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CYCLIC SEDIMENTATION OF THE UPPER PENNSYLVANIAN (LOWER WOLFCAMPIAN) BURSUM FORMATION, CENTRAL NEW MEXICO: TECTONICS VERSUS GLACIOEUSTASY

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Abstract—In New Mexico, the Bursum Formation represents the transitional facies between underlying, dominantly shallow-marine Upper Pennsylvanian carbonate deposits and overlying Lower Permian continental red beds. The Bursum Formation in the Joyita Hills and hilly area east of Socorro, central New Mexico, is as much as 120 m thick and composed of alternating shallow marine limestone and shale and nonmarine red beds. These alternating marine and nonmarine sediments locally form well-developed cyclic successions. However, strong lateral variations in thickness and stratigraphic distributions of facies are observed, which has led to the recognition of three regional members of the Bursum Formation: (a) Bruton Member, (b) Red Tanks Member and (c) Oso Ridge Member. The cyclic succession and lateral variability in thickness and distributions of lithofacies indicate that sedimentation of the Bursum Formation in the Joyita Hills and hilly area east of Socorro was influenced by both glacio-eustatic sea-level changes and tectonic movements of the ancestral Rocky Mountain (ARM) orogeny. Sea-level changes are responsible for the cyclic pattern, and tectonic movements for the strong lateral variability.Unconformities are present at the base and at the top of the Bursum Formation that are the result of major tectonic pulses. The tectonic pulse responsible for the lower unconformity caused a sharp facies change from dominantly shallow marine carbonate sedimentation to mixed siliciclastic-carbonate sedimentation of alternating nonmarine and marine sediments. The upper unconformity resulted from a major tectonic event of the ARM deformation, causing a rejuvenation of basement uplifts that resulted in increased siliciclastic influx and deposition of nonmarine red beds of the Abo Formation. There is also evidence for tectonic activity during sedimentation of the Bursum Formation.

INTRODUCTION

Cyclic sedimentary rocks of Pennsylvanian-Permian age occur throughout the American Midcontinent (e.g., Wanless and Weller, 1932; Imbrie et al., 1964; Moore, 1964; Heckel, 1986, 2006), in the foreland basin of the Appalachians (Klein and Willard, 1989; Klein and Kupperman, 1992), the Paradox basin of the Four Corners (Williams, 1996; Gianniny and Simo, 1996; Grammer et al., 1996) and the Orogrande basin of south-central New Mexico (Wilson 1967; Mack and James 1986; Raatz et al., 1994; Soreghan, 1994; Schoderbek, 1994). The Pennsylvanian age "Kansas-type" cycles, which were named "cyclothems" by Wanless and Weller (1932), are now interpreted by most geologists to be related to glacioeustatic sea-level changes caused by the late Paleozoic Gondwana glaciation (e.g., Wanless and Shepard, 1936; Crowell, 1978; Ross and Ross, 1985, 1988; Heckel, 1986; Veevers and Powell, 1987). Klein and Willard (1989) pointed out that the Kansas-type cyclothems formed on a relatively stable platform by eustatic sea-level fluctuations, and were affected only moderately by tectonic movements. Wilson (1975) stated that these mid-continent cyclothems may have resulted from glacioeustatic sea-level changes and from local tectonic movements.

Upper Carboniferous-Lower Permian cycles related to glacioeustatic sea-level fluctuations have also been reported from outside North America, for example, from northwestern Europe (Ramsbottom, 1979), the Russian Platform (Ross and Ross, 1988) and the Carnic Alps in Europe (Massari and Venturini, 1990, Massari et al., 1991; Krainer, 1992; Flügel et al., 1997; Forke et al., 1998).

The Gondwana glaciation began in the late Visean (Smith and Read, 2000), achieved its maximum extent during the Moscovian, waned during the Sakmarian and died out during the Kazanian (Crowell, 1995). This long-lasting glaciation produced high-frequency sea-level fluctuations that strongly influenced sedimentation on many stable shelf areas (e.g., Grammer et al., 1996; Weber et al., 1994, 1995). However, Isbell et al. (2003) argued that the Gondwana glaciation reflects three non-overlapping Glacial Episodes, and that larger ice-sheets were present in Gondwana only during Glacial Episode III, which lasted from the Stephanian to the Sakmarian, and possibly into the Kungurian. Only during this interval could the waxing and waning of these ice sheets have produced glacioeustatic sea-level changes causing the formation of cyclothems.

However, glacioeustatic sea-level fluctuations caused by the Gondwana glaciation were not the only mechanism driving the formation of cyclic sediments during the late Paleozoic. The formation of Appalachian-type cycles, for example, was strongly influenced by tectonic processes (Klein and Willard, 1989; Klein and Kupperman, 1992). In New Mexico, tectonic processes related to the ancestral Rocky Mountain (ARM) deformation were a significant factor controlling Middle Pennsylvanian-Early Permian sedimentation. For example, cycles of the Pennsylvanian-Lower Permian Alamitos Formation in the Rowe-Mora Basin of northern New Mexico are interpreted to have been mainly induced by tectonic movements (Krainer et al., 2004). Krainer and Lucas (2004) and Lucas and Krainer (2004) concluded that the cyclic sediments of the Red Tanks Member of the Upper Pennsylvanian Bursum Formation at Carrizo Arroyo (central New Mexico) were mainly caused by regional tectonic processes, although eustatic sea level fluctuations may also have influenced sedimentation. In the present paper we will demonstrate that sedimentation of the Upper Pennsylvanian Bursum Formation of central New Mexico, particularly in the Joyita Hills and hilly area east of Socorro (Fig. 1), was mainly the product of local tectonic processes related to the ARM deformation.

GEOLOGICAL SETTING

The Joyita Hills and adjacent hills to the south are a structurally complex series of fault blocks east of the Rio Grande Valley east and northeast of Socorro, Socorro County, central New Mexico (Fig. 1). Here we refer to the whole hilly area east of Socorro informally as the Joyita Hills. Read and Wood (1947), Kottlowski (1960), Stewart (1970), Kottlowski and Stewart (1970), Siemers (1983), Baars (1982), Altares (1990) and Beck and Johnson (1992) consider the Joyita Hills to represent a late Paleozoic (ARM) uplift. Kottlowski and Stewart (1970) demonstrated that sediments of the Bursum Formation unconformably truncate Missourian (Atrasado Formation), Desmoinesian (Gray Mesa Formation), Atokan (Sandia Formation) and Precambrian rocks northward, and that Bursum facies thins out from north to south under the Abo Formation. They concluded that a tectonic event occurred before or during sedimentation of the Bursum Formation. In the southern Joyita Hills, the Bursum strata abut against basement rocks composed of Precambrian gneiss, indicating that these remnant hills stood above sea-level during the time of Bursum deposition.

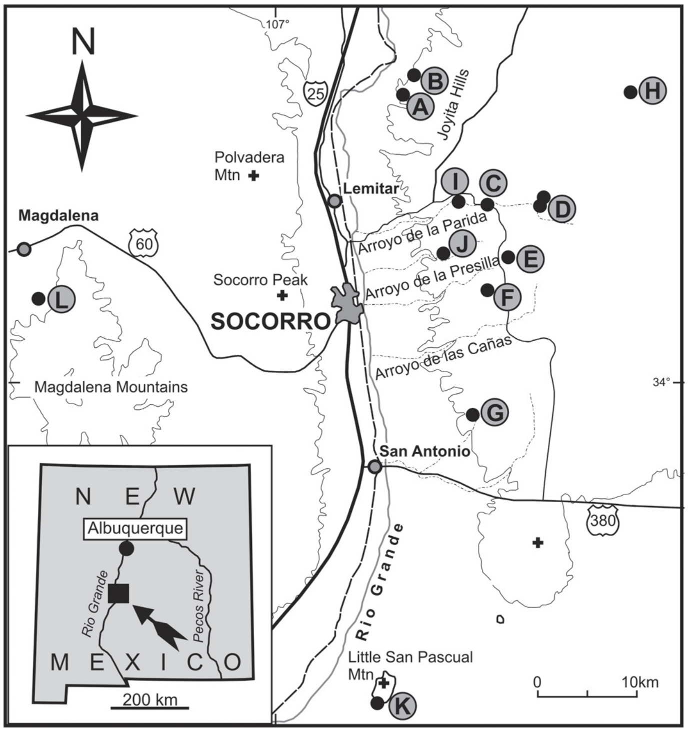

FIGURE 1. Map of part of central New Mexico showing location of Bursum sections studied. See Figures 3, 4 and 5 for sections and the appendix for map coordinates of the sections. A = Joyita Hills A; B = Joyita Hills B; C = Mesa del Yeso; D = Sierra de la Cruz; E = Arroyo Tinajas; F = Loma de las Cañas; G = Cerro del Viboro; H = Agua Torres; I Gallina Well; J = Minas de Chupadera; K = Little San Pascual Mountains; L = Magdalena.

Across much of New Mexico, the upper Virgilian to lower Wolfcampian Bursum Formation represents a transitional facies between underlying Pennsylvanian shallow marine platform carbonates and overlying nonmarine Permian red beds. The Bursum Formation is composed of alternating siliciclastic red beds and shallow marine limestone and shale. Regional and local facies variations within the Bursum Formation led to the recognition and definition of four regional members (Fig. 2): (1) the mostly marine Bruton Member present in the Joyita Hills area, Cooke´s Range, Oscura, northern San Andres and Caballo Mountains, (2) the mixed siliciclastic-carbonate Laborcita Member of the eastern shelf of the Orogrande Basin, (3) the thin and dominantly nonmarine Oso Ridge Member in the Zuni Mountains, and (4) the mixed siliciclastic-carbonate, locally cyclic Red Tanks Member present at many localities in central New Mexico (Krainer and Lucas, 2004; Lucas and Krainer, 2004). The regional lithostratigraphy of the Bursum Formation is reviewed by Lucas et al. (2000, 2002) and by Lucas and Krainer (2004).

