that the shoaling environment was higher on the volcanic mound and is now eroded. According to the isopach map of Young (1976), the thick carbonates extend up the mound to the eroded scarp (Fig. 4A). If the carbonate shoaling complex was at this distance of ~4500 ft (~1370 m) away from the Lower McKinney Falls outcrop, this would locate the Lower McKinney Falls strata at the outcrop at a water depth of ~300 ft (90 m). These water depths are too deep to support a carbonate factory; therefore, the shallow-water sediments deposited in this area must have been transported in by gravity-flow processes. In water depths of approximately 150 to 300 ft (~45 to 90 m), deeper-water biota would be expected to be deposited. Therefore, a mixture of shallow- and deep-water biotas is justified.

DEPOSITIONAL MODEL AND HISTORY FOR THE AREA OF THE LOWER MCKINNEY FALLS STRATA AT MCKINNEY FALLS STATE PARK

Young et al. (1975) provided an outcrop cross-section (cross-section B–B') that includes the Lower McKinney Falls outcrop (Fig. 4B). The cross-section shows the McKown limestone to thin down the northwest flank of the volcano (Figs. 4A and 4B). In this cross-section, the McKown Formation is underlain by the pyroclastic ash beds and overlain by the Pflugerville Formation. We interpret the thick section of the limestone that is high up on the mound to be the high-energy beach or shoal sys-

