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Sedimentary petrography and depositional environments of the type section of the Mississippian Lake Valley Formation, Sierra County, New Mexico

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2012, pp. 293-304. https://doi.org/10.56577/FFC-63.293

in:

Geology of the Warm Springs Region, Lucas, Spencer G.; McLemore, Virginia T.; Lueth, Virgil W.; Spielmann, Justin A.; Krainer, Karl, New Mexico Geological Society 63 rd Annual Fall Field Conference Guidebook, 580 p. https://doi.org/10.56577/FFC-63

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SEDIMENTARY PETROGRAPHY AND DEPOSITIONAL ENVIRONMENTS OF THE TYPE SECTION OF THE MISSISSIPPIAN LAKE VALLEY FORMATION, SIERRA COUNTY, NEW MEXICO

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Abstract—At its type section, located in the historic Lake Valley mining district in southwestern Sierra County, New Mexico, the Mississippian Lake Valley Formation rests on the Mississippian Caballero Formation, has an exposed thickness of 71 m and includes the (ascending order) Andrecito, Alamogordo, Nunn and Tierra Blanca members. The Caballero Formation represents a transgressive succession of hummocky cross-bedded siltstone to fine-grained sandstone of the lower shoreface, grading into muddy limestone and marly shale with intercalated thin limestone beds of a deeper shelf environment. The Andrecito Member of the Lake Valley Formation is composed of a shallowing upward succession of marly shale and intercalated limestone beds, grading upward into dominantly limestone. Grain size of the fossiliferous limestone increases upwards, and near the top, limestone is partly cross-bedded, indicating a facies change from near storm wave base to lower shoreface. The Caballero Formation and Andrecito Member form a depositional sequence composed of a transgressive systems tract, represented by the Caballero Formation, and a progradational systems tract, represented by the Andrecito Member. The Alamogordo Member is composed of mudstone and wackestone indicating deposition in a low-energy deeper shelf environment below storm wave base. The overlying Nunn Member, represented by marl and marly shale with intercalated thin limestone beds, appears to have been deposited on a deeper shelf near storm wave base. The Tierra Blanca Member is characterized by coarse-grained fossiliferous limestone (grainstone, packstone and rudstone), partly displaying trough cross-bedding. We interpret these limestones as storm deposits (tempestites), which accumulated when storm-generated currents transported sediment from a shallower shelf setting into deeper water between fair weather and storm wave base. The Alamogordo, Nunn and Tierra Blanca members represent a transgressive-regressive depositional sequence, composed of a transgressive systems tract (Alamogordo and basal Nunn members) and a progradational systems tract (Nunn and Tierra Blanca members). Both Lake Valley Formation depositional sequences correlate with depositional sequences recorded from the Lake Valley Formation in the San Andres and Sacramento Mountains to the east. Limestones of the Lake Valley Formation, particularly of the Andrecito and Tierra Blanca members, are composed of a bryonoderm grain association dominated by skeletons of echinoderms and bryozoans that is common in Late Paleozoic successions. This association indicates that sediments of the Lake Valley Formation probably were deposited on a thermocline-stratified ramp.

INTRODUCTION

The discovery and recognition of Mississippian rocks in New Mexico took place in 1881 at Lake Valley in southern New Mexico. Edward Drinker Cope (1840-1897), who was one of the founders of vertebrate paleontology in the United States, made this discovery. Based in Philadelphia, Cope had invested significant sums in silver mines in Colorado and New Mexico, a mistake that ultimately cost him a fortune.

In August 1878, silver was discovered in the Lake Valley area (Eveleth, 1986), and Cope was an early investor in the mines. To check on his investments, Cope travelled to Lake Valley in August 1881. Ultimately, although Cope lost money investing in the Lake Valley mines, his association with them added to his long list of scientific discoveries.

In Spring 1881, he was sent some invertebrate fossils from the mining district. He referred them to U. S. Geological Survey paleontologist Charles A. White (1826-1910), who assigned them a "Middle Carboniferous" age (White, 1881). In October of 1881, Cope published a description of the mining district, describing the stratigraphic section as "the lowest sedimentary rock seen in place is a quartzite" that is "overlaid by one or two hundred feet of a fine carbonaceous shale from which most of the valleys are eroded" (Cope, 1881, p. 831). He then stated that "overlying the shale are 150 to 200 feet of more or less siliceous limestone, the upper part of which is very fossiliferous." This is a reasonable reconnaissance description of the strata exposed at Lake Valley, which are the "quartzite ridge" of Ordovician and Silurian carbonates, followed by a valley of Devonian shale capped by the Mississippian limestones that hosted the ore. Cope also sent Lake Valley fossils to Samuel A. Miller (1836-1897), curator of paleontology of the Cincinnati Society of Natural History, which Miller (1881) published on, proclaiming them Lower Carboniferous. Cope (1882, p. 158) published a short article listing identifications of fossils by Miller of the "silver-bearing carboniferous limestone of Lake Valley, New Mexico." In this phrase, he is credited with coining the stratigraphic name Lake Valley Limestone (e.g., Wilmarth, 1938; Laudon and Bowsher, 1949).

Since Cope's work, much has been written about the phenomenal fossil record of the Lake Valley Formation (Limestone) at its type section (see Kues, 1986 for a review). However, relatively little has been written about the rocks, themselves. This is partly because Laudon and Bowsher (1949), in their classic study of the Mississippian strata of southwestern New Mexico, did such a

good job of describing the type section of the Lake Valley Limestone. In so doing, they divided it into four members (also see Laudon and Bowsher, 1941) and provided a detailed description of the section and its fossil content. Here, we present the first study of the petrography of the Lake Valley type section to elucidate its microfacies and interpret its depositional environments and sequence stratigraphy.

LOCATION

The type section of the Lake Valley Formation that we measured is exposed on the northwestern slope of Apache Hill (5585 ft; 1793 m) immediately north of the Lake Valley mining district in the southwestern part of Sierra County (Fig. 1). This is the type section described by Laudon and Bowsher (1949, fig. 29) in the NE1/4 NW14 sec. 21, T18S, R7W. The base of the section is at UTM zone 13, 259270E, 3624884N and the top is at 259202E, 3624275N (datum: NAD 83).

LITHOLOGY

The measured section is ~ 88 m thick and includes the Caballero Formation (17 m) and most of the overlying Lake Valley Formation, with an exposed thickness of ~71 m (Figs. 2-3). The Lake Valley Formation is regionally divided into six members (in ascending order): Andrecito, Alamogordo, Nunn, Tierra Blanca, Arcente and Doña Ana members. The type sections of these members are located in the Sacramento Mountains (Andrecito, Alamogordo, Arcente and Doña Ana members) and on Tierra Blanca Creek in Sierra County (Nunn and Tierra Blanca members). At the type section, only four of these members are present: Andrecito, Alamogordo, Nunn and Tierra Blanca. Regionally, the Lake Valley Formation is overlain by the Mississippian Rancheria Formation. However, at the type section the top of the Lake Valley Formation is eroded so that the Arcente and Doña Ana members are absent. According to Armstrong et al. (2004, fig. 4), the Caballero Formation, and Andrecito and Alamogordo members are dated Kinderhookian, whereas the Nunn, Tierra Blanca, Arcente and Doña Ana members are Osagean. According to Bachtel and Dorobek (1998, fig. 2) and Dorobek and Bachtel (2001, fig. 2), the Andrecito Member of the Lake Valley Formation is probably of latest Kinderhookian age, and the Doña Ana Member extends into the Meramecian. Lane (1974) concluded from conodont studies that the Lake Valley Formation is of Osagean and possibly earliest Meramecian age.