In the Joyita Hills, the thickest Bursum section is exposed at Gallina Well (120 m). Somewhat thinner Bursum sections are exposed at Sierra de la Cruz (ca. 80 m), Arroyo Tinajas (53 m), Loma de las Cañas (53 m), Cerro del Viboro (46 m) and Minas de Chupadera (31 m). In the northern Joyita Hills, the Bursum Formation is very thin--it measures 9 m at Central Canyon and 10.5 m south of Central Canyon (Figs. 1, 3, 4, 5; map coordinates of the measured sections are in the Appendix). R. Colpitts (written commun., 2009) suggests that faulting in our Gallina Well and Sierrita de la Cruz sections may have added stratal thickness to those sections. However, we recognized the faults in those sections (see Figs. 4-5) and are convinced that little or no thickness has been added across them; indeed, we suspect that strata have been removed at these faults, making the sections appear slightly thinner than they actually are.

In addition, we studied sections in the Los Piños Mountains (Abo Pass and Agua Torres) and southern Ladron Mountains. At the southern end of the Little San Pascual Mountains (south of Socorro) and at the Kelly Mine near Magdalena (west of Socorro), the Bursum Formation is absent. In the Little San Pascual Mountains, the Abo Formation rests on limestones of the Atrasado Formation, and at the Kelly Mine the Abo rests on the Gray Mesa Formation (Figs. 3-4; Table 1). According to Kottlowski and Stewart (1970) there is a small area in the southern part of Los Cañoncitos where the Bursum Formation is absent, and the Abo Formation lies directly on Precambrian crystalline rocks.

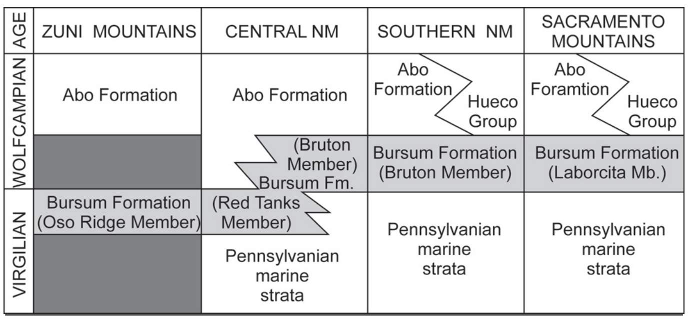

FIGURE 2. Regional stratigraphic nomenclature and correlation of the Bursum Formation (after Lucas and Krainer, 2004).

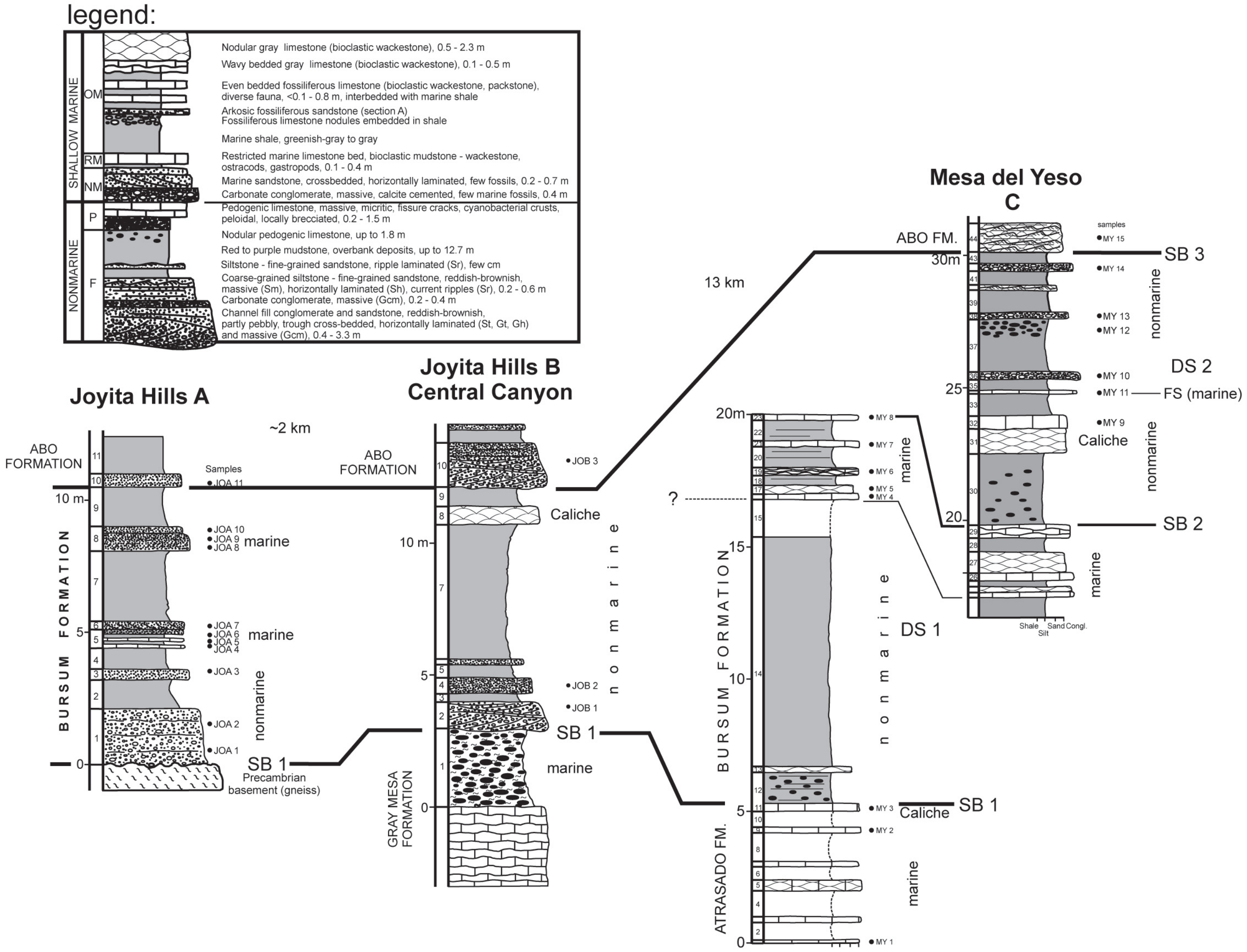

FIGURE 3. Selected measured sections of the Bursum Formation in the Joyita Hills. SB = sequence boundary, DS = depositional sequence, FS = flooding surface.

FACIES TYPES

Mudstone/Siltstone

The main lithofacies of all Bursum sections is red, gray, reddish gray and variegated non-fissile mudstone to fissile gray, greenish-gray and olive-gray mudstone and siltstone, comprising 55% (section Joyita Hills B) to 85% (Mesa del Yeso) of the total succession. Locally, the red mudstone contains abundant small pedogenic carbonate nodules. Intercalated in the mudstone/siltstone facies are: (1) sandstone (0.2% at Mesa del Yeso to 18.8% at Cerro del Viboro); (2) conglomerate (0% at Cerro del Viboro to 20% at Joyita Hills A); (3) limestone (0% at Joyita Hills B to 14.5% at Sierra de la Cruz); (4) nodular limestone (0% at Joyita Hills A to 24.4% at Joyita Hills B); and (5) pedogenic limestone (0% at Joyita Hills A and Sierra de la Cruz to 6.3% at Mesa del Yeso.

Siltstone at Sierra de la Cruz is composed mostly of angular quartz grains, and a few detrital micas (< 5%) and opaque grains. The rock is stained red by finely dispersed hematite in the fine-grained matrix.

Interpretation

We interpret the red mudstone/siltstone to be of nonmarine origin, particularly when associated with pedogenic nodules or pedogenic carbonate horizons. In contrast, greenish-gray and gray mudstone at Sierra de la Cruz associated with marine limestone beds, rarely containing marine fossils, is interpreted as shallow marine.

The dominant architectural element of the red, fine-grained siliciclastic sediments is floodplain fines composed of variable amounts of red mudstone and siltstone. These fine-grained sediments were deposited on distal alluvial plains by settling from sheetfloods, by filling of floodplain ponds and in shallow, broad, abandoned channels. Locally, isolated pedogenic nodules are present, representing stage 2 pedogenic carbonate development (Machette, 1985), which indicates thousands of years of soil for-