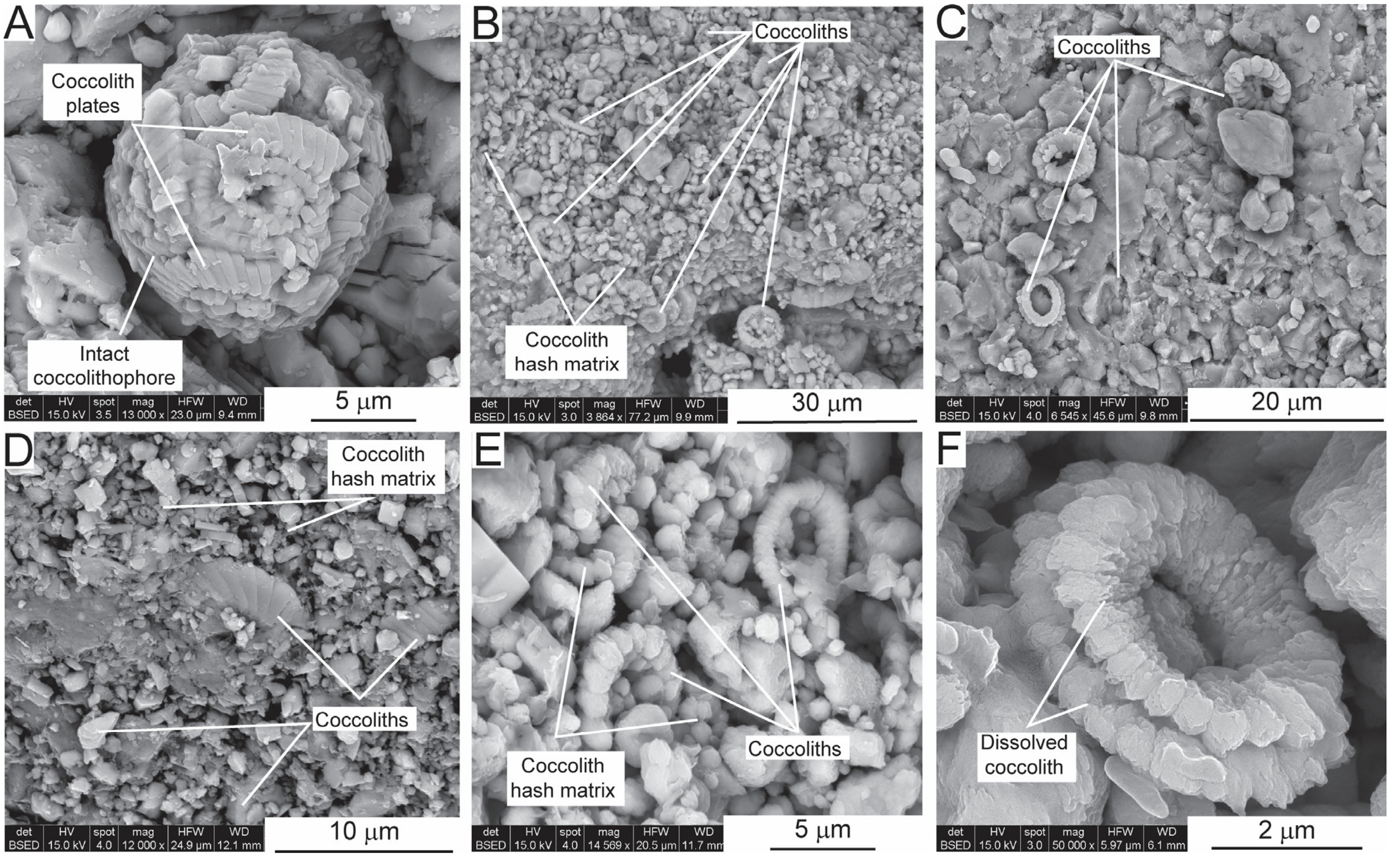


Figure 17. SEM images of the McKown packstones. (A) Intact coccolithophore displaying coccolith plates. (B) Limestone matrix composed of coccoliths and coccolith hash. (C) Coccoliths in matrix. (D) Close up of coccolith hash. (E) Coccoliths and coccolith hash with abundant micropores. (F) Individual coccolith with dissolution seam around the plate.

tem of the McKown Formation. This is supported by the limestones in this area being cross-bedded (Fig. 4B). The Lower McKinney Falls outcrop section is much thinner and as discussed above it was deposited in an estimated 150 ft (45 m) of water depth down the slope of the mound. However, if the shoaling complex was higher on the eroded mound, water depths of over 300 (90 m) can be considered. These water depths are supported by the mixture of the deep- and shallow-water biotas and dominant packstone texture. Gravity-flow processes transported the sediments from the area of the updip shallow-water carbonate factory. The strata are now preserved as grain-rich debrites and hyperconcentrated-density-flow deposits. Young et al. (1975) showed the McKown limestone to pinchout further downdip. This is a logical profile for carbonate deposits on the flank of a volcanic mound that has a relatively-steep slope into deeper, open-marine waters.

The depositional history of the carbonates associated with the Pilot Knob volcano can be summarized in several stages. During the latter part of Late Cretaceous Austin Chalk deposition in the McKinney Falls State Park area, a prominent stage of volcanic activity occurred in the Balcones Igneous Province in South and Central Texas (Griffin et al., 2010). Pilot Knob, located in eastern Travis County is one of these volcanoes. The volcano built a mound on the deeper-water platform (>300 ft [>90 m] water depth) into a small subaerial platform. During periods where the volcano was dormant or volcanic activity ceased, a shallow-water carbonate factory (e.g., shoal complex) was able to become established. Abundant shallow-water organisms were generated and a large amount of carbonate material they generated was transported off mound by debris flow processes forming debrites and hyperconcentrated-density-flow deposits on the deeper-water flanks. During transport, the shallow-water biota was mixed with the deeper-water biota. This describes the strata observed at the Lower McKinney Falls outcrop.

CONCLUSIONS

The strata at Lower McKinney Falls section have been previously interpreted as being deposited in a shallow-water beach environment. A reinterpretation of these strata using new biota data, analysis of the underlying pyroclastics, and slope/water depth relationships has provided evidence that these strata were deposited in deeper water (~150 to 300 ft; ~45 to 90 m) by gravity-flow processes down the volcano flank. The actual beach or shoal complex is interpreted to be higher up (i.e., closer to) the flank of the Pilot Knob volcano (to the southeast), and this area is what supplied the shallow-water biota grains that formed the deeper-water gravity-flow deposits. Also, the Pflugerville limestones are generally characterized as marly chalk, but at Lower McKinney Falls this limestone is similar to the McKown limestones below. Either this is a coarse-grained lithofacies of the Pflugerville limestone or this interpreted Pflugerville section by Young et al. (1975) is actually an upper section of the McKown Formation. This reinterpretation of the Lower McKinney Falls strata integrates all available data and forms a coherent depositional interpretation for a deeper-water setting down the flank of the Pilot Knob volcano.