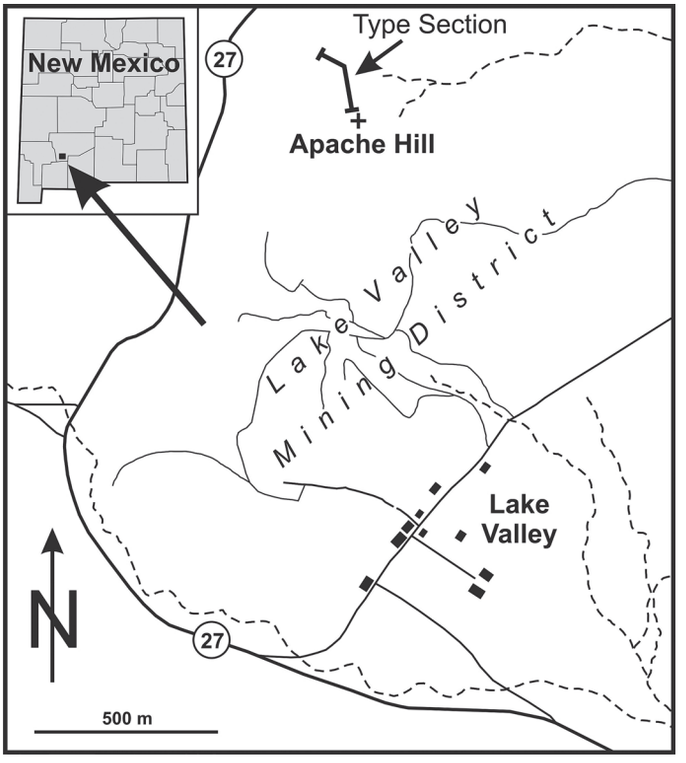


FIGURE 1. Index map showing location of type section of Lake Valley Formation in southern New Mexico.

Caballero Formation

The Caballero Formation rests on greenish shale of the Percha Formation (Box Member) and can be divided into three lithologic units (Figs. 2-3). The lower unit (5.3 m) starts with a 0.1-m-thick hematitic layer (probably a hardground at the Devonian-Mississippian unconformity) overlain by 2.9 m of hummocky cross-bedded siltstone to fine-grained calcareous sandstone with rare synsedimentary deformation structures and horizontal burrows on top. This unit is overlain by thin nodular limestone and a limestone bed containing brachiopods on top. The top of this unit is composed of 0.1 to 0.4-m-thick, gray, micritic limestone beds and intercalated yellowish-brownish marly shale. Thin limestone beds are wavy, and thicker beds are evenly bedded. The hematitic layer is composed of mm-thick hematite and hematite cemented siltstone to fine-grained sandstone, overlain by hematite-free siltstone to fine-grained sandstone. The maximum grain size is 0.1 mm.

The second part of the Caballero Formation is mixed siliciclastic-carbonate siltstone to fine-grained sandstone that is composed of abundant recrystallized carbonate grains, some of which are stained dark brown (Fig. 4A). Siliciclastic grains, including mono- and polycrystalline quartz, chert and rare feldspar grains, and a few opaque grains are subordinate. Small fossil fragments (ostracods, echinoderms, shell debris) are common. A few larger skeletons of brachiopods, bryozoans and echinoderms and intraclasts up to >20 mm in size float in the siltstone.

The hummocky cross-bedded packstone consists of abundant brownish and gray carbonate grains, quartz grains (5-10%), many skeletons (strongly fragmented shell debris, echinoderms, ostracods) and rare opaque grains (Fig. 4B). Individual layers are laminated and contain up to approximately 50% siliciclastic grains (mostly monocrystalline quartz, rare polycrystalline quartz and feldspar grains), abundant recrystallized carbonate grains and rare phosphatic grains (Fig. 4C). Skeletons of echinoderms and ostracods are less common in this lithology. Rare, large echinoderm fragments and shell fragments up to 2 mm in size float in the siltstone matrix. Locally, the rock is bioturbated.

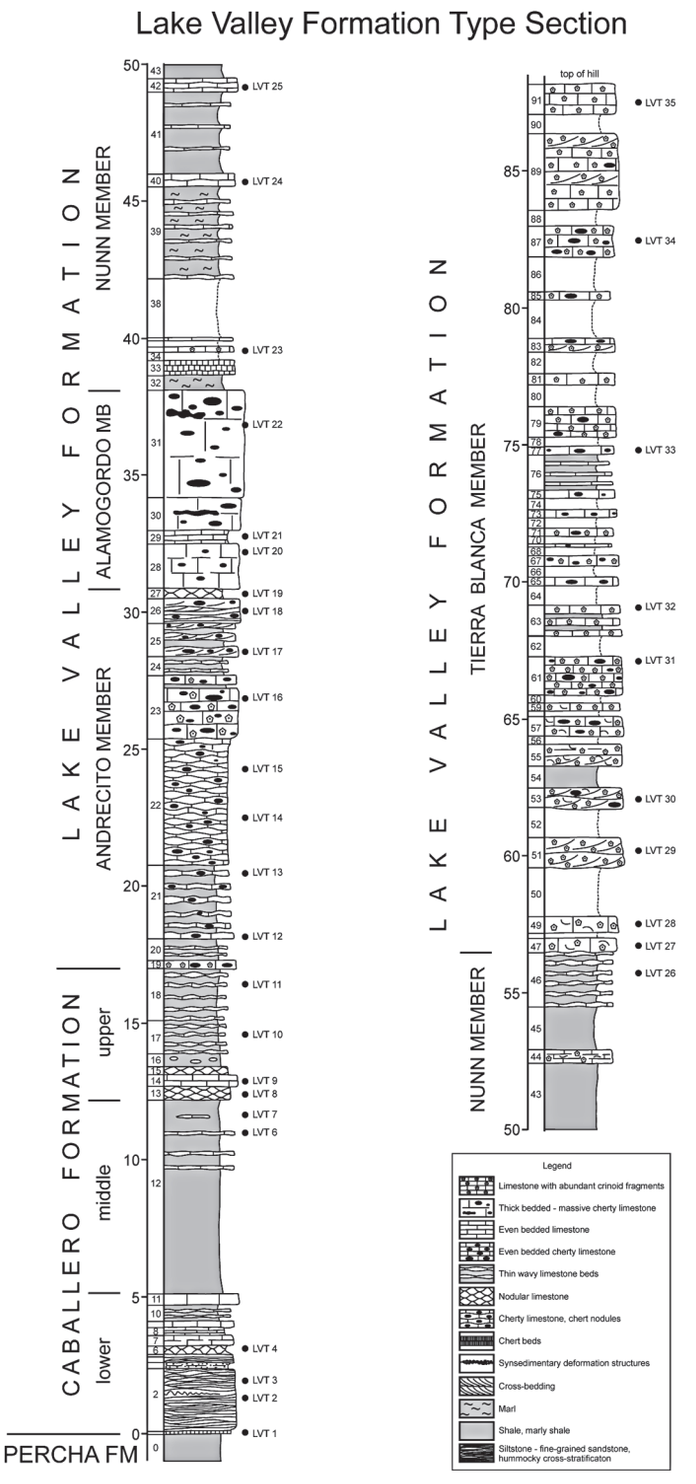


FIGURE 2. Measured stratigraphic section of the type section of the Mississippian Lake Valley Formation.

