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THE GUADALUPIAN SERIES AND THE PERMIAN TIMESCALE

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Abstract—The Permian System was divided into two series, lower and upper, for more than a century, but in the 1990s a third middle series was added to reflect better the physical and biological events of Permian Earth history. The three Permian series also received formal names (ascending: Cisuralian, Guadalupian, and Lopingian). The Guadalupian Series consists of three stages (ascending: Roadian, Wordian, and Capitanian) that have Global Stratotype Sections and Points (GSSPs) that define their bases in the Guadalupe Mountains of west Texas. Beginning in 2013, a new effort began to restudy the Guadalupian GSSPs, and it has revealed problems with all three Guadalupian stage-base GSSPs. Clearly, there is a need to redefine the GSSPs of at least the base of the Roadian and Wordian. The problems with the Guadalupian GSSPs reveal the politics of the International Commission on Stratigraphy (which led to premature and unsubstantiated original definitions during the 1990s) and the relative lack of understanding and agreement on stratigraphic ranges and the taxonomy of the conodonts used as primary signals to define the GSSPs. Clearly, more work is needed and expected to redefine and refine Guadalupian chronostratigraphy as a part of the Permian timescale.

INTRODUCTION

The relative geological timescale is a hierarchical classification based on a chronostratigraphic scale that consists of units that range from eonothems to stages. More than 150 years of development of the chronostratigraphic scale included the naming of numerous stages, many of which overlap each other temporally and/or are only of very local applicability. During the 1960s, the International Commission on Stratigraphy (ICS) of the International Union of Geological Sciences set out to standardize a set of global stages. This began with the use of boundary stratotypes to define chronostratigraphic units, and, in the 1980s, these came to be called GSSPs (Global Stratotype Sections and Points; Fig. 1).

The GSSP is a point (stratigraphic level) in a specific location (stratigraphic section) that defines the base of a stage. The GSSP is correlated by a primary signal, usually a biostratigraphic datum, and by secondary signals—biostratigraphic, chemostratigraphic, magnetostratigraphic, and radioisotopic, among others. The GSSP is not placed at an unconformity or at a lithologic change, so it is at a stratigraphic level of "continuous" sedimentation. GSSPs go through a formal process of proposal and ratification by the voting of earth scientists, as specified by the procedures of the ICS. The GSSP method has done much to standardize chronostratigraphy, but it is not above criticism, particularly the politics of the ICS voting bodies (Lucas, 2018). Approximately three-quarters of the Phanerozoic stage-base GSSPs (77 of 102 in 2022) have been ratified (https://stratigraphy.org/ICSchart/ChronostratChart2022-02.pdf).

However, few of these GSSPs are in North America. Most are in Europe or China. Three of the few North American GSSPs define the bases of the Middle Permian stages and are located in the Guadalupe Mountains of west Texas (Fig. 2). Here, I review the history and context of these GSSPs and list ongoing problems with their definitions.

Series	Stage	Substage
Lopingian	Changhsingian	Meishanian
		Baoqingian
	Wuchiapingian	Laoshanian
		Laibinian
Guadalupian	Capitanian	
	Wordian	
	Roadian	
Cisuralian	Kungurian	Cathedralian
		Hessian
	Artinskian	Baigendzhinian
		Aktastinian
	Sakmarian	Sterlitamakian
		Tastubian
	Asselian	Shikhanian
		Uskalykian
		Sjuranian

FIGURE 1. Permian chronostratigraphic scale (after Lucas and Shen, 2018). As of early 2023, all of the bases of the Permian stages, except the Kungurian, have formally defined and ratified GSSPs.

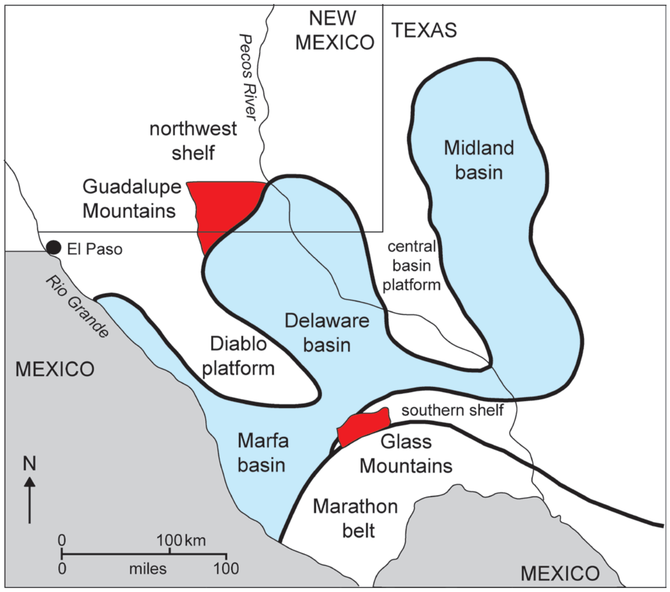

FIGURE 2. Map of the Permian Delaware Basin and vicinity showing the location of the Guadalupe Mountains and the Glass Mountains (after Hill, 1996).