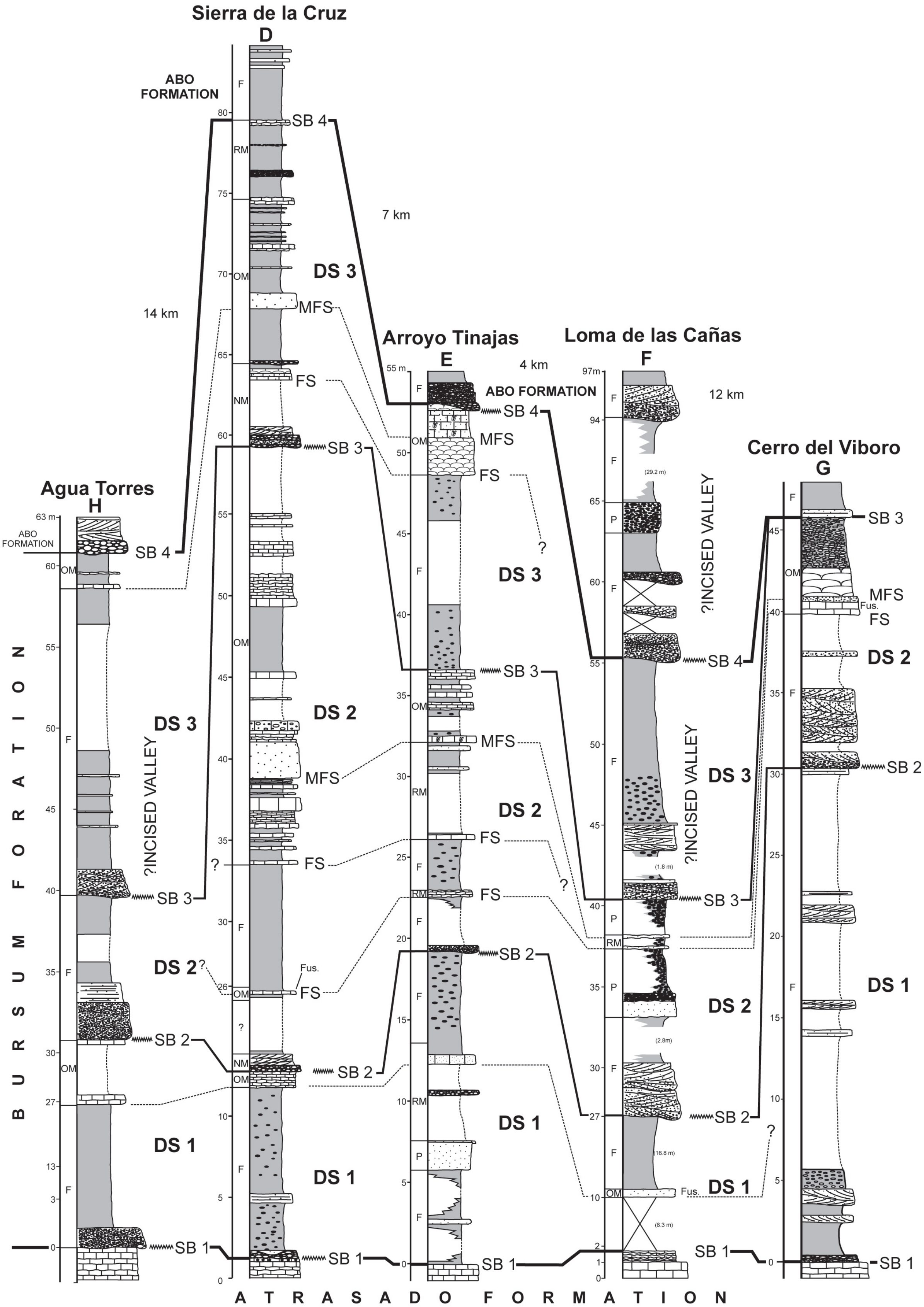

FIGURE 4. Selected measured sections of the Bursum Formation in the Joyita Hills. SB = sequence boundary, DS = depositional sequence, FS = flooding surface, MFS = maximum flooding surface, OM = open marine, RM = restricted marine, NM = nearshore marine, F = fluvial, P = pedogenic, Fus = fusulinids. For legend to lithologic symbols, see Figure 3.

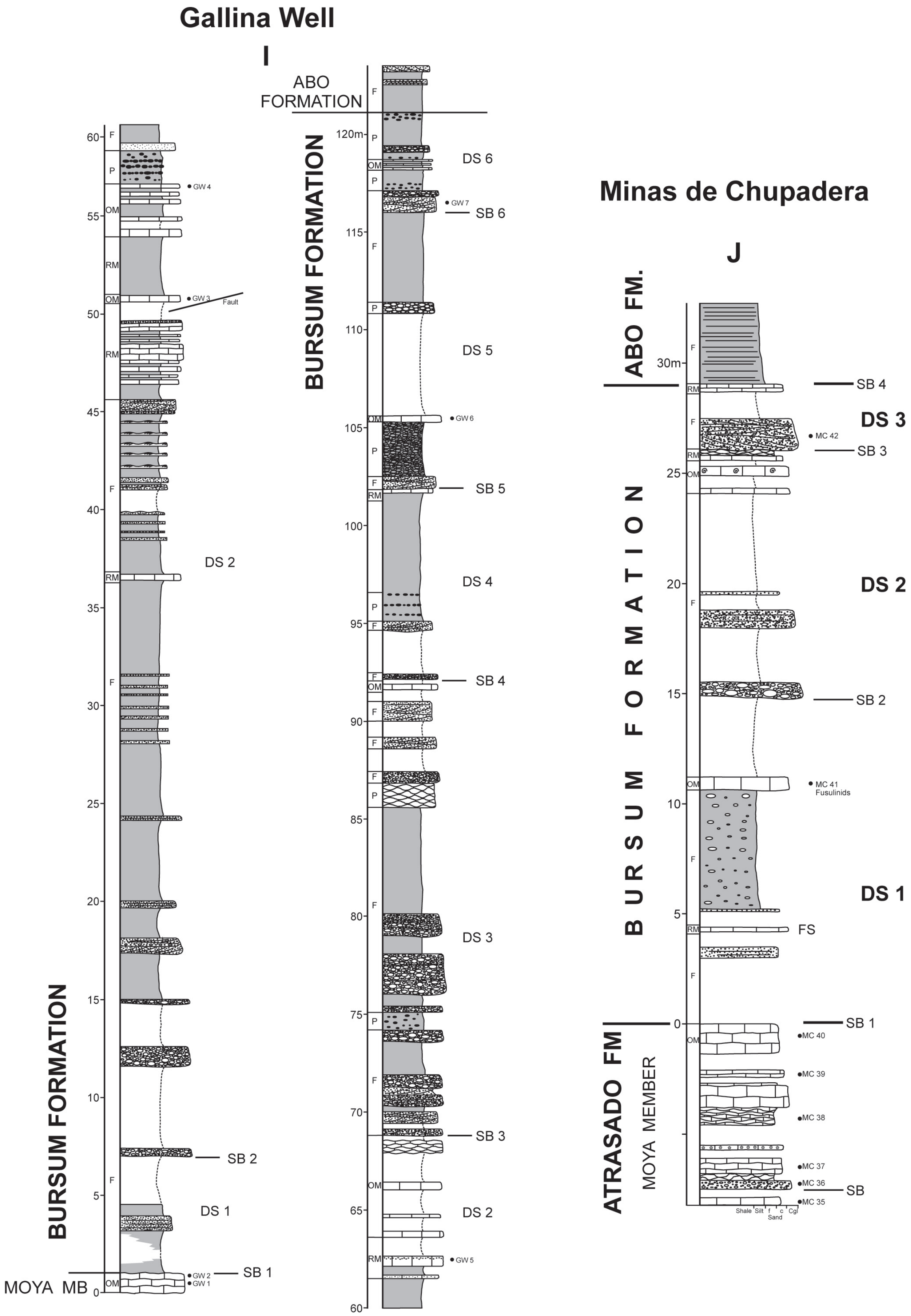

FIGURE 5. Selected measured sections of the Bursum Formation in the Joyita Hills. SB = sequence boundary, DS = depositional sequence, FS = flooding surface, OM = open marine, RM = restricted marine, NM = nearshore marine, F = fluvial, P = pedogenic. For legend to lithologic symbols, see Figure 3.

TABLE 1. Main characteristic features of the sections of the Bursum Formation in the Joyita Hills.

	Locality	Thickness (m)	Facies	Cycles	Member of Bursum Fm.
A	Joyita Hills A	10.5	red bed	not well devel.	Oso Ridge
B	Joyita Hills B	9	red bed	not well devel.	Oso Ridge
C	Mesa del Yeso	30	marine-nonmarine	not well devel.	Red Tanks
D	Sierra de la Cruz	80	marine-nonmarine	transgressive	Bruton
E	Arroyo Tinajas	53	marine-nonmarine	transgressive	Bruton
F	Loma de las Canas	53	red bed	nonmarine FU	Red Tanks
G	Cerro del Viboro	46	red bed	nonmarine FU	Red Tanks
I	Gallina Well	120	marine-nonmarine	not well devel.	Red Tanks
J	Minas de Chupad.	31	marine-nonmarine	transgressive	Red Tanks

mation. Intercalated nodular and massive calcrete horizons indicate longer periods of nondeposition and calcrete formation.

Fluvial Sandstone

In the Bursum Formation, sandstone of fluvial origin is most abundant at Loma de las Cañas and Cerro del Viboro, where several sandstone and pebbly sandstone horizons with thicknesses of 0.4 to 3.3 m are intercalated throughout the section. We classify sandstone lithofacies using the scheme of Miall (1996). Sandstone is commonly trough cross-bedded, with an erosional lower contact (lithofacies St). Thicker sandstone units are composed of grouped sets of trough cross-bedded sandstone. Fine-grained sandstone beds range in thickness from 0.2 to 0.6 m and are massive (lithofacies Sm) or indistinctly-horizontally stratified (Sh), rarely trough and low-angle cross-bedded (St, Sl). At Gallina Well, cm-thick sandstone beds with ripple cross lamination (current ripples; Sr) and horizontal lamination (Sh) are intercalated in greenish-gray and reddish shale-siltstone in the lower part of the section (Fig. 5). Coarse-grained sandstone may be pebbly and grade into conglomerate with individual pebbles up to several cm in diameter. Sandstone is common at Joyita Hills A and B, and at Loma de las Cañas and Cerro del Viboro, but rare in the Sierra de la Cruz and Arroyo Tinajas sections (Figs. 3-4).

The fine-grained conglomerates and sandstones form prominent ledges with a thickness of up to 3.3 m, extending laterally over tens of meters to more than 100 meters forming sheet sand bodies. Locally, these coarse-grained intervals display an upward-fining trend; their bases are erosional. Fine-grained conglomerate or coarse, pebbly, trough cross-bedded sandstones occur at the base.

Sandstone is classified as subarkose to arkose, containing 23 to 34% detrital feldspars at Arroyo Tinajas and Cerro del Viboro and 11 to 27% at Agua Torres. The amount of granitic rock fragments ranges from 8 to 39%. The amount of detrital feldspar and monocrystalline quartz increases with decreasing grain size. Coarse-grained sandstones contain higher amounts of granitic rock fragments. Fine- to medium-grained sandstone is moderately to well sorted, and coarse-grained sandstone is poorly to moderately sorted. Grains are angular to subrounded (Fig. 6A). At Gallina Well, sandstone is mixed siliciclastic-carbonate in composition.

At Joyita Hills section A (Fig. 3), gneiss of the Precambrian basement is unconformably overlain by Bursum deposits consisting of immature, poorly-sorted, red, pebbly sandstone with abundant chert grains. A few mono- and polycrystalline quartz grains, detrital feldspars (mostly potassium feldspars, including microcline and perthitic types) and granitic rock fragments are also present.

Conglomerate

Based on their petrographic composition, three types of conglomerates are recognized: (a) siliciclastic, (b) mixed siliciclastic-carbonate, and (c) carbonate. Conglomerate beds are 0.2 to 2.3 m thick. Siliciclastic and mixed siliciclastic-carbonate conglomerates commonly show trough cross-bedding (Gt), whereas carbonate conglomerates mostly do not show any stratification (Gcm).