The limestone bed of unit 9 under the microscope appears as mixed siliciclastic-carbonate siltstone to fine-grained sandstone composed of abundant carbonate grains and up to approximately 10% quartz grains (Fig. 4D). Phosphatic grains are rare, glauconite grains and reworked ooids are very rare. Skeletons include

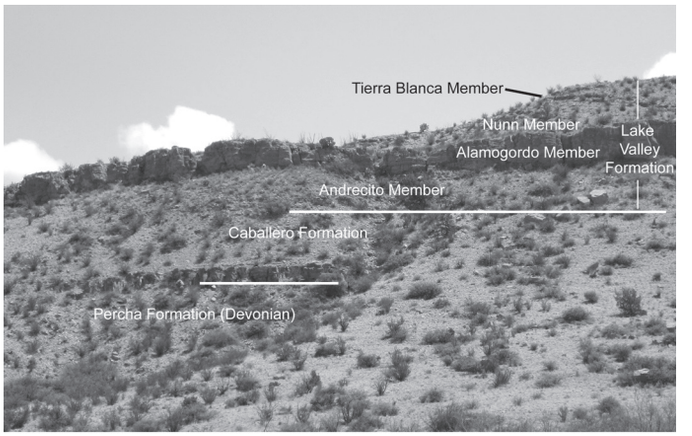


FIGURE 3. Outcrop photograph of the type section of the Lake Valley Formation showing slope-forming Devonian Percha Formation overlain by ledgy and slope-forming Caballero Formation and Andrecito Member of Lake Valley Formation, followed by prominent ledge (Alamogordo Member), another slope (Nunn Member) and the ledgy top of the hill (Tierra Blanca Member).

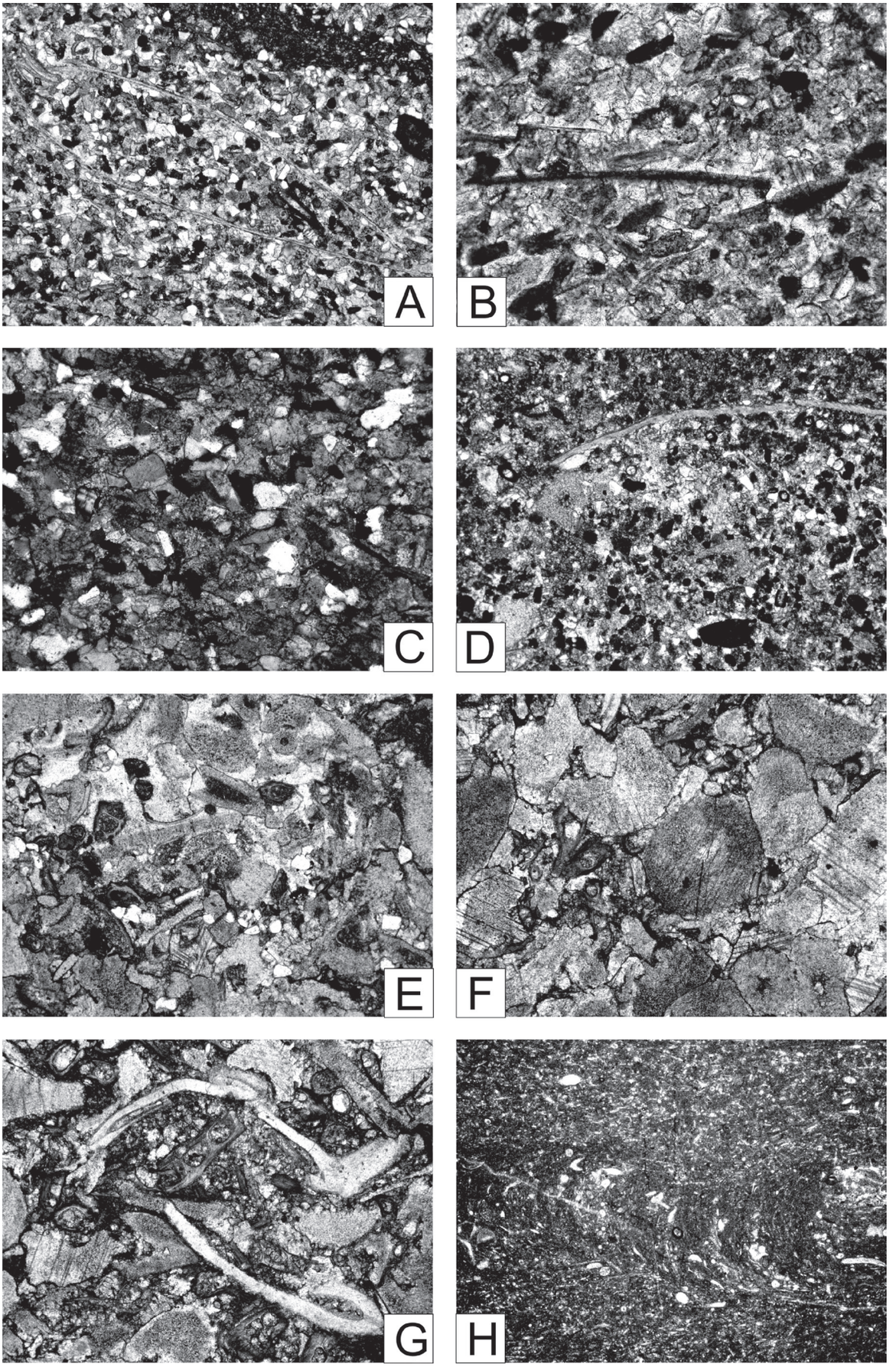
ostracods, echinoderms, brachiopods and brachiopod spines. A few larger echinoderm and brachiopod fragments float in the fine-grained sediment.

The middle part (6.9 m thick) of the Caballero Formation is composed of pale green marly shale that in the lower part is mostly covered. In the upper part, a few thin, marly limestone beds and lenses are intercalated. These intercalated limestone beds are composed of fine-grained packstone containing a few (<5%) detrital quartz grains, many skeletons of ostracods, echinoderms, brachiopods and a few phosphatic fossils. A few larger skeletons of echinoderms and brachiopods float in the silty sediment.

The upper part (4.8 m thick) of the Caballero Formation starts with nodular limestone with intercalated crinoidal limestone, overlain by thin wavy limestone beds and lenses alternating with pink marly shale. Limestone beds are reddish-gray and mostly composed of lime mudstone, and subordinately contain crinoidal debris.