PERMIAN SERIES

All students of the Permian know that legendary British geologist Roderick Murchison (1792–1871) named the Permian as a result of fieldwork he undertook in Russia. This fieldwork, in 1840 and 1841, is well documented by Murchison's own publications (especially Murchison et al., 1845). Nevertheless, it has long been clear that Murchison's type Permian is not the entirety of the Permian of most later usage. Thus, the strata in Russia that Murchison identified as Permian encompass the latest early Permian, middle Permian, late Permian, and even a part of the earliest Triassic in current usage. Murchison regarded as Carboniferous the underlying strata that are now considered the majority of the lower Permian Series.

Extension of the base of the Permian downward took place in two ways. First, inclusion of the central European Rotliegend in the Permian, a miscorrelation first advocated by Murchison, immediately brought strata older than the "type" Permian into the system (Lucas and Shen, 2018). Second, subsequent studies of ammonoids by Russian paleontologist Alexander Karpinsky (see especially Karpinsky's 1889 monograph) included the Russian Artinskian strata (the "grits of Artinsk," considered Carboniferous by Murchison) and its much later recognized, older subdivisions, the Asselian and Sakmarian, in the Permian.

An important point is that continental European geologists had long united the German Rotliegend and Zechstein into one "group" or "system." These were a portion of the "Flötz" rocks of the 18th century German miners and geologists, an economically important stratigraphic interval (in German, "Flötz" means lode or seam, "Zeche" means mine). Thus, Permian strata were some of the first rocks studied stratigraphically, notably in the late 1700s by the first German stratigraphic geologists, Johann Gottlieb Lehman (1719–1767) and Georg Christian Füchsel (1722–1773). They were also a part of Abraham Werner's (1749–1817) "Flotzformations" of the 1780s, because they included important sources of copper from the famed copper slates (Kupferschiefer of the Zechstein). The underlying rocks without metal ores were the Rotliegend, literally the "red underlayer" of the old German miners. Dividing the Permian into two series, lower and upper, corresponding in some sense to the European Rotliegend and Zechstein, thus had a tremendous amount of precedence to as far back as the 1700s. Indeed, Harland et al. (1990, fig. 3.7) used the terms "Rotliegendes" and "Zechstein" to denote the two Permian series (Fig. 3).

A threefold division of the Permian was proposed a few times but only found a limited following. Early, Munier-Chalmas and de Lapparent (1893) divided the European (primarily nonmarine) Permian into Autunian, Saxonian, and Thuringian (the former two = Rotliegend, the latter = Zechstein). These terms found favor among some paleobotanists working in Europe. Much later, Waterhouse (1976, 1978) suggested a pre-Kungurian early Permian, a Kungurian-Dzhulfian middle Permian, and a late Permian equivalent to the Griesbachian, which is now regarded as Triassic (Fig. 3). This met with no followers.

In North America, four Permian series were identified by Adams et al. (1939)—Wolfcamp, Leonard, Guadalupe, and Ochoa—but the first two of these were primarily used as stages by subsequent workers (Wolfcampian and Leonardian). The Ochoa Series of Adams et al. (1939) was based on a very thick (up to 1700 m) but evaporite-dominated section in west Texas–southeastern New Mexico (in ascending order, the Castile, Salado, Rustler, and Dewey Lake/Quartermaster formations). Ochoan strata yield very few fossils of biostratigraphic value, so Lucas and Anderson (1994, 1997) advocated recognizing an Ochoa Group as a lithostratigraphic unit, rather than as a chronostratigraphic unit.