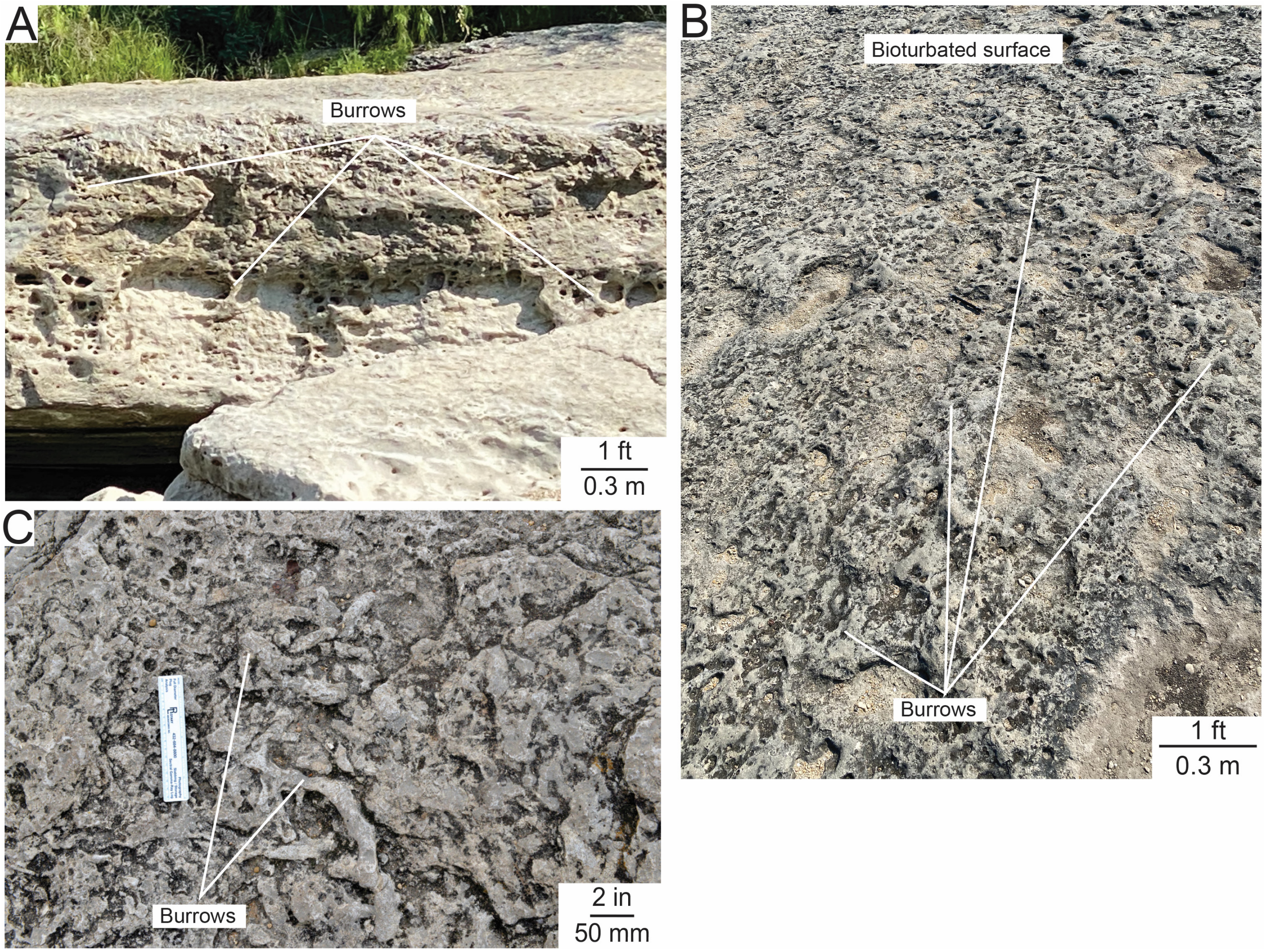


Figure 18. Burrowed zones in the Pflugerville Formation. (A) Vertical exposure of a well-developed burrowed zone. Burrows are interpreted as *Thalassinoides* and *Planolities* burrows. (B) Upper surface of the Lower McKinney Falls outcrop showing abundant bioturbation. (C) Close up of burrowed surface. *Thalassinoides* and *Planolities* burrows are evident.

ACKNOWLEDGMENTS

The authors of this report express our appreciation to the Texas and Wildlife Department for providing a permit to conduct this investigation at McKinney Falls State Park. They allowed us to collect outcrop hand-sized samples in the vicinity of the Lower McKinney Falls. We also want to thank the personnel at the McKinney Falls State Park for their cooperation during our field work. We would especially like to thank Superintendent Tommy Cude for his supervision of our permit. Funding for this project came from the STARR (State of Texas Advanced Oil and Gas Resource Recovery) and RCRL (Carbonate Reservoir Characterization and Research Laboratory) programs at the Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin. We also want to recognize Deb Loucks, Hongliu Zeng, and Josh Lambert for accompanying us in the field. Mark Longman, Carl Steffenson, and Mark Thompson reviewed the manuscript and provided comments and suggestions that improved the content of the manuscript. Publication authorized by the Director, Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin.