Siliciclastic conglomerate occurs at Loma de las Cañas and Cerro del Viboro, rarely in the upper part of the Minas de Chupadera section, and is composed of abundant quartz and granitic rock fragments. Mixed siliciclastic-carbonate conglomerate occurs in the Gallina Well, Arroyo Tinajas and Agua Torres sections (Figs. 4-5).

Conglomerate beds display trough cross-bedding (lithofacies Gt), horizontal bedding (Gh) or rarely appear massive (lithofacies Gcm). Mixed conglomerates are composed of carbonate clasts and granitic debris. Individual clasts are up to 4 cm in diameter, rarely up to 20 cm; the grain size is mostly less than 1 cm. Carbonate clasts are various types of reworked bioclastic wackestone containing fusulinids, smaller foraminifers, calcareous algae, ostracods and trilobites. Micritic carbonate pebbles, and a few reworked pedogenic carbonates identified by inhomogenous micritic texture and the presence of small fissure cracks, are present. The conglomerate contains abundant mono- and polycrystalline quartz grains, detrital feldspars and granitic rock fragments, mostly of sand size. The clasts are cemented by coarse, blocky calcite.

Carbonate conglomerate only occurs in the upper part of the Mesa del Yeso, lower part of Arroyo Tinajas and the Minas de Chupadera sections as 0.2 to 0.6 m thick beds intercalated in red mudstone (Figs. 3, 4, 5). The uppermost conglomerate in the Gallina Well section, which overlies coarse-grained, trough cross-bedded sandstone, is also composed of carbonate clasts and contains abundant bone fragments. The conglomerate is massive (lithofacies Gcm), clast supported and poorly sorted; the grains are subangular to rounded. Clast size is commonly below 2 cm, and rarely up to 10 cm. Most abundant are gray, micritic limestone clasts; Individual layers contain abundant reworked pedogenic carbonate clasts derived from syndepositional erosion of pedogenic limestone. The sandy matrix contains some small angular quartz grains and feldspars. Pore space between the clasts is partly filled with recrystallized micritic matrix, but most pore space is cemented by sparry calcite (Fig. 6D).

Marine Sandstone and Conglomerate

Marine sandstone and conglomerate is rare and only occurs at the Sierra de la Cruz section and at the base of the Agua Torres section (Fig. 4). At Sierra de la Cruz, two horizons of marine conglomerate and sandstone, each 1.1 m thick, occur. The conglomerate appears massive, is clast-supported and contains carbonate clasts up to 10 cm in diameter; a few marine fossils, such as broken shell fragments, ostracods, and very rare smaller foraminifers (*Tetrataxis*) are present. The conglomerate is mostly composed of gray micritic mudstone clasts, and a few reworked bioclastic mudstone-wackestone clasts containing fragments of ostracods; bryo-

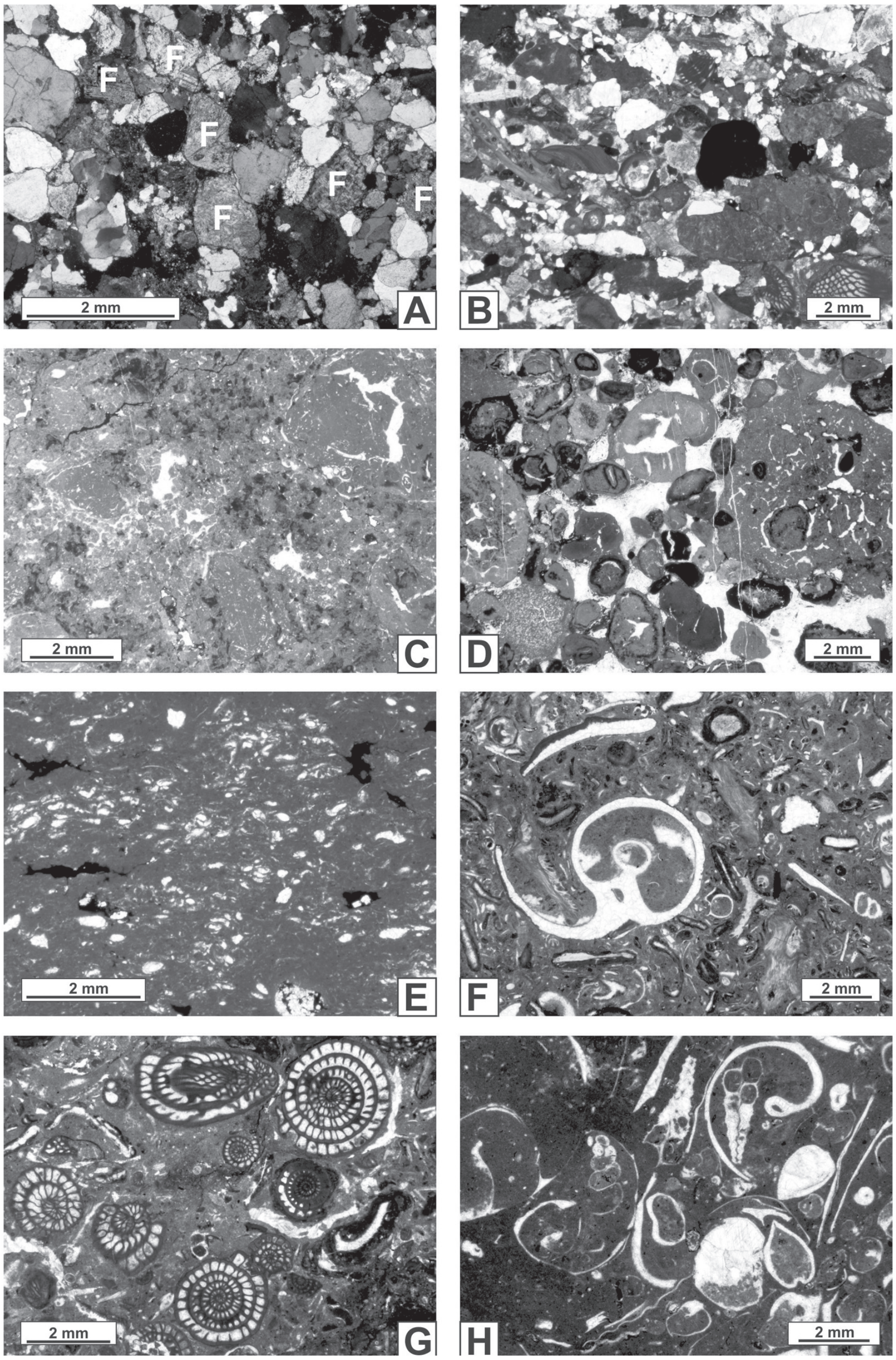

FIGURE 6. Thin section photographs of different facies of the Bursum Formation in the Joyita Hills. **A,** Coarse-grained, moderately sorted, subangular arkosic sandstone containing abundant untwinned detrital feldspars (F). Crossed nicols, sample AT 9 (Agua Torres). Fluvial facies. **B,** Mixed carbonate-siliciclastic coarse-grained, poorly sorted, subangular sandstone composed of various types of carbonate grains, detrital quartz and feldspar, and some bioclasts such as fusulinids, echinoderms, bryozoans and shell fragments. Plane light, sample AT 3 (Agua Torres) Marine sandstone. **C,** Nodular pedogenic limestone, micritic, locally peloidal, containing abundant, partly circumgranular fissures. Plane light, sample MY 3 (Mesa del Yeso). **D,** Poorly sorted, pebbly sandstone composed of subangular to subrounded carbonate clasts including many pedogenic limestones with fissures. Pore space is filled with calcite cement. Plane light, sample MY 14 (Mesa del Yeso). Fluvial facies. **E,** Ostracod wackestone/mudstone composed of abundant ostracods shells floating in micritic to pelmicritic matrix. Plane light, sample JAT 14a (Arroyo Tinajas). Restricted marine facies. **F,** Bioclastic wackestone containing a diverse fauna including gastropods, bivalves, bryozoans, ostracods, smaller foraminifers, echinoderms, echinoid spines and rare trilobite fragments. Plane light, sample JAT 11 (Arroyo Tinajas). Open marine facies. **G,** Fusulinid (*Triticites*) wackestone composed of abundant, partly broken fusulinid tests, recrystallized ?phylloid algae encrusted by cyanobacteria, shell debris, echinoderms, bryozoans, ostracods, smaller foraminifers, and gastropods embedded in micritic matrix. Plane light, sample SC 5 (Sierra de la Cruz). Open marine facies. **H,** Bioclastic wackestone containing shell fragments of bivalves, gastropods, brachiopods, rare brachiopod spines, bryozoans, echinoderms, ostracods and smaller foraminifers in micritic matrix. Plane light, sample SC 11 (Sierra de la Cruz). Open marine facies.

zoans and gastropods are also present. The sandy matrix contains some angular siliciclastic grains, mostly quartz. Calcite cement is also present. The conglomerate grades upward into pebbly sandstone and coarse-grained sandstone, which is gray to brownish, cross-bedded or horizontally laminated, and meters thick. The lower sandstone horizon is mixed siliciclastic-carbonate, coarse grained, and poorly to moderately sorted. Siliciclastic grains are subangular; carbonate grains are commonly better rounded, containing various types of reworked bioclastic wackestone and mudstone, reworked pedogenic carbonate, and fragments of echinoderms, bryozoans, fusulinids, probable phylloid algae, brachiopods, ostracods, and gastropods. Sandstone of the upper horizon is arkosic, moderately sorted, composed mostly of quartz, subordinately of potassium feldspar, granitic rock fragments, rare biotite and metamorphic rock fragments. The sandstone is cemented by calcite that randomly replaces quartz and feldspar.

At Agua Torres the basal 1.2 m of the Bursum Formation is composed of poorly exposed, cross-bedded conglomerate grading into cross-bedded, coarse-grained sandstone. The conglomerate is poorly sorted and mostly contains carbonate clasts up to 20 cm in diameter and a few fragments of marine fossils, including echinoderms, bryozoans, fusulinids, brachiopods, brachiopod spines and probable phylloid algae. Siliciclastic grains such as mono- and polycrystalline quartz, potassium feldspars, granitic rock fragments and rare chert grains are also present (Fig. 6B). Sandstone is moderately sorted, arkosic, cemented by coarse, blocky calcite, and contains a few bioclasts such as shell fragments and bryozoans.