In the 1990s, it became clear to many students of the Permian timescale that dividing the Permian into three series would better represent physical and biotic events during the period (Fig. 3). Thus, they advocated and ultimately agreed on lower, middle, and upper Permian series and named them the Cisuralian,

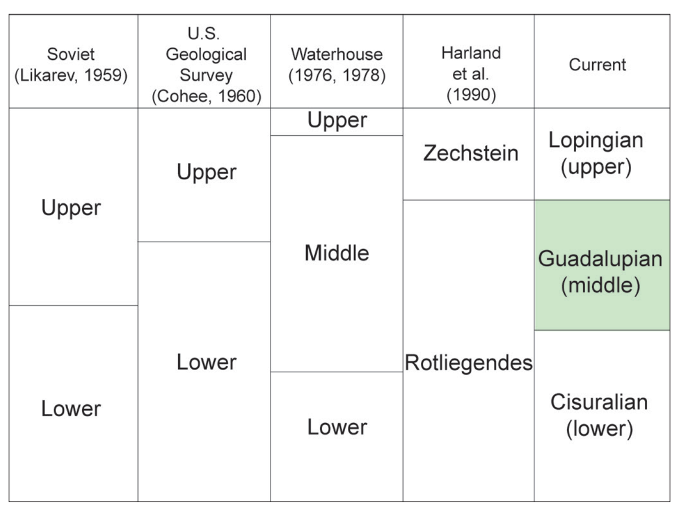

FIGURE 3. Selected subdivision of the Permian System into series compared to the currently accepted Permian series.

Guadalupian, and Lopingian (Fig. 1). The Guadalupian was the time of the most extensive marine transgression and the warmest climates of the Permian. More than one Large Igneous Province (LIP) erupted during the Guadalupian (Shen et al., 2020). Among ammonoids, the cyclolobids and ceratitidans first appeared during the Guadalupian. The advanced fusulinids (Verbeekinidae, Pseudodoliniacea) diversified, and the fusulinid taxa Neoschwagerinida, Polydexodinidae, and Tangchienidae appeared. The goniatitid cephalopods and most of the fusulinids disappeared at or by the end of the Guadalupian at a substantial extinction event (e.g., Chen and Shen, 2021). The Guadalupian was followed by a basal Lopingian major regression that is the boundary between the middle and upper parts of the Absaroka megasequence.

Girty (1902, p. 368) coined the term "Guadalupian Period" as "a regional name which shall be employed in a force similar to Mississippian and Pennsylvanian," and he subsequently (Girty 1909a, b) documented its macrofossil assemblages and advocated its correlation as younger than what was then considered Permian (but older than Triassic). Adams et al. (1939) used Guadalupian as a series, but some other workers (e.g., Glenister and Furnish, 1961) used it as a stage. Glenister et al. (1992) reviewed use of the term "Guadalupian" and formally proposed it as a series to include the Roadian, Wordian, and Capitanian stages. This proposal was approved by the Subcommission on Permian Stratigraphy and ratified by the ICS in early 2001 (Henderson et al., 2020; Fig. 1).

Glenister et al. (1992) argued that a three series Permian better represents the major physical and biological events of the Permian (see above). I also note that shorter chronostratigraphic units are better than longer units. Thus, shorter chronostratigraphic (temporal) units provide for more precise age determinations and correlations. So, in principle, three series are better than two series to divide Permian time into shorter time intervals.

GUADALUPIAN STRATA

The Permian marine strata in two mountain ranges that are about 240 km apart in southeastern New Mexico–west Texas, the Glass Mountains and Guadalupe Mountains (Fig. 2), have played a fundamental role in the development of Permian chronostratigraphy. The Glass Mountains outcrops of the original Wolfcamp and Leonard formations provided the basis for the lower Permian Wolfcamp and Leonard Series of Adams et al. (1939), now treated as stages. The Guadalupian Series is defined in the thick succession of marine strata in the Guadalupe Mountains of New Mexico–Texas. However, the lithostratigraphic units upon which the Guadalupian stage names Roadian and Wordian are based have their type sections in the Glass Mountains, whereas the Capitanian is based on the Capitan Limestone (Formation) in the Guadalupe Mountains.