The dominant microfacies of the intercalated limestone beds are poorly sorted crinoidal wackestone to packstone (Figs. 4E-G, 5A). The most common fossil fragments are echinoderms (mostly crinoids) and subordinate bryozoan fragments. Some skeletons are up to 4 mm in size. Rare are trilobite (Fig. 4G) and brachiopod fragments, ostracods, very rare corals, gastropods and the foraminifer *Earlandia*. A few phosphatic skeletons are present. Locally, peloids occur. Fossils are strongly fragmented.

In the packstones, skeletons are densely packed and cemented by calcite. Crinoid grains display syntaxial overgrowths. In the wackestones, skeletons are embedded in silty matrix, which is composed of abundant quartz grains, some glauconite grains and micrite. In individual beds the matrix is peloidal micrite. Wackestone may contain many spicules and may be bioturbated (Figs. 4H, 5B). Laudon and Bowsher (1949) listed a variety of macrofossils (mostly brachiopods) from the Caballero Formation.


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Lake Valley Formation

Andrecito Member (13.9 m)

The base of this member is a dark gray micritic limestone bed containing chert nodules up to ~ 15 cm in diameter (Fig. 2). Above this basal cherty limestone bed, is a 3.5-m-thick succession of pink, wavy, micritic limestone beds (5 to 20 cm thick) containing dark gray chert nodules and lenses, crinoidal debris and bryozoans. The limestone beds alternate with marly shale.

The next unit is 4.6-m thick and composed of wavy bedded, reddish cherty limestone with dark gray chert nodules and lenses. The limestone contains abundant crinoidal debris and bryozoans, and beds are separated by thin, marly shale partings.

This unit is overlain by 2.3 m of medium bedded (up to 40 cm), very cherty limestone. The limestone is wavy bedded with thin shale partings. The limestone contains abundant crinoid and bryozoan fragments. The next unit is 0.7 m thick and composed of thin, wavy cherty limestone beds alternating with thin shale beds.

The uppermost 2.5 m of the Andrecito Member consist of coarse-grained, cross-bedded crinoidal limestone beds containing chert nodules and lenses up to 30 cm long. The coarse-grained limestone beds are separated by thin, finer-grained limestone beds and grade upward into coarse-grained, cross-bedded (?hummocky cross-bedding), crinoidal limestone containing some chert nodules and silicified fossils. The top of the Andrecito Member is composed of 0.4 m of reddish nodular limestone.

Limestone beds of the Andrecito Member are composed of wackestones-packstones, grainstones and floatstones. The wackestone is composed of micritic, partly peloidal matrix in which skeletons are embedded (Fig. 5D). It may be laminated and is locally bioturbated. In the floatstones, cm-size skeletons are embedded in micrite, and locally some calcite cement fills the pore space (Fig. 5C, F). The packstone is coarse-grained and poorly sorted. Echinoderm fragments commonly display syntaxial overgrowths (Fig. 5E).

Grainstone is poorly sorted, well washed and calcite cemented, and locally contains small amounts of micrite (Fig. 5G). The dominant skeletal grain types are echinoderm (mostly crinoid) and bryozoan fragments, which both constitute more than 90% of the rock. Other skeletons include ostracods, fragments of brachiopods, gastropods and rare other skeletons. The grainstone-packstone of sample LVT 19 contains many algae incertae sedis (Algospongia) *Asphaltinella*, the foraminifer *Endothyra* ex gr. *prisca* and a few micritic intraclasts. Many echinoderm fragments are partly replaced by chert.

According to Laudon and Bowsher (1949), fossils other than fenestelloid bryozoans are not abundant in the Andrecito Member.

Alamogordo Member (7.2 m)

This member is composed of cliff-forming, thick bedded to massive, light gray micritic limestone containing chert nodules and lenses (Figs. 2-3). The limestone is very cherty near the top. In the lower part, a thin-bedded interval (0.5 m thick) of light gray micritic limestone is intercalated.

Microfacies types of the Alamogordo Member are bioclastic mudstones and subordinately crinoidal wackestones to packstones. Bioclastic mudstone is composed of micritic to microsparitic matrix in which a few bioclasts (spicules, ostracods, echinoderms, brachiopods, bryozoans, trilobites and (?)worm tubes) float (Fig. 5H). Locally, a few peloids are present. This type grades into bioclastic wackestone.

Crinoidal wackestone to packstone contains subordinately bryozoans, ostracods, rare brachiopod shells and spines and worm tubes(?), which are embedded in micrite containing abundant spicules (mostly calcified monaxon sponge spicules).

Nunn Member (17.6 m thick)

The base of the Nunn Member is composed of 0.6 m of marl, overlain by three chert beds which are separated by thin shale partings. Above follows a succession of greenish marl and marly shale that is mostly covered in the lower part, and marly limestone containing crinoids and bryozoans. Thin, wavy limestone beds (5 to 10 cm thick) are intercalated, some containing abundant crinoid and bryozoan skeletons, and a few thicker (0.4-0.6 m), fossiliferous, marly limestone units that also contain abundant crinoidal debris and bryozoans.

Limestone of the Nunn Member consists of wackestones to packstones that are poorly sorted, indistinctly laminated and

FIGURE 4. Thin section photographs of selected microfacies of the Caballero Formation. **A,** Mixed siliciclastic-carbonate siltstone to fine-grained sandstone composed of abundant carbonate grains, quartz grains and a few fossils. Sample LVT 1, lowermost part of the Caballero Formation, plane light, width of the photograph is 3.2 mm. **B,** Fine-grained packstone containing abundant carbonate grains, a few quartz grains and many skeletal grains. Sample LVT 2, lowermost part of the Caballero Formation, plane light, width of the photograph is 1.2 mm. **C,** Mixed siliciclastic-carbonate siltstone to fine-grained sandstone containing quartz, carbonate grains and few skeletal grains. Sample LVT 3, lower part of the Caballero Formation, polarized light, width of the photograph is 1.2 mm. **D,** Siltstone composed of carbonate grains, peloids, quartz grains and skeletal grains including large echinoderm and brachiopod fragments. Sample LVT 5, lower part of the Caballero Formation, plane light, width of the photograph is 3.2 mm. **E,** Crinoidal packstone, poorly sorted, containing abundant echinoderm fragments (mostly crinoids), a few bryozoans and other skeletons, and many small quartz grains. Sample LVT 8, base of upper Caballero Formation, plane light, width of the photograph is 3.2 mm. **F,** Crinoidal packstone, poorly sorted, composed of abundant echinoderm fragments (mostly crinoids), and rare other skeletons such as bryozoans, brachiopods and ostracods, cemented by calcite. Sample LVT 9, upper Caballero Formation, plane light, width of the photograph is 3.2 mm. **G,** Bioclastic packstone containing abundant echinoderm fragments, subordinate brachiopod and trilobite fragments, ostracods and rare other skeletal grains, cemented by calcite. Sample LVT 9, upper Caballero Formation, plane light, width of the photograph is 3.2 mm. **H,** Fine-bioclastic mudstone to wackestone containing spicules, ostracods, echinoderms and rare other skeletal grains embedded in micrite. A horizontal burrow is visible in the middle of the photograph. Sample LVT 11, upper Caballero Formation, plane light, width of the photograph is 6.3 mm.

locally bioturbated. Wackestones are composed of fine-bioclastic matrix containing many spicules and small recrystallized skeletons (Fig. 6A-B). Larger skeletons embedded in the matrix are ostracods, echinoderms, bryozoans, brachiopods and rare trilobite fragments. Rarely, crinoid fragments are encrusted by bryozoans.