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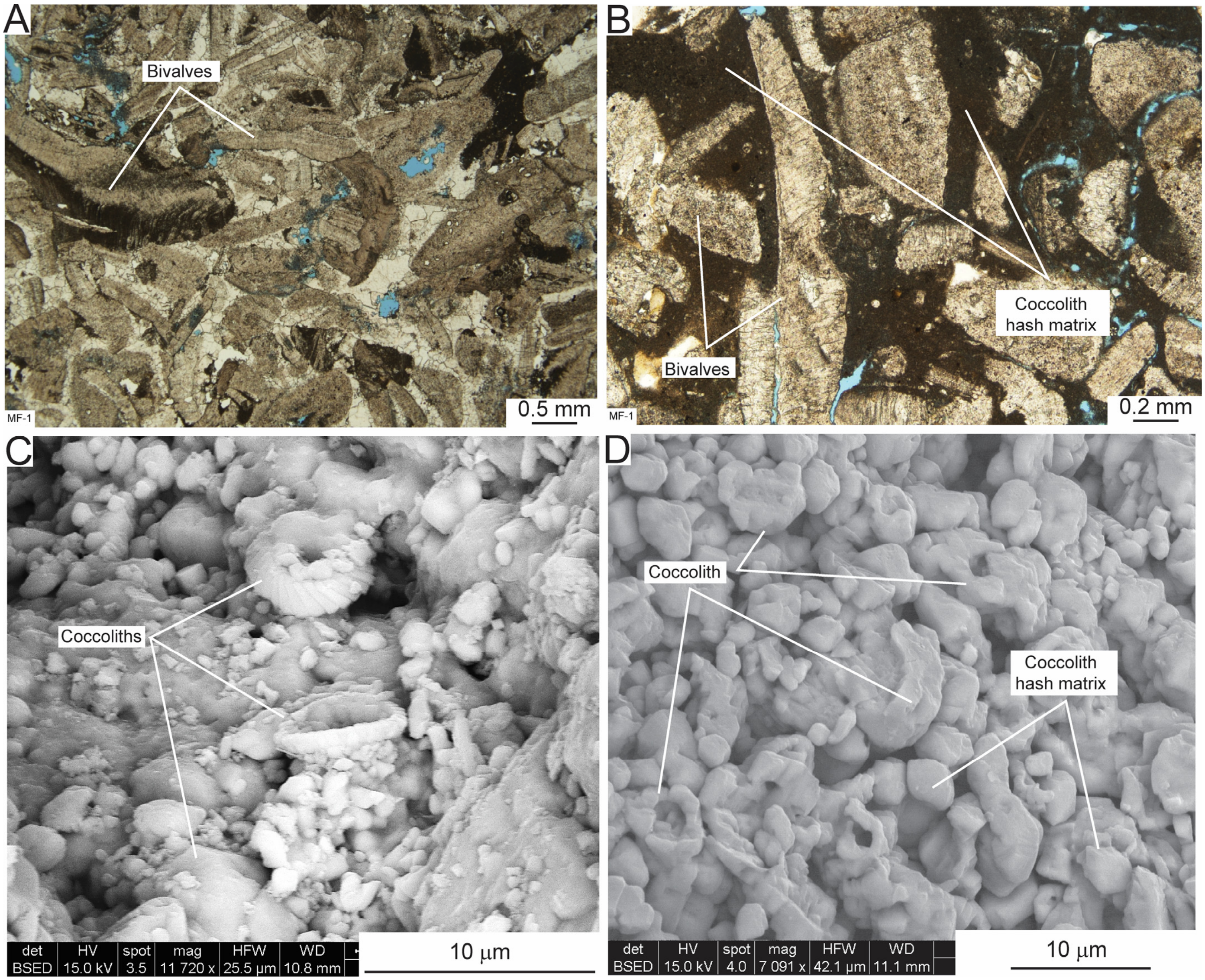

Figure 19. Thin-section photomicrographs and SEM images of the Pflugerville Formation. (A) Thin section of bivalve grainstone with calcite cement. (B) Thin section of bivalve packstone. (C) SEM image showing matrix composed of coccoliths and coccolith hash. (D) SEM image displaying several coccoliths with some calcite overgrowths. Coccolith elements well displayed.