Coarse-grained, fossiliferous arkosic sandstone is present in the upper part of the section Joyita Hills A. The sandstone is very poorly sorted and contains abundant large crinoid stem fragments, subordinate bryozoans and brachiopod shells. Grains are cemented by coarse, blocky calcite.

Interpretation of Sandstone and Conglomerate

Siliciclastic, trough cross-bedded sandstone and pebbly sandstone (St), common at Loma de las Cañas and Cerro del Viboro, are interpreted as fluvial channel-fill deposits. The trough cross-beds formed by migration of fluvial bedforms (dunes) in the channels. Fluvial transport is also indicated by the poor sorting and rounding of the detrital grains. Most quartz and fresh feldspar grains as well as the granitic rock fragments are derived from a nearby granitic source rock (Precambrian basement); subordinate metamorphic and sedimentary rock fragments are present, indicating that such rocks have also been reworked. Poor rounding and sorting and a high amount of detrital feldspars (subarkose to arkose) indicate short distances of transport. The different lithofacies types are arranged to form architectural elements (sensu Miall, 1996) that are characterized by a distinct facies assemblage, internal geometry, external form and locally by vertical succession. Intercalated coarser lithofacies (Gt, St) are arranged to form the architectural elements CH (channel) and LS (laminated sand sheet).

The coarse intercalations are mostly assigned to the element CH (channel), composed dominantly of the lithofacies Gt and St, subordinately of Gh, Sh and Sl. The channels are characterized by concave-up erosional bases, multi-story fills and gradational tops. The channels may extend laterally over more than 100 m, displaying a sheet-like external geometry. Some channels display a well-developed, fining-upward succession with decreasing set thickness and grain size: lithofacies Gt and St at the base, grading into St and Sh, and rarely Sl.

We interpret these sheet-like sandstones and conglomerates as deposits of broad, shallow channels that probably formed in a braided stream system. This facies is very similar to the sheet sandstone facies of the Cutler Formation described by Eberth and Miall (1991). In contrast, the thin, carbonate-conglomerate beds of lithofacies Gcm in the upper part of the Mesa del Yeso section, uppermost part of the Gallina Well section and lower part of the Arroyo Tinajas and Minas de Chupadera sections probably formed from turbulent debris flows.

Thin, fine-grained sandstone beds composed of lithofacies Sr, Sm and Sh, rarely Sl and St, form thin sand sheets that locally can be traced laterally for at least tens of meters (Gallina Well, Arroyo Tinajas, Sierra de la Cruz). Such sand sheets (element LS, "laminated sand sheets" according to Miall, 1996) are interpreted to have resulted from sheet splays. Thin sandstone lenses associated with the sand sheets may represent crevasse channels.

The presence of fragments of various marine fossils in calcite-cemented, mixed siliciclastic-carbonate conglomerate and sandstone at Sierra de la Cruz and at the base of the Agua Torres section indicates deposition in a nearshore, high-energy shallow marine setting.

Limestone

Limestone is most abundant at Sierra de la Cruz (14.5% of the total section) and Arroyo Tinajas (10.5% of the total section). Individual limestone beds are commonly 0.2 to 0.5 m thick, and arranged in intervals up to about 8 m thick composed of even, wavy and nodular limestone beds and intercalated thin mudstone. Nodular limestone is present in almost all sections, commonly associated with evenly or wavy bedded limestone. The most common microfacies types of the limestone are bioclastic mudstone and bioclastic wackestone to packstone with rare rudstone and grainstone.

Bioclastic mudstone is composed mostly of micrite or peloidal micrite. Ostracod shells are the most common bioclasts. Bioclastic wackestone (Fig. 6F, H) to packstone commonly contains a diverse assemblage of shell fragments, bryozoans, echinoderms, ostracods, smaller foraminifers, trilobite fragments, echinoid and brachiopod spines, rare fusulinids and recrystallized phylloid algae. Rarely, fusulinid wackestone (Fig. 6G) and ostracod wackestone (Fig. 6E) are present. Grainstone is only recognized in the uppermost part of the Arroyo Tinajas section. The grainstone is coarse-grained and composed of abundant recrystallized fossil fragments (mostly shell debris, gastropods, subordinate echinoderms, ostracods and probable phylloid algal fragments). The amount of siliciclastic grains, mostly detrital quartz grains, subordinately feldspars and granitic rock fragments, is between 10 and 20%. The grains are cemented by coarse, sparry calcite.

The thin limestone beds of the Joyita Hills section A are composed of rudstone containing fragments of bryozoans up to a few cm in size, with minor echinoderm (crinoid) and brachiopod fragments. In the Gallina Well section (Fig. 5), dark gray micritic limestone (mudstone) predominates in the lower part (up to unit 41), whereas fossiliferous, gray to light gray limestone (mostly bioclastic wackestone to packstone) is characteristic of the upper part. Common fossils are crinoid fragments, brachiopods, bryozoans, gastropods and calcareous algae. The limestone of unit 86 at Gallina Well contains abundant echinoid spines up to 5 cm long. The uppermost thin limestone beds contain abundant bivalves (*Dunbarella)*. Limestone is commonly even to wavy bedded, and nodular limestone is rare in the Gallina Well section. At Minas de Chupadera, intercalated limestone beds are rare and thin (0.2-0.6 m); they contain crinoids, brachiopods, gastropods and fusulinids (Fig. 5).

Interpretation

The low diversity fossil association dominated by ostracods, and the high mud content of the bioclastic mudstone (including ostracod mudstone) point to deposition in a restricted, low-energy, shallow marine environment. The bioclastic wackestone and packstone, characterized by a higher taxonomic diversity of shelly biota and the typical muddy wackestone texture, wavy to nodular bedding and intercalated thin shale indicate deposition in an open, low-energy shallow shelf environment with normal salinity (standard microfacies types [SMF] 9 and 10: Flügel 2004).

Grainstone (SMF-type 11), which was only recognized in the upper part of the Arroyo Tinajas section, shows that high-energy conditions occurred only rarely. The thin rudstone beds of the Joyita Hills A section are interpreted to represent storm layers that formed in a nearshore environment of a shallow, mixed siliciclastic carbonate shelf.

Bioclastic wackestone/packstone, ostracod wackestone/mudstone and bioclastic mudstone, all containing a fossil assemblage like that in the Joyita Hills, are the dominant microfacies of the Red Tanks Member of the Bursum Formation in the Lucero uplift at Red Tanks Arroyo and Coyote Draw (Lucas and Krainer, 2004) and at Carrizo Arroyo (Krainer and Lucas, 2004). Limestone of the Bursum Formation at the type section in the Oscura Mountains also consists dominantly of bioclastic wackestone and mudstone with a similar fossil assemblage (Lucas et al., 2002). This indicates that the depositional environment of the limestone facies of the Bursum Formation was very similar across central New Mexico: restricted to open marine, dominantly low energy shallow shelf environments.

Nodular and Massive Limestone

Horizons of nodular and massive pedogenic limestone (0.2 to 1.5 m thick) are present at Sierra de la Cruz, Arroyo Tinajas, Mesa del Yeso, Gallina Well and Cerro del Viboro (Figs. 3-5). Pedogenic carbonate nodules are up to a few cm in diameter, floating in mudstone. Massive pedogenic limestone is composed of inhomogenous gray, nodular micrite, and subordinately of peloidal mudstone. The pedogenic limestone contains abundant fissure cracks and irregular voids that are filled with calcite cement (Fig. 6C). Locally, cyanobacterial crusts with calcite cement between individual laminae occur, and the rock is brecciated. Fossils are absent.

Interpretation

Nodular and massive pedogenic limestone within the Bursum Formation is interpreted as being of pedogenic origin. This rock is very similar to the nodular and massive caliche of the Abo Formation described by Mack et al. (1991), although rhizoliths are very rare. Nodular pedogenic limestone of the Bursum Formation is assigned to stage 2, and the massive type to stage 3 and stage 4 of calcrete development of Machette (1985).

DEPOSITIONAL SEQUENCES

Alternation of nonmarine and marine facies allows a subdivision of the Bursum Formation into depositional sequences (Figs. 3-5). Here, we use the term depositional sequence to refer to a stratigraphic unit of genetically-related strata bounded at its base and top by unconformities, which define the sequence boundaries (Van Wagoner et al. 1988, 1990). In the Bursum Formation the sequence boundaries are frequently characterized by subaerial exposure, and locally associated with substantial subaerial erosion associated with a basinward shift in facies. Nonmarine or marginal marine rocks (fluvial or nearshore conglomerate and sandstone, nonmarine red shale) directly overlie shallow marine rocks (shallow marine mudstone and limestone), indicating the presence of type 1 sequence boundaries *sensu* Van Wagoner et al. (1988). Although it is not possible to trace the sequence boundaries in the field from one section to the other due to local structure and outcrop discontinuity, and although the facies shows considerable vertical and lateral facies changes, we tried to correlate the studied sections based on distinct marine limestone intervals and sequence boundaries (Figs. 3-5).

The Bursum Formation of the Joyita Hills is composed of up to six depositional sequences that range in thickness from <10 m to 60 m. The thin Bursum successions of Joyita Hills sections A and B consist of only one depositional sequence, sections C (Mesa del Yeso) and G (Cerro del Viboro) consist of two; sections D, E, F, H, J (Sierra de la Cruz, Arroyo Tinajas, Loma de las Cañas, Agua Torres, Minas de Chupadera) are composed of three depositional sequences (Figs. 3- 5); and, in the thickest section, I (Gallina Well), six depositional sequences are recognizable.