Tierra Blanca Member (31.7 m thick)

The base of this member is a distinct, 0.5-m-thick, coarse limestone bed (rudstone) full of crinoids and fenestrate bryozoans with subordinate fistuliporid bryozoan fragments. This basal limestone bed is overlain by a succession of fossiliferous limestone alternating with marly shale (up to 0.8 m thick) and many covered intervals (0.2 to 1.8 m thick), most likely also representing marly shale.

Limestone intervals are 0.1 to 2.8 m thick, and composed of individual limestone beds and bedded limestone intervals. Limestone is mostly coarse-grained (rudstone) and very fossiliferous, containing abundant skeletons of crinoids (crinoidal packstone) and bryozoans. Many limestone beds contain chert nodules and subordinate chert lenses. Bed thickness of thicker, bedded limestone intervals is mostly 20 to 30 cm. A few limestone beds display well-developed trough-cross-bedding.

Limestones of the Tierra Blanca Member consist of packstones-rudstones, grainstones and wackestones-floatstones. All types are poorly sorted, indistinctly laminated, and the fossils are strongly fragmented. Elongate grains (bryozoans, brachiopods) are commonly oriented parallel to the bedding plane. Locally, intraclasts up to several mm in diameter are present. In the wackestones, the matrix is fine-bioclastic micrite containing spicules (Fig. 6C). Rarely, floatstone is present (Fig. 6F). Grainstones, packstones and rudstones are cemented by coarse, blocky calcite and contain small amounts of micrite (Fig. 6D, E, G, H).

The fossil assemblage is the same as in the underlying members. Echinoderm (crinoid) fragments and bryozoans dominate; subordinate are ostracods, brachiopods, trilobite fragments and (?)worm tubes (Fig. 6D-H). Laudon and Bowsher (1949) report that fossils other than crinoid fragments are not abundant in the Tierra Blanca Member. Most common are large brachiopods such as *Spirifer rowleyi* and *Cliothyridina obmaxima.*