Middle Permian strata in the two mountain ranges can be simply divided into "reef" (that word is used loosely here to recognize that some workers prefer other terms), back-reef, and basinal facies (Fig. 4). In the Glass Mountains, the Guadalupian section is (in ascending order) the Road Canyon, Word, Vidrio, Capitan, Gilliam, and Altuda formations (e.g., King, 1930; Hill, 1996). The Road Canyon Formation is 30–100 m thick and consists of bituminous limestone intercalated with some beds of shale, siltstone, and dolomite. The Word Formation is up to 450 m thick and consists of dolomitic limestone, sandstone, shale, and some chert. It is unconformably overlain by the Vidrio Formation, as much as 510 m of fine-grained dolomite with a single sandstone bed in its upper part. The Capitan Formation is bedded carbonate up to 400 m thick that represents the reef facies. The back-reef facies is the Gilliam Formation, as much as 800 m of dolomitic grainstone and stromatolitic dolomite interbedded with sandstone and evaporites. The basinal facies is the Altuda Formation, up to 120 m of thin-bedded dolomite, sandy limestone, and shale. Furnish

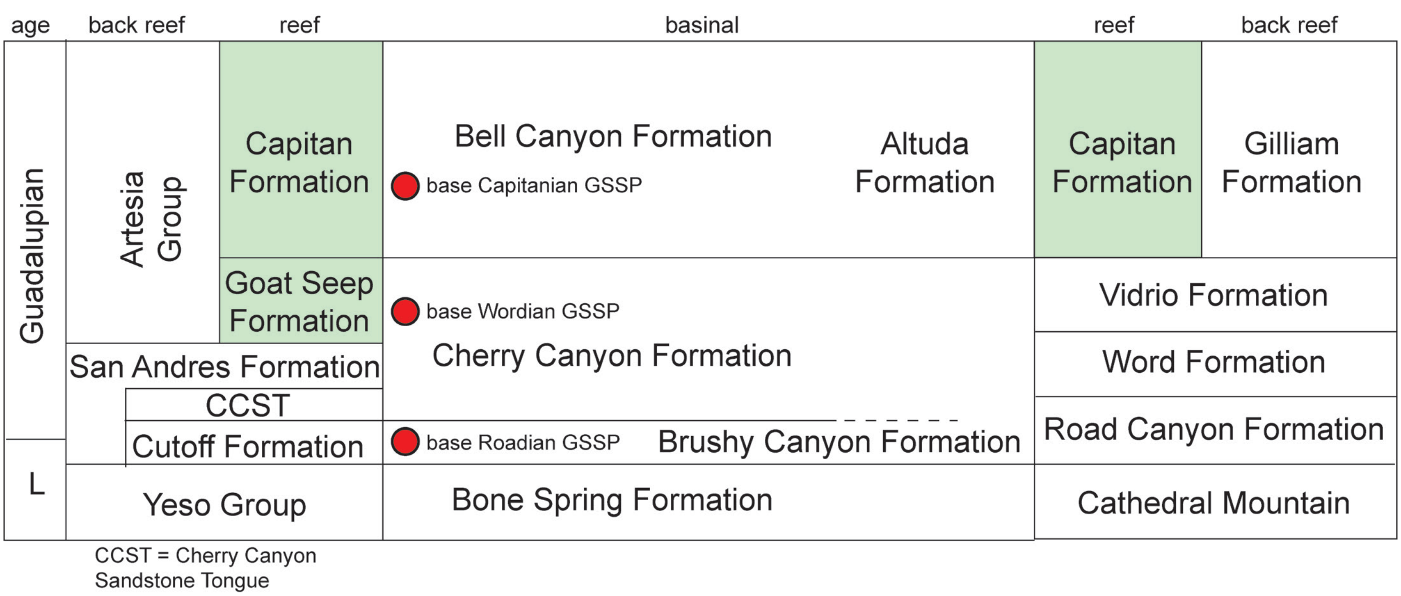

FIGURE 4. Correlation of Guadalupe Mountains (left of figure) and Glass Mountains (right of figure) showing Guadalupian lithostratigraphic units and locations of the three Guadalupian GSSPs (modified from Hill, 1996). The Brushy Canyon, Cherry Canyon, and Bell Canyon formations make up the Delaware Mountain Group.

(1973) based the Roadian and Wordian stages on the rich record of ammonoids of the Road Canyon and Word formations (see below).

The stratigraphic succession in the Guadalupe Mountains (Fig. 4) is more complex (e.g., King, 1948; Boyd, 1958; Hill, 1996). The Guadalupian strata begin in the Cutoff Formation, about 100 m thick and mostly black platy shale and lime mudstone, which encompasses the lower-middle Permian boundary. The overlying Cherry Canyon Sandstone Tongue is 60–90 m thick and mostly irregularly bedded arkosic sandstone. The Cutoff Formation and Cherry Canyon Sandstone Tongue are equivalent to the west with the upper part of the San Andres Formation, which crosses the early-middle Permian boundary. The overlying Goat Seep Formation is up to 400 m of thick-bedded to massive dolomite. It is considered a reefal facies and is overlain by the classic Permian reef, the Capitan Limestone (Fig. 5).