Depositional Sequence 1 (DS 1)

Depositional sequence 1 of sections C (Mesa del Yeso) to J (Minas de Chupadera) starts with a marked facies change on top of marine limestones of the Atrasado Formation (Figs. 3-5). This facies change from marine to nonmarine deposits represents a type 1 sequence boundary (SB 1). Locally, the topmost limestone of the Atrasado Formation is pedogenically overprinted (sections C, D, G; Mesa del Yeso, Sierra de la Cruz, Cerro del Viboro), and overlain by nonmarine red mudstone that may contain pedogenic carbonate nodules (section C, Mesa del Yeso). At section D (Sierra de la Cruz) channel-fill sandstone up to 40 cm thick erosively overlies a pedogenic limestone. At section E (Arroyo Tinajas), limestone of the Atrasado Formation is directly overlain by nonmarine red shale, and probably also at sections F, I and J (Loma de las Cañas, Gallina Well, Minas de Chupadera) (covered intervals).

Most of depositional sequence 1 is composed of nonmarine red shale, locally containing pedogenic carbonate nodules and thin pedogenic carbonate horizons (sections C, E; Mesa del Yeso, Arroyo Tinajas). Rarely, thin fine-grained sandstone layers (sections D, E, I, J; Sierra de la Cruz, Arroyo Tinajas, Gallina Well, Minas de Chupadera) and a thin, fine-grained carbonate conglomerate (section E; Arroyo Tinajas) are intercalated. Thin, shallow marine limestone beds composed of bioclastic wackestone and fusulinid wackestone are developed in the upper parts of sections C, D, H and J (Mesa del Yeso, Sierra de la Cruz, Agua Torres, Minas de Chupadera). The fusulinid-bearing limestone horizon of section D (Sierra de la Cruz) most probably correlates with the fusulinid limestone in the middle of section F and J (Loma de las Cañas, Minas de Chupadera) and with the ostracod-bearing silty limestone of section E, both overlain by red shale. At section G, Cerro del Viboro (and probably also at section I, Gallina Well) depositional sequence 1 is entirely nonmarine, composed of red shale with intercalated thin, fine-grained sandstone (Sm, Sl, Sh) and trough cross-bedded, fine- to coarse-grained arkosic sandstone (St) representing fluvial channel fills.

Depositional Sequence 2 (DS 2)

The boundary between DS 1 and DS 2 is characterized by a major facies change (SB 2). At sections C (Mesa del Yeso) and E (Arroyo Tinajas), DS 2 starts with nonmarine red mudstone on top of shallow marine nodular limestone (Figs. 3-4). At section D (Sierra de la Cruz) we draw the boundary at the erosive base of a thin marine carbonate conglomerate overlain by marine, cross-bedded sandstone. At sections F, G and H (Loma de las Cañas, Cerro del Viboro, Agua Torres), DS 2 begins with fluvial conglomerate and arkosic pebbly sandstone that show a distinct erosive base. At section H (Agua Torres), DS 2 is entirely nonmarine, displaying a fining-upward trend from conglomerate to sandstone and thick overbank fines. At section I (Gallina Well) we place SB 2 at the base of a coarse-grained conglomerate with boulders up to 20 cm in diameter. At section J (Minas de Chupadera) the boundary is at the base of a fluvial conglomerate.

At section I (Gallina Well), DS 2 is approximately 60 m thick, dominantly nonmarine in the lower part and marine in the upper part (Fig. 5). At section C (Mesa del Yeso), DS 2 is mostly nonmarine and composed of red shale with pedogenic carbonate nodules and a pedogenic carbonate horizon in the lower part, and thin, fine-grained carbonate conglomerate beds and a thin, fine-grained rippled sandstone layer in the upper part. The only marine facies is a thin limestone in the middle of the section representing a distinct marine flooding surface (FS).

At section D (Sierra de la Cruz), DS 2 is entirely shallow marine and composed of greenish and greenish-gray shale with a thin ostracod wackestone intercalated in the lower part and several intercalated even, wavy and nodular bedded limestones of a shallow, open marine environment in the middle and upper part. The thicker nodular limestone in the middle of DS 2 is a candidate for the maximum flooding surface (MFS), which separates the transgressive systems tract from the overlying highstand systems tract. The topmost limestone bed is a mudstone containing a restricted fauna, indicating the beginning of the regression.

At section E (Arroyo Tinajas), the lowermost part of DS 2 is composed of nonmarine red shale with pedogenic carbonate nodules and intercalations of a thin marine conglomerate layer (shoreface environment) and two thin limestone layers containing a restricted shallow marine fauna. These intercalations are distinct flooding surfaces (FS). The uppermost part of DS 2 is composed of thin, shallow marine limestone beds alternating with marine shales. The limestone bed composed of bioclastic wackestone and large burrows at the base of this open marine succession probably marks the maximum flooding surface (MFS).

At section F (Loma de las Cañas), DS 2 is mostly nonmarine with only two thin marine limestone beds intercalated in red shale with abundant pedogenic nodules in the upper part. At section G (Cerro del Viboro), the nonmarine facies fines upward and is overlain by a fossiliferous wackestone marking a marine flooding surface. We draw the maximum flooding surface at the base of the nodular, fusulinid-bearing limestone. Also at section J (Minas de Chupadera), the nonmarine facies grades upward into a thin, shallow marine limestone facies.

Depositional Sequence 3 (DS 3)

DS 3 is developed at sections D, E, F, H, I and J (Sierra de la Cruz, Arroyo Tinajas, Loma de las Cañas, Agua Torres, Gallina Well, Minas de Chupadera; Fig. 4-5). At sections F, H, I and J (Loma de las Cañas, Agua Torres, Gallina Well, Minas de Chupadera), the base of DS 3 is formed by fluvial, cross-bedded, coarse, pebbly sandstone and fine-grained conglomerate that erosively overlie nonmarine red shale and nodular pedogenic carbonate. At section E (Arroyo Tinajas), nonmarine red shale with pedogenic carbonate nodules overlies shallow marine limestone. At section C (Mesa del Yeso), carbonate conglomerate and coarse-grained, cross-bedded sandstone containing marine fossils erosively (?) overlie marine shale, which is poorly exposed.

At section D (Sierra de la Cruz), DS 3 is probably completely marine, and mostly consists of gray marine shale with intercalated even to wavy bedded or nodular limestone beds of an open, shallow marine environment. The uppermost thin limestone layers indicate a restricted shallow marine setting. The uppermost marine limestone bed is overlain by nonmarine red shale of the Abo Formation. Intercalated limestone beds represent marine flooding surfaces. We draw the maximum flooding surface at the base of the thicker nodular limestone interval.

At section E (Arroyo Tinajas), DS 3 is composed of a thick succession of nonmarine red shale containing pedogenic carbonate nodules, overlain by nodular limestone that in its lower part contains a restricted marine fauna, and in its upper part an open shallow marine fauna. The uppermost part is formed by a bioturbated sandy limestone (grainstone) that is erosively overlain by conglomerate of the Abo Formation.

At section F (Loma de las Cañas), DS 3 is entirely nonmarine; the basal sandstone is overlain by purple mudstone with pedogenic carbonate nodules and nonmarine red mudstone. At section H (Agua Torres), the basal conglomerate is overlain by thick, in part poorly exposed red mudstone with a few intercalated thin, massive, fine-grained sandstone layers in the lower part. In the uppermost part, two thin fossiliferous limestone layers indicating a shallow open marine environment are intercalated. At section I (Gallina Well), DS 3 is a well-developed transgressive sequence starting with conglomerate-dominated facies that grade upward into shale with intercalated fluvial sandstone and a pedogenic horizon capped by a thin, open marine limestone bed (Fig. 5). DS 3 is only about 3 m thick at section J (Minas de Chupadera), consisting of a basal sandstone and conglomerate, overlain by a covered interval and a thin sandy limestone on top (Fig. 5).

DS 3 is bounded on top by nonmarine red beds of the Abo Formation, which locally form an erosive contact overlain by conglomerate. The Abo Formation base is nonmarine red shale and fine-grained sandstone.

Depositional Sequences 4 – 6 (DS 4-6)

At section I (Gallina Well; Fig. 5), three additional depositional sequences are recognized, separated by sequence boundaries. DS 4 is dominantly nonmarine, with a thin marine limestone on top. DS 5 and 6 are also dominantly nonmarine. In DS 5 a thin open-marine limestone bed with abundant echinoid spines is present in the lower part. In DS 6 several 2-3 cm thick limestone beds containing abundant *Dunbarella* occur in the middle of the sequence, representing the uppermost marine facies in this section.

The thin successions of Joyita Hills sections A and B (Fig. 3) are difficult to correlate with the other Bursum sections. It is also unclear how to correlate these two sections: Section A rests on Precambrian gneiss, and starts with nonmarine redbeds that grade upward into shallow marine fossiliferous limestone and sandstone with intercalated shale. In contrast, Joyita Hills section B erosively rests on fossiliferous nodular limestone with shale of the uppermost Gray Mesa Formation. The Bursum Formation of section B begins with fluvial, channel-fill conglomerate, grading upward into overbank shale with an intercalated pedogenic carbonate horizon. Section B does not contain marine strata. Both sections are bounded on top by nonmarine red beds of the Abo Formation.

DISCUSSION

The Bursum Formation represents the "transitional facies" between the underlying shallow marine, dominantly carbonate sediments of the Gray Mesa and Atrasado formations and the overlying nonmarine red beds of the Abo Formation. In the Joyita Hills, the Bursum Formation displays strong lateral variations in facies and thickness: Sections D and E (Sierra de la Cruz, Arroyo Tinajas) are dominantly shallow marine, whereas sections C, F, G, H, I and J (Mesa del Yeso, Loma de las Cañas, Cerro del Viboro, Agua Torres, Gallina Well, Minas de Chupadera) are dominantly nonmarine with a few thin marine intercalations. Thicknesses range from 120 m at section I (Gallina Well) to 10 m at section Joyita Hills A and 9 m at section Joyita Hills B (Fig. 7).

In central New Mexico, the Bursum Formation locally rests on Precambrian to Virgilian strata with an angular unconformity. In some areas, part or all of the Virgilian is missing, and the Bursum Formation rests on pre-Virgilian strata, as already recognized by Kottlowski and Stewart (1970). In the Joyita Hills, the Bursum Formation rests on limestones of the Atrasado or Gray Mesa formations, locally on the Precambrian basement rocks, and is unconformably overlain by nonmarine red beds of the Abo Formation.