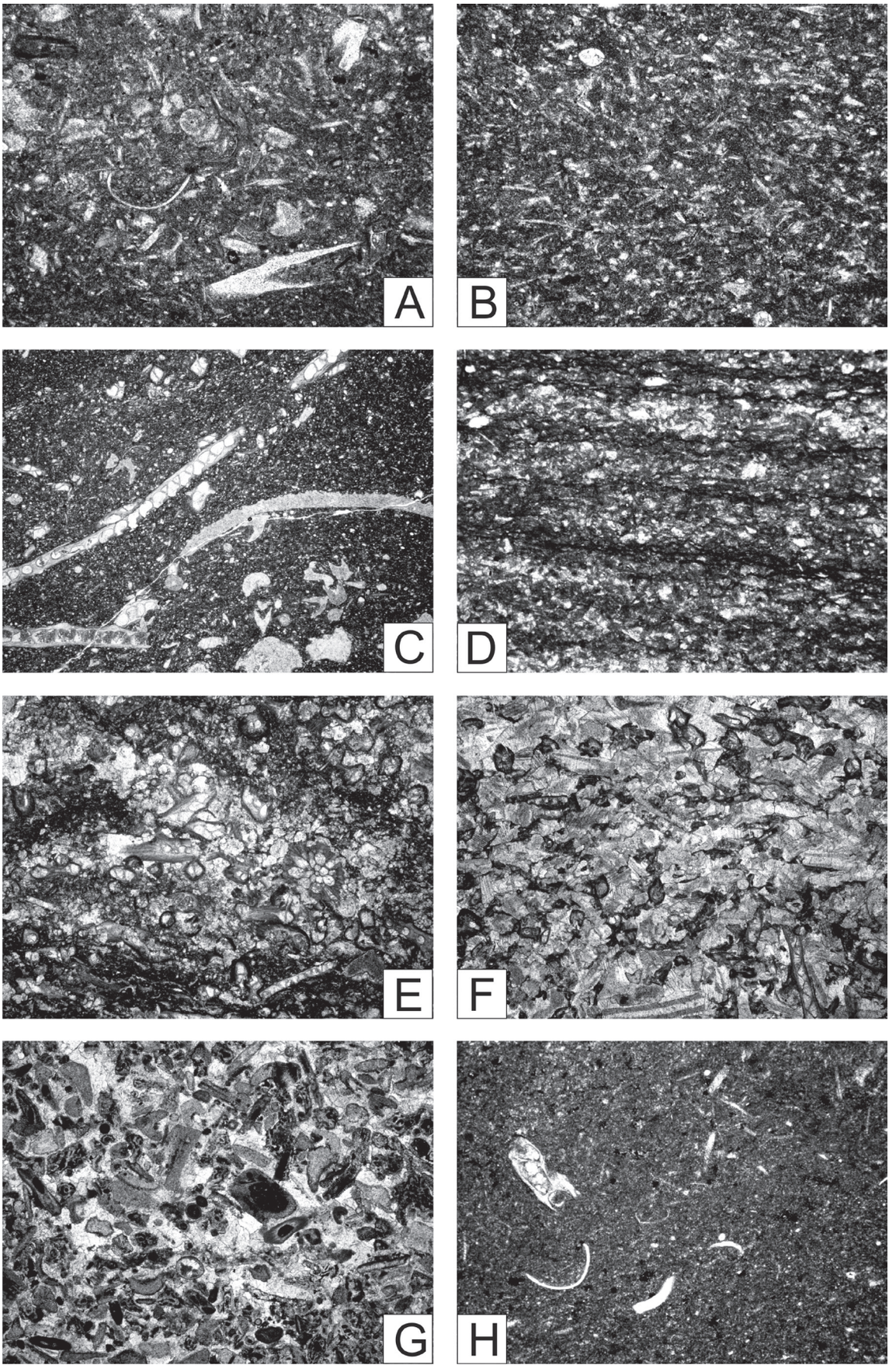
DEPOSITIONAL ENVIRONMENTS

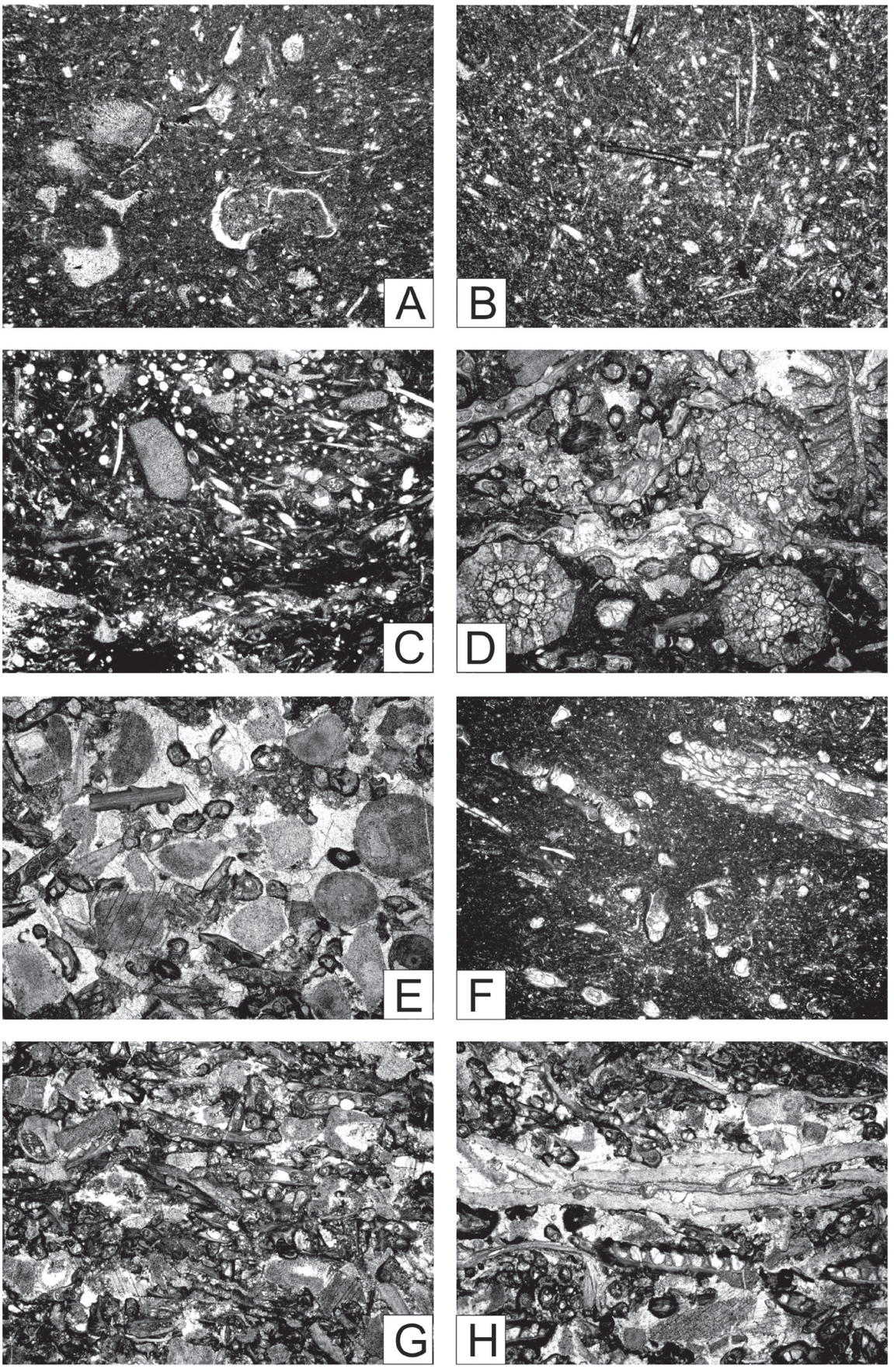
The facies and fossil assemblages of Mississippian carbonate rocks, particularly the bioherms, are well studied in the San Andres and Sacramento Mountains, starting with Laudon and Bowsher (1941, 1949) and continued by Pray (1958), Wilson (1971, 1975a, b), Lane (1974, 1975), Meyers (1974, 1975), Jackson and De Keyser (1984), George and Ahr (1986), Bachtel and Dorobek (1994, 1998), Giles (1998) and Stanton et al. (2002), among others. Surprisingly, little has been published on the type section of the Lake Valley Formation since Laudon and Bowsher (1949) first described it.

In the Sacramento and San Andres Mountains, Bachtel and Dorobek (1998) recognized three depositional sequences within the Caballero and Lake Valley formations. Depositional sequence 1 includes the Caballero Formation and Andrecito Member of the Lake Valley Formation, and depositional sequence 2 the Alamogordo, Nunn and Tierra Blanca members of the Lake Valley Formation. These depositional sequences are composed of a muddy transgressive systems tract (mudstone to wackestone) and a dominantly grainy progradational systems tract (packstone to grainstone). Lowstand systems tract strata are absent in the depositional sequences.

In the Sacramento and San Andres Mountains, the second depositional sequence, the Alamogordo Member, is the transgressive unit, composed mostly of thin bedded, dark gray, locally cherty lime mudstone to skeletal wackestone/packstone deposited below storm wave base. The Nunn Member consists of thin- to medium-bedded argillaceous skeletal packstones to grainstones and, locally, wackestones, commonly onlapping the mound facies. The Tierra Blanca Member is composed of thin-bedded to massive, very coarse-grained and locally cherty limestone formed mainly of bioclastic and lithoclastic grainstones/packstones. Limestones were mainly deposited from sediment gravity flows, and in the upper part they were probably influenced by storm waves (Bachtel and Dorobek, 1998; Dorobek and Bachtel, 2001). According to Meyers (1978), the Alamogordo Member, which is composed of echinoderm-bryozoan packstones and wackestones, grades northward into peritidal stromatolitic dolomites and pel-

FIGURE 5. Thin section photographs of limestone of the upper Caballero Formation and Lake Valley Formation (Andrecito and Alamogordo members). **A,** Wackestone containing echinoderm fragments, bryozoans, ostracods and rare other skeletal grains floating in micrite. Sample LVT 11, upper Caballero Formation, plane light, width of the photograph is 3.2 mm. **B,** Wackestone-bioclastic mudstone containing spicules, ostracods and a few other skeletal grains embedded in micrite. Sample LVT 11, upper Caballero Formation, plane light, width of the photograph is 3.2 mm. **C,** Floatstone containing large skeletons of bryozoans, brachiopods and echinoderms floating in fine-bioclastic micritic matrix. Sample LVT 14, Andrecito Member, plane light, width of the photograph is 6.3 mm. **D,** Fine-grained, laminated wackestone containing small echinoderm fragments, ostracods and other skeletal grains embedded in micrite. Sample LVT 15, Andrecito Member, plane light, width of the photograph is 3.2 mm. **E,** Bryozoan floatstone containing abundant fragments of bryozoans, and subordinate other skeletal grains embedded in recrystallized micrite (microsparite). Sample LVT 17, Andrecito Member, plane light, width of the photograph is 6.3 mm. **F,** Crinoidal packstone containing abundant echinoderm fragments (mostly crinoids), subordinate bryozoans and other skeletal grains cemented by calcite. Sample LVT 18, upper Andrecito Member, plane light, width of the photograph is 6.3 mm. **G,** Grainstone containing abundant echinoderms and subordinate skeletons of bryozoans, brachiopods and ostracods, cemented by calcite. Sample LVT 19, upper Andrecito Member, plane light, width of the photograph is 6.3 mm. **H,** Bioclastic mudstone composed of a few skeletal grains (bryozoans, echinoderms, ostracods, spicules) floating in micritic matrix. Sample LVT 21, Alamogordo Member, plane light, width of the photograph is 3.2 mm.


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oid-algal limestones (Caloso Formation). Lime mudstone of the Alamogordo Member represents probably the deepest facies. The Nunn Member is characterized by echinoderm-bryozoan wackestones and packstones. The Tierra Blanca Member is dominated by echinoderm-bryozoan packstones and grainstones deposited during progradation and aggradation of a subtidal shallow-water skeletal sand shelf facies.