The Capitan Reef system is the most extensive and most studied reef system in the rock record. It encompasses a reef belt about 8 km wide and 650 km long that defines the western margin of the Delaware Basin (Fig. 2). About 450–600 m thick, the Capitan Limestone consists of a massive reef member of limestone and a forereef member that is thick-bedded limestone and bioclastic debris derived from the reef. The back-reef facies is the Artesia Group and has been the subject of much sequence stratigraphic study (e.g., Meade-Roberts et al., 1991). These strata grade northwestward into the deposits of a siliciclastic shelf that extended to Santa Fe and Bernalillo Counties in central New Mexico (Lucas, 2013).

The basinal facies is the Delaware Mountain Group, the (ascending) Brushy Canyon, Cherry Canyon, and Bell Canyon formations (Fig. 4). These formations are composed largely of fine-grained siliciclastic sediment and reach a total thickness of up to 1600 m near the basin center. Along the margin of the basin, however, the Bell Canyon and Cherry Canyon formations contain named carbonate members that, in the Guadalupe Mountains, grade into the shelf-margin facies of the Capitan/Goat Seep formations. It is in the strata of the Delaware Mountain Group that the three Guadalupian GSSPs are located (Fig. 4).

The Guadalupian strata in the Glass Mountains and the Guadalupe Mountains have extensive and distinctive fossil assemblages, particularly of biostratigraphically important fusulinids, brachiopods, ammonoids, and conodonts (e.g., Dunbar et al., 1960; Cooper and Grant, 1972; Furnish, 1973; Wilde, 1990; Henderson et al., 2020). However, the biostratigraphic primary signals for the Guadalupian stage GSSPs are based only on the hypothesized evolution of the species of the conodont genus *Jinogondolella*.

GUADALUPIAN STAGES

The Guadalupian Series as proposed by Glenister et al. (1992) consists of three stages (ascending): Roadian, Wordian, and Capitanian (Fig. 1). This chronostratigraphic scheme found rapid acceptance in the Permian Subcommission of the ICS (Jin et al., 1994, 1997). GSSPs have been defined for the bases of the Guadalupian stages in the Guadalupe Mountains of west Texas.

Roadian

In the Glass Mountains, the "first limestone member" of the Word Formation became the Road Canyon Member and was later elevated to formation rank (Cooper and Grant, 1964). It provided the basis for the Roadian Stage of Furnish (1973), who drew attention to its distinctive ammonoid assemblage, which includes diverse adrianitids, abundant *Eumedlicottia burckhardti*, and *Perrinites hilli*.

The base of the Roadian Stage was first defined by its GSSP in the El Centro Member of the Cutoff Formation at Stratotype Canyon along what has been called the "border fault zone" in the southwestern part of the Guadalupe Mountains National Park, Texas (Henderson et al., 2020, fig. 24.4). Its primary signal for correlation is the first appearance of the conodont *Jinogondolella nankingensis*, hypothesized to have descended from its ancestors among *Mesogondolella idahoensis* (Glenister et al., 1999; Mei and Henderson, 2002; Henderson et al., 2020).

Wordian

Furnish (1973) first used Wordian as a stage to refer to the distinctive ammonoid fauna of the Word Formation in the Glass Mountains of west Texas (also see Böse, 1917). Notably, this was the base of the Guadalupian Series of Furnish (1973), marked by the appearance of the widespread ammonoid *Waagenoceras*. The base of the Wordian is now defined by its GSSP in the Getaway Limestone Member of the Cherry Canyon Formation at Guadalupe Pass in the Guadalupe Mountains National Park, which is near the southern end of the Capitan escarpment (Henderson et al., 2020, fig. 24.5). Its primary signal for correlation is the first appearance of the conodont *Jinogondolella aserrata* in a hypothesized lineage as the descendant of *J. nankingensis* (Glenister et al., 1999; Mei and Henderson, 2002; Henderson et al., 2020). Yuan et al. (2021) recently provided a detailed description of the base Wordian GSSP section at Guadalupe Pass that focused on conodont biostratigraphy and chemostratigraphy.

Capitanian

Richardson's (1904) Capitan Limestone was named after the famous El Capitan promontory, a mountain of reef carbonate at the southern end of the Guadalupe Mountains escarpment in west Texas (Fig. 5). Miller and Furnish (1940) first used Capitanian as a biostratigraphic concept to refer to the *Timorites* ammonoid zone, and Furnish (1973) recognized the