These two unconformities are the result of major tectonic pulses. The tectonic pulse responsible for the lower unconformity caused a sharp facies change from dominantly shallow marine carbonate sedimentation to mixed siliciclastic-carbonate sedimentation of alternating nonmarine and marine sediments. The upper unconformity resulted from a major tectonic pulse of the ARM deformation, causing again a rejuvenation of basement uplifts that resulted in increased siliciclastic influx and deposition of nonmarine red beds of the Abo Formation. But, there is also some evidence for tectonic activity during sedimentation of the Bursum Formation. Locally, the Bursum Formation or part of it is absent, probably due to erosion prior to the deposition of the Abo red beds.

Unconformity at Base of Bursum Formation

The sharp facies boundary between the underlying strata (Atrasado, Gray Mesa formations) and the Bursum Formation (Figs. 3-5) reflects a distinct unconformity. In the Joyita Hills, the basal conglomerate of the Bursum Formation locally overlies pre-Virgilian strata with an erosional unconformity. The basal conglomerate contains abundant reworked limestone clasts, indicating local erosion of substantial parts of underlying carbonates. The age of the uppermost Atrasado Formation in much (if not all) of the Joyita Hills is middle Virgilian, indicating that the basal Bursum unconformity represents a hiatus equivalent to the late Virgilian.

The angular unconformity between the Bursum Formation and the underlying Precambrian to Virgilian strata locally observed in central New Mexico can only be explained by a major tectonic pulse. Tectonic movements caused reactivation of basement uplifts (as in section Joyita Hills A), rejuvenation of the relief and increased siliciclastic influx, and locally considerable erosion of pre-Bursum strata.

Tectonic Influences during Bursum Sedimentation

Locally, like at sections D and E (Sierra de la Cruz, Arroyo Tinajas), which are dominantly shallow marine, and particularly at section I (Gallina Well), Bursum sedimentation seems to have been mainly controlled by glacioeustatic sea-level changes (Fig. 4-5). But, cyclic sedimentation of the Bursum Formation was also influenced by tectonism, which is responsible for increased siliciclastic influx and alternation of nonmarine and shallow marine strata. Tectonism was also responsible for the lateral facies changes. At some sections, depositional sequences are entirely nonmarine, probably due to the erosion of the marine strata and to conglomerate erosively overlying nonmarine shale and siltstone at the base of the next depositional sequence (e.g., DS 2 at section H, Agua Torres, or DS 3 at section F, Loma de las Cañas).

Section I (Gallina Well) is the thickest Bursum section in the Joyita Hills, composed of six depositional cycles of nonmarine and shallow marine strata. Towards the south the Bursum Formation thins and is increasingly composed of nonmarine red beds. At the southernmost section, G (Cerro del Viboro), only two depositional sequences are developed. Farther south, in the Little San Pascual Mountains, the Bursum Formation is absent (Fig. 7).

From the Gallina Well section, towards the northwest and west the Bursum also thins; it is only 9-10 m thick at sections Joyita Hills A and B and it is absent in the Magdalena Mountains (Fig. 7). Sections Joyita Hills A and B are of particular interest. At section Joyita Hills A, the Bursum overlies the Precambrian basement, and at the nearby section Joyita Hills B the Bursum erosively rests on shallow marine carbonates of the Gray Mesa/Atrasado(?) Formation. As the carbonates of the Gray Mesa/Atrasado do not show any coarse, granitic siliciclastic influx, the basement rocks of section A must have been uplifted after deposition of the Gray Mesa/Atrasado, i.e., prior to or during sedimentation of the Bursum Formation. Both sections consist of only one depositional sequence. Due to a lack of biostratigraphic data for sections Joyita Hills A and B, correspondence of the depositional sequences at these localities with the depositional sequences in the thicker sections to the south is unclear.

The Bursum Formation of the Lucero basin (e.g., Carrizo Arroyo and Coyote Draw sections; see Krainer and Lucas, 2004; Lucas and Krainer, 2004; Lucas et al., 2004) is of similar thickness to section I (Gallina Well, 100 – 120 m: Fig. 7), composed of six DS that probably can be correlated to the six DS of section I (Gallina Well). But, all other Bursum sections in the Joyita Hills display only up to three depositional sequences, suggesting that sedimentation in the different basins was also affected by tectonic processes causing different rates of subsidence and uplift that locally caused erosion of Bursum strata prior to deposition of the Abo red beds.

Unconformity at Boundary between Bursum and Abo Formations

The Bursum Formation is unconformably overlain by nonmarine red beds of the Abo formation (Figs. 4-5). Locally, the Abo Formation base is a conglomerate that erosively overlies the Bursum Formation (sections Joyita Hills B and sections E, F, H; Arroyo Tinajas, Loma de las Cañas, Agua Torres). Limestone clasts in this conglomerate indicate that, locally, substantial parts of the Bursum Formation were eroded prior to deposition of the Abo red beds, probably forming deeply incised valleys. This is also indicated by the fact that in the thickest Bursum section I (Gallina Well) six depositional sequences are present, whereas in all other sections at least three depositional sequences are absent, most probably due to erosion prior to deposition of the Abo red beds. This unconformity is also recognized at other locations and indicates a major tectonic pulse near the Virgilian/Wolfcampian boundary.

At the Kelly Mine near Magdalena (Magdalena Mountains), cherty limestone of the Gray Mesa Formation is overlain by the Abo Formation, which begins with a basal limestone conglomerate. Limestone clasts are probably derived from Bursum or Atrasado strata that were eroded prior to deposition of the Abo Formation. At the southern end of the Little San Pascual Mountains, thick-bedded, brownish dolomitic limestone of the Atrasado Formation is overlain by nonmarine red mudstone containing pedogenic carbonate nodules, intercalated pedogenic nodular carbonate horizons, red sandstone, partly coarse-grained and pebbly, and fine-grained conglomerate containing abundant limestone clasts. A weathered surface is developed on top of the Atrasado, indicating subaerial exposure and erosion of the uppermost Atrasado and probably also of the Bursum Formation.

Near the northern end of the Fra Cristobal Mountains, the Bursum Formation is only 7.5 m thick, rests on gray fossiliferous limestone of the Bar B Formation and is overlain by nonmarine red mudstone and sandstone. Also, in the southern Fra Cristobal Mountains the Bursum is thin (about 15 m at Hellion Canyon, 25 m at Red Gap). In the Cuchillo Mountains, at Deep Well Creek, the Bursum also is thin, measuring 26.5 m.

In the Caballo Mountains at Red Hill Tank, the Bar B Formation is overlain by 4-5 m thick Bursum sediments, overlain by a polymict conglomerate containing abundant reworked limestone clasts, followed by fine-grained Abo red beds. In the McLeod Hills the upper Bar B is overlain by Abo red beds with intercalated fine-grained carbonate conglomerates. The Bursum Formation is absent.

At many locations, particularly where the Bursum is very thin to absent, carbonate conglomerates occur in the lower part of the Abo Formation that contain abundant limestone clasts, particularly bioclastic mudstone and bioclastic wackestone. These are the dominant microfacies of limestones of the Bursum Formation. These limestone conglomerates therefore demonstrate that substantial parts of the Bursum Formation were eroded prior to deposition of the Abo Formation, indicating that a major tectonic pulse caused the unconformity between the Bursum and overlying Abo Formation. The considerable variations in thickness; the strong lateral facies variation; and the difficult correlation of depositional sequences from section to section indicate that sedimentation of the Bursum Formation was strongly affected by local tectonic movements causing different rates of subsidence and uplift within a relatively small area.

This unconformity is even recognized at the base of the Hueco Limestone in the Orogrande Basin, represented by the Powwow Conglomerate Member. The Powwow Conglomerate Member of the Hueco Limestone in the Hueco Mountains was originally described as a succession of conglomerate and red beds by King and King (1929). They placed the Powwow Conglomerate Member below the Virgilian/Wolfcampian unconformity. Later, King (1934) correctly placed the Powwow Conglomerate Member above this unconformity. According to Pray and Otté