Caballero Formation

At the Lake Valley type section, offshore marine shales of the Devonian Percha Formation are overlain by hummocky cross-bedded siltstone to fine-grained sandstone of the basal Caballero Formation. Hummocky cross-stratification forms above but near the storm wave base, i.e., on the lower shoreface during storms, where aggradation rates are high enough to preserve the hummocks (Dumas and Arnott, 2006).

The sharp lithologic boundary between shale of the Percha Formation and the basal Caballero Formation represents a drop of sea level and thus a sequence boundary. Indeed, it is also a substantial hiatus between Upper (but not uppermost) Devonian and Lower (but not lowermost) Mississippian strata. Offshore shales are overlain by hummocky cross-bedded sediments of a storm-dominated lower shoreface environment with siliciclastic influx.

Overlying muddy limestone beds indicate deposition in a low-energy shelf environment slightly below storm wave base, interrupted by short periods of storm activity and deposition of thin siltstone to fine-grained sandstone. The marly shale in the middle part is interpreted as deposits of the deeper shelf below the storm wave base. The thin limestone beds composed of wackestones to packstones, which are intercalated in marly shale in the upper part of the Caballero Formation, indicate deposition under moderate to high energy conditions. We interpret these thin limestone beds to have formed during storm events (distal storm layers).

Within the Caballero Formation, a transgressive trend is observed from the shoreface deposits at the base, followed by muddy limestone of a deeper shelf environment representing the maximum transgression (Figs. 2, 7). We interpret marly shale with intercalated limestone beds as distal storm layers in the upper part of the Caballero Formation that indicate a slight drop in sea-level and thus the beginning of the regressional phase.

Lake Valley Formation

Andrecito Member

The facies of the lower part of the Andrecito Member is similar to the upper part of the Caballero Formation. Limestone is more abundant, and grain size increases upward. In the lower and middle part of the member, limestone is mostly composed of wackestone and packstone, and in the upper part packstones, grainstones and rudstones predominate. Increasing grain size and the presence of cross-bedding (and probably hummocky cross-bedding) in the limestone beds of the upper Andrecito Member indicate shallowing and an increase in energy level. The cross-bedded limestone beds are interpreted as storm layers that formed on the lower shoreface. Shale was deposited between storm events.

The coarsening upward trend within the Andrecito Member and the facies change from near storm wave base to lower shoreface indicates that the Andrecito Member was deposited during falling sea level (Figs. 2, 7). The regression that started during deposition of the upper part of the Caballero Formation continued during deposition of the Andrecito Member.

The Caballero Formation and Andrecito Member correlate to the depositional sequence 1 of Bachtel and Dorobek (1998): the Caballero Formation represents the transgressive systems tract and the Andrecito Member the progradational systems tract (Fig. 7).

Alamogordo Member

Micritic limestone (dominantly bioclastic mudstone and wackestone) of the Alamogordo Member indicates deposition in a low-energy, deeper shelf environment below storm wave base. Spicules, which are locally abundant and mostly calcified, are derived from siliceous sponges, which are traditionally regarded as the source of the chert nodules and lenses. According to Meyers (1978), and we concur, the Alamogordo Member represents the deepest facies of the Lake Valley Formation.

The sharp lithologic boundary between the lower shoreface deposits of the uppermost Andrecito Member and the dominantly

FIGURE 6. Thin section photographs of the Lake Valley Formation (Nunn and Tierra Blanca members). **A**, Wackestone composed of fine-bioclastic matrix and larger skeletons of echinoderms, ostracods, bryozoans and spicules. Sample LVT 24, Nunn Member, plane light, width of the photograph is 3.2 mm. **B,** Wackestone composed of abundant spicules (spiculite) and a few other small skeletal grains embedded in micrite. Sample LVT 25, Nunn Member, plane light, width of the photograph is 3.2 mm. **C,** Wackestone to packstone containing skeletons of echinoderms, bryozoans, brachiopods and many spicules. Skeletons are partly silicified. Spicules are all preserved in silica. Sample LVT 27, basal Tierra Blanca Member, plane light, width of the photograph is 3.2 mm. **D,** Rudstone composed of abundant bryozoan fragments and rare echinoderm and brachiopod skeletons. Sample LVT 29, Tierra Blanca Member, plane light, width of the photograph is 6.3 mm. **E,** Packstone to rudstone containing abundant echinoderm fragments, bryozoans, and rare other skeletons, cemented by calcite. Echinoderm fragments display syntaxial overgrowths. Sample LVT 30, Tierra Blanca Member, plane light, width of the photograph is 6.3 mm. **F,** Floatstone containing abundant bryozoan fragments, few echinoderm and other skeletal grains floating in fine-bioclastic matrix containing many spicules. Sample LVT 32, Tierra Blanca Member, plane light, width of the photograph is 6.3 mm. **G,** Packstone, poorly sorted, composed of echinoderm and bryozoan fragments and rare other skeletons, cemented by calcite. Sample LVT 33, Tierra Blanca Member, plane light, width of the photograph is 3.2 mm. **H,** Rudstone composed of abundant large bryozoan fragments, subordinate brachiopods and echinoderms cemented by calcite. Elongate grains are oriented parallel to the bedding plane. Sample LVT 34, Tierra Blanca Member, plane light, width of the photograph is 6.3 mm.

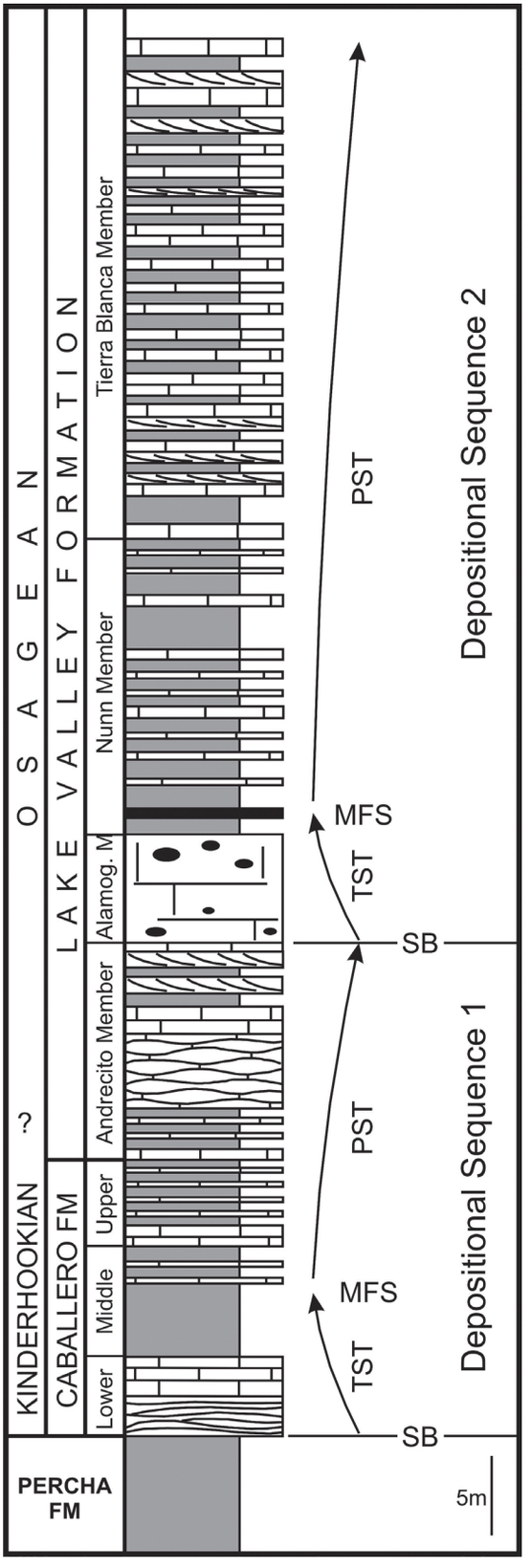


FIGURE 7. Interpretation of the sequence stratigraphy of the type section of the Lake Valley Formation. See text for discussion. MFS = maximum flooding surface, PST = progradational systems tract, SB = sequence boundary and TST = transgressive systems tract.

mudstone-wackestone facies of the Alamogordo Member indicates a sudden rise in sea level and thus a sequence boundary (base of depositional sequence 2).