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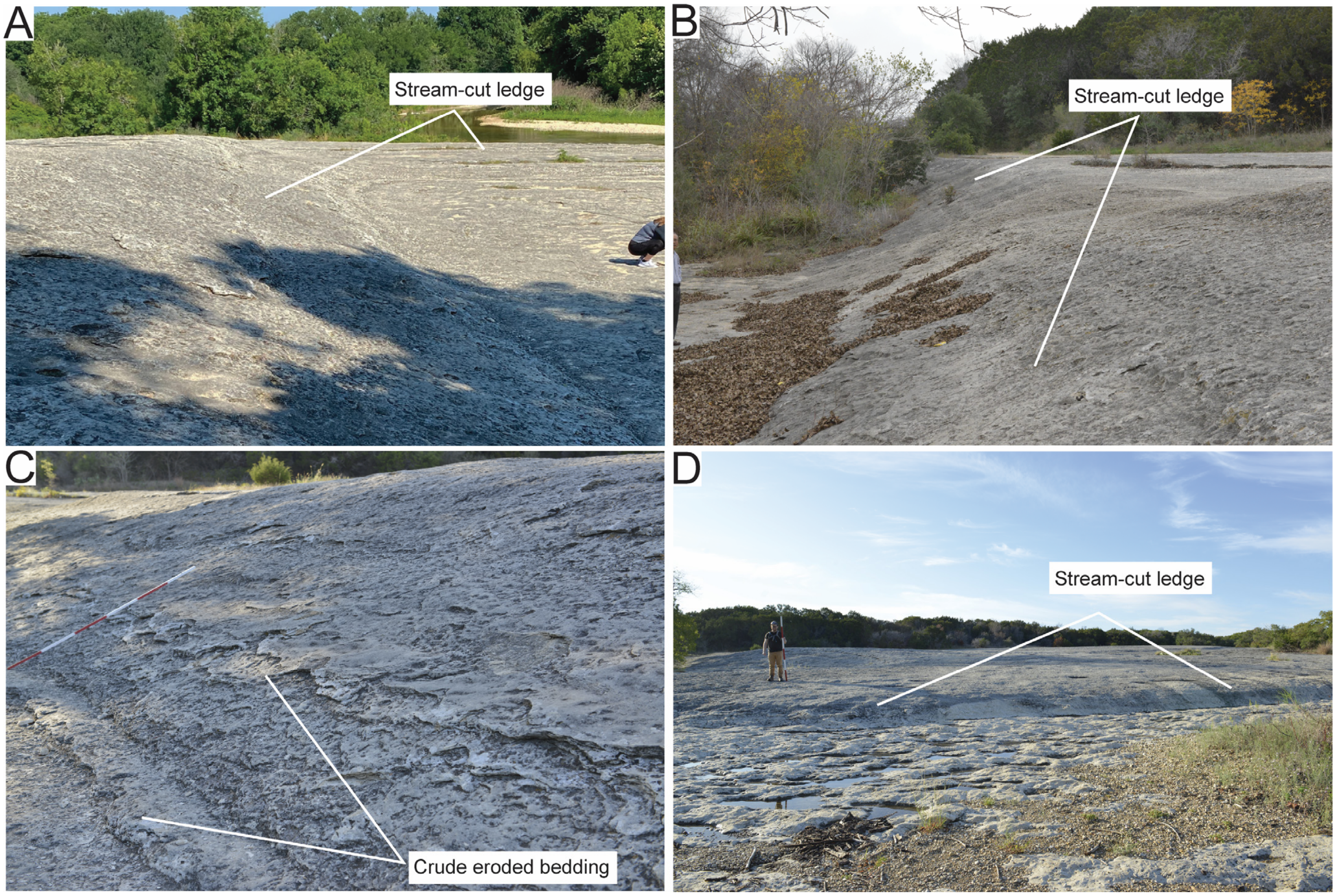

Figure 20. Photographs of stream-cut ledge. The ledge is approximately 8 to 9 ft (~2.4 to 2.7 m) high. The ledge was interpreted by Young et al. (1975) as a paleo-beach berm. See Figure 1C for stream-cut ledge location. (A) Ledge with smooth slope that curves to the right in the distance. (B) Ledge with upper flat surface to the right. A beach berm would slope landward into the back-beach area, this area is flat. (C) Stream erosion along the ledge exposing crude bedding. (D) Ledge shows eroded bedding and is orientated at a 90° angle with the main stream-cut ledge (see Fig. 1C).

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