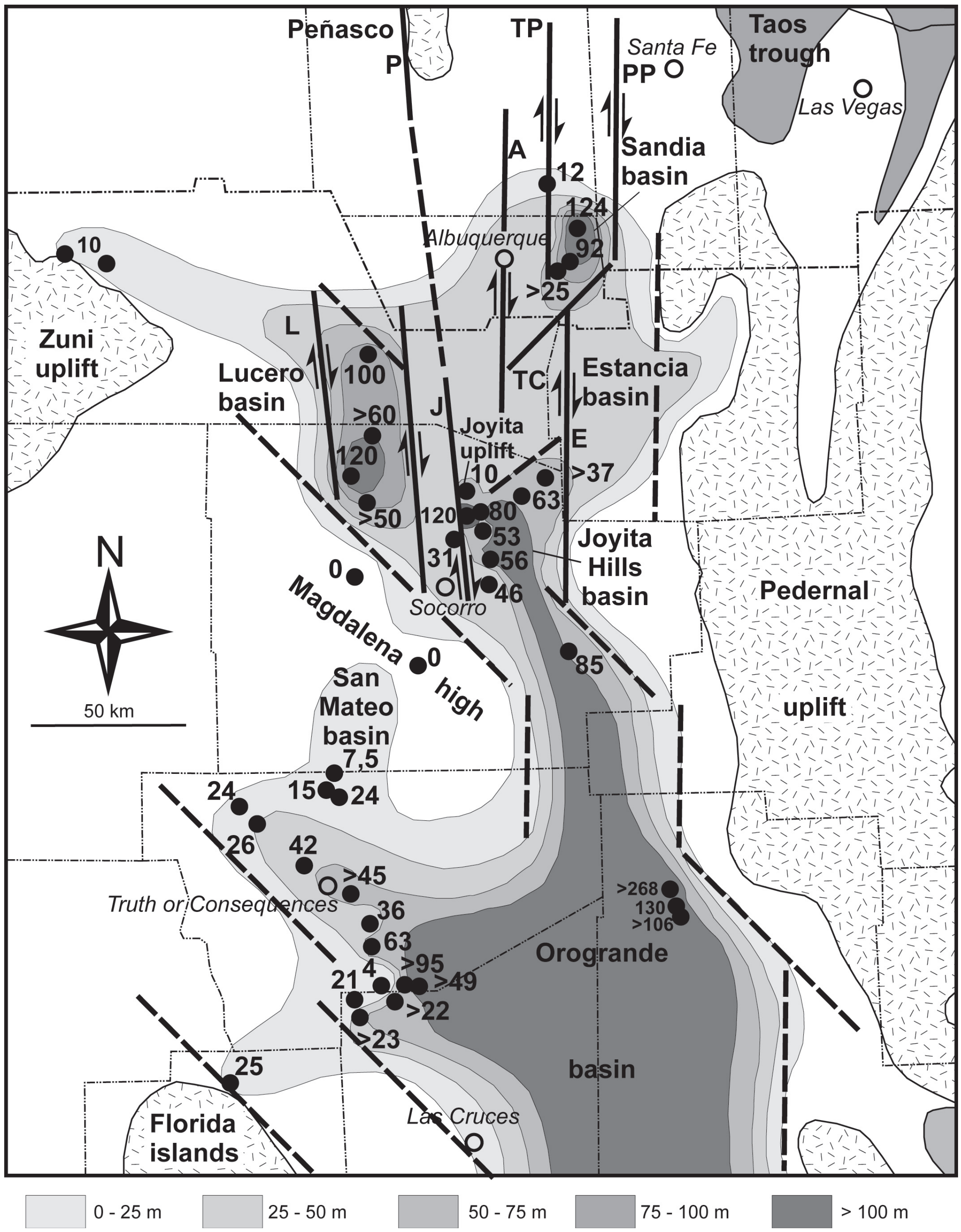

FIGURE 7. Isopach map of Bursum Formation and major tectonic elements during Bursum Formation deposition. A = Albuquerque fault; E = Estancia fault; J = Joyita Hills fault, L = Lucero fault; P = Peñasco fault; PP = Picuris-Pecos fault; TC Tijeras-Cañoncito fault; TP = Tusas-Picurs fault. Dots indicate measured Bursum sections and their thicknesses (in m).

(1954), the Powwow Conglomerate Member correlates with the basal Abo Formation. Deposition of massive mudstones and siltstones and intercalated conglomerates of the Powwow Conglomerate Member was also caused by tectonic activity. According to Fitchen et al. (1995) the Powwow Formation in the northern Sierra Diablo of west Texas is no younger than middle Wolfcampian in age and represents a time-transgressive, alluvial to marginal marine facies.

Beck and Chapin (1991) and Beck and Johnson (1992) demonstrated that the Joyita Hills uplift (Fig. 7) is bounded by faults that were active during the ARM deformation. According to these authors, the two sets of normal faults offset early Wolfcampian

(Bursum Formation) strata, Pennsylvanian strata and Proterozoic basement rocks. These faults do not occur within the Abo Formation and thus predate Abo deposition, but were probably active during deposition of the Bursum Formation. This is indicated by the fact that along the westernmost fault, the Bursum and Abo formations are thin in the footwall and thicken towards the west (hanging wall) and also towards the east. North-striking faults show a component of left-lateral slip. The Peñasco uplift (Nacimiento-San Pedro Mountains area) probably extends to the south, and the Joyita uplift may represent the southern end of this uplift, a concept already developed by Baars (1982) (Fig. 7). Nelson (written commun., 2008) described a number of outcrops in the Joyita Hills area that demonstrate that tectonic folding, tilting, and faulting took place during deposition of uppermost Atrasado, Bursum, and basal Abo sediments.

According to Beck and Johnson (1992), the arkosic sedimentary rocks of the Bursum Formation represent syntectonic detritus shed from late Paleozoic uplifts. Fusulinids from outcrops of Bursum Formation east of the Proterozoic core indicate an early Wolfcampian age, so a major deformation event occurred during the early Wolfcampian. Tectonic phases of the Atokan and middle Desmoinesian are thought to be minor events (precursor events) during the tectonic development of the Joyita uplift. Tectonic interpretation on a more regional scale is presented by Armstrong (1962), Armstrong and Mamet (1988), Peterson (1980), Kluth and Coney (1981), Kluth (1986), Woodward et al (1999) and Dickinson and Lawton (2003).

Kluth and Coney (1981) proposed that the late Paleozoic Ancestral Rocky Mountain uplifts and basins of Colorado, New Mexico and adjacent areas formed by northwest-southeast crustal shortening caused by the collision of North America with South America/Africa that produced the Ouachita-Marathon orogeny. This model is based on the assumption that north-striking faults of Late Paleozoic age underwent left slip, which is consistent with northwest-southeast crustal shortening. However, according to Woodward et al. (1999), most of the 125 km of pre-Laramide right-lateral offset in northern New Mexico occurred along north-trending major faults during the late Paleozoic. Late Paleozoic deformation in this interpretation was probably caused by northeast-southwest crustal shortening related to a northwest-trending subduction zone along the southwest margin of North America (Ye et al., 1996). Recently Dickinson and Lawton (2003) argued that diachronous subsidence of ancestral Rocky Mountains basins was coincident with sequential closure of the Ouachita suture to the southeast. Basin formation and subsidence was induced by intracontinental stress associated with continued subduction of part of Laurentia.

According to Beck and Chapin (1991), the San Mateo and Lucero basins were once continuous, north-trending basins (Fig. 7). The lack of the Bursum Formation near Magdalena (Gray Mesa limestone directly overlain by red beds of the Abo Formation) and in the Little San Pascual Mountains indicates the probable presence of a northwest-southeast-trending structural high southwest of Socorro ("Magdalena high") separating these two basins during deposition of the Bursum Formation.

CONCLUSIONS

Across much of New Mexico, strata of the Pennsylvanian-Permian transition are represented by the Bursum Formation, which is generally less than 100 m thick, and is composed of interbedded siliciclastic red beds and marine limestone and shale. The Bursum is distinguished from underlying Pennsylvanian strata by its substantial content of red-bed shale and mudstone and some beds of limestone-pebble conglomerate and trough cross-bedded sandstone. Many sections display a cyclic alternation of nonmarine and marine facies.

Unlike immediately overlying Permian strata, the Bursum contains beds of marine limestone and calcareous shale. Thus, the Bursum is transitional between dominantly shallow marine carbonate facies of the Pennsylvanian and the continental red bed facies of the Lower Permian.

Regional and local variation in Bursum lithofacies is best expressed by recognizing four members of the formation: (1) Bruton Member, a moderately thick (< 85 m), mostly marine lithofacies present in the Joyita Hills (Sierra de la Cruz, Arroyo Tinajas), Cooke's Range and the Oscura, northern San Andres, Fra Cristobal (Hellion Canyon, Red Gap) and Caballo Mountains; (2) Laborcita Member, a thick (< 330 m) unit mostly of nonmarine red-beds, basement-cobble conglomerates, bedded fossiliferous limestones and algal bioherms in the Sacramento Mountains; (3) Oso Ridge Member, a thin (< 12 m) unit containing much reworked local basement in the Zuni Mountains and locally present also in the Joyita Hills (sections A and B); and (4) Red Tanks Member, a moderately thick (up to 120 m) unit of mostly nonmarine shale and mudstone present in the Lucero uplift, Sandia, Manzano and Los Pinos Mountains and locally in the Joyita Hills (Gallina Well, Minas de Chupadera, Cerro del Viboro, Loma de las Cañas, Mesa del Yeso).

In the Joyita Hills east of Socorro, the Bursum Formation is characterized by considerable lateral changes in facies and thickness within a relatively small area. Regional synsedimentary tectonic movements of the ARM orogeny strongly influenced Bursum sedimentation, resulting in such conspicuous lateral variations in lithofacies and thickness. A tectonic pulse responsible for the unconformity at the base of the Bursum Formation caused a sharp facies change from dominantly shallow marine carbonate sedimentation to mixed siliciclastic-carbonate sedimentation of alternating nonmarine and marine sediments. The unconformity is locally angular, truncating all older Paleozoic units. The unconformity on top of the Bursum Formation resulted from another major tectonic pulse of the ARM deformation, causing a significant rejuvenation of basement uplifts that resulted in increased siliciclastic influx and deposition of nonmarine red beds of the Abo Formation. There is also plentiful and unequivocal evidence for tectonic activity during sedimentation of the Bursum Formation.

The widespread Bursum Formation (Virgilian-early Wolfcampian) thus represents a significant tectonic pulse or series of pulses affecting large areas of New Mexico during the ancestral Rocky Mountain orogeny. Glacioeustatic sea-level changes related to the Permo-Carboniferous glaciation of the Gondwana supercontinent are assumed to have been responsible for the cyclic pattern of strata of the Bursum Formation, although sedimentation was strongly overprinted by tectonic movements resulting in strong lateral and vertical facies changes, strong variations in thickness, and locally to erosion of the Bursum Formation or parts of it prior to deposition of the Abo Formation.

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APPENDIX—MEASURED SECTION LOCATIONS

Here we list the UTM coordinates of all the measured sections in Figures 3-5. Map datum is NAD 27

A. Joyita Hills A--section at 13, 331122E, 379244N; this is very close to section JH-6 of Kottlowski and Stewart (1970).

B. Joyita Hills B—at 13, 332126E, 3794242N; this is very close to section JH-3 of Kottlowski and Stewart (1970).

C. Mesa del Yeso—base at 13, 339132E, 3780539N, top at 13, 339044E, 3780849N.

D. Sierra de la Cruz—base at 13, 344021E, 3780601N, top at 13, 344035E, 3780754; this is the same section as section 2 of Altares (1990).

E. Arroyo Tinajas—base at 13, 340524E, 3775705; top at 13, 340673E, 3775630N; this is the same section as section 3 of Altares (1990).

F. Loma de las Cañas—base at 13, 338391E, 3771680N; top at 13, 338546E, 3771396N.

G. Cerro del Viboro—base at 13, 337023E, 3758833N; top at 13, 337117E, 3758645N; this is the same section as section 5 of Altares (1990).

H. Agua Torres—base at 13, 353051E, 3791717N; top at 13, 353156E, 3791695N.

I. Gallina Well—base at 13, 340645E, 3780398N; top at 13, 339993E, 3780818N.

J. Minas de Chupadera—base at 13, 332836E, 3775630N; top at 13, 332882E, 3775706N.