Nunn Member

The facies of the Nunn Member is similar to that of the upper Caballero Formation and basal Andrecito Member, i.e., marl and marly shale with intercalated thin limestone beds, which are mostly composed of wackestones to packstones. This lithology indicates deposition in a deeper shelf environment near the storm wave base.

Tierra Blanca Member

Limestone of the Tierra Blanca Member is mostly coarse-grained and fossiliferous; the dominant microfacies types are grainstone, packstone and rudstone. Fossils are strongly fragmented, and trough cross-bedding observed in several limestone intervals indicate deposition in a high-energy shelf environment.

We interpret these limestone intervals as storm deposits that formed between the fair weather wave base and storm wave base when strong unidirectional currents were storm generated that transported sediment from a shallower shelf environment offshore into deeper water. The storm deposits are separated by marly shale intervals that represent the "background sediment" which accumulated under low-energy conditions.

The Alamogordo, Nunn and Tierra Blanca members represent a transgressive- regressive depositional sequence correlating well with depositional sequence 2 of Bachtel and Dorobek (1998) in the San Andres and Sacramento Mountains (Fig. 7). Deposits of the Alamogordo Member and lower part of the Nunn Member form the transgressive systems tract. The maximum flooding is probably documented by the bedded chert in the lowermost part of the Nunn Member. The overlying Nunn Member was deposited during beginning regression, and the Tierra Blanca Member is interpreted as the progradational systems tract.

Limestones of the Lake Valley Formation (particularly Andrecito and Tierra Blanca members) and upper Caballero Formation are dominantly composed of echinoderm (commonly crinoids) and bryozoan fragments with minor amounts of other fossil fragments, including brachiopods, ostracods and trilobites. Calcareous algae and foraminifers are absent. This is indicative of the bryonoderm grain association type of Beauchamp (1994) and Beauchamp and Desrochers (1997). This grain association is considered to be typical of low-latitude, deeper water shelf to high-latitude, deep- to shallow-water shelf environments and assumed to indicate cool- and cold-water conditions (Flügel, 2004). Flügel (2004) also notes that Paleozoic bryozoans were more common in tropical environments except during times of significant cooling. Nevertheless, Stanton et al. (2002) concluded from stable isotope data obtained from brachiopod shells of the Alamogordo Member that the climate was tropical at that time. According to Lees and Miller (1995), Waulsortian mounds developed in tropical environments in ramp and basinal settings.

DISCUSSION AND CONCLUSIONS

During Mississippian time, south of the positive transcontinental arch in southern New Mexico, a shallow-water carbonate shelf facies (ramp) was developed passing into a starved basin facies farther south (Lane, 1982). According to Wilson (1975b), the Lake Valley Limestone was probably formed on a shelf of moderate depth occupying an intermediate position between the shelf and the starved basin.

Mounds which are known as "Waulsortian mounds" are developed within the Lake Valley Formation of the Sacramento and San Andres Mountains, which, in the southern end of the Sacramento Mountains, are more than 100 m thick (Pray, 1958; Wilson, 1975b). According to Armstrong (1962), mounds are also present in the Lake Valley Formation west of the Rio Grande. Waulsortian mounds (upper Tournaisian – lower Visean) are common in northern Europe, North America, central Asia and probably also in north Africa (summary in Lees and Miller, 1995).

Dorobek and Bachtel (2001) distinguished three types of mounds that developed on the Lake Valley ramp from north to south–lenticular, transitional and hemispherical mounds–the latter representing the largest mounds located farthest downdip on the Lake Valley ramp (see also Jeffery and Stanton, 1996). Farther south, Mississippian strata thin and are essentially absent, and south of New Mexico a presumed starved basin was filled with cherty platy limestone of the Middle Mississippian Ranchero Formation. According to Armstrong (1962), shelf sediments ("shelf encrinites") were deposited in the southwestern part of New Mexico.

The Caballero and Lake Valley formations at the type section are composed of two transgressive-regressive depositional sequences, which correlate well with the depositional sequences 1 and 2 of Bachtel and Dorobek (1998) in the San Andres and Sacramento Mountains. Depositional sequence 1 is represented by the transgressive systems tract of the Caballero Formation and progradational systems tract of the overlying Andrecito Member of the Lake Valley Formation. Depositional sequence 2 is composed of the transgressive systems tract represented by the Alamogordo and lowermost Nunn members and by the progradational systems tract of the Nunn and Tierra Blanca members.

Limestone, particularly of the Andrecito and Tierra Blanca members, is mainly composed of crinoid and bryozoan skeletons, thus representing a typical bryonoderm grain association commonly regarded as typical of cool- and cold-water carbonate deposits. However, recognition of cold-water carbonate deposits is difficult, because many critical components that are present in modern environments are absent in Paleozoic deposits (James and Lukasik, 2010). Most of the Paleozoic cool-water carbonates are known from the Mississippian to Permian and are related to the global cooling caused by the Late Paleozoic Ice Age.

Meyers (1978) studied calcite cements of skeletal packstones and grainstones, particularly syntaxial calcite overgrowths on echinoderm fragments, concluding that cementation occurred during a worldwide late Mississippian regressional event. Martindale and Boreen (1997) presented the "thermocline facies model" based on detailed studies of Mississippian carbonates in parts of the Western Canadian Sedimentary Basin. According to this model, carbonate sediments accumulated on a thermocline-stratified ramp on which shallow-water sediments containing ooids, calcareous green algae and other photozoan elements were deposited on the inner ramp in warm waters above the thermocline. Basinward, the photozoan facies grades into a heterozoan facies of the mid to outer ramp, deposited in cold waters below the thermocline. Mid-ramp deposits are rich in bryozoans and crinoids. Crinoid shoals are developed above the fair weather wave base, from where they may be transported basinward to the mid and outer ramp during storms, forming coarse-grained tempestites rich in crinoids and bryozoans. This model may also be applied to the Lake Valley Formation, which probably was deposited on a gently inclined, thermocline-stratified ramp.

ACKNOWLEDGMENTS

We thank Daniel Vachard (Lille) for helpful comments concerning the identification of fossils and Julia Wallraf (Innsbruck) for preparation of thin sections. Dana Ulmer-Scholle and Daniel Vachard provided helpful reviews of the manuscript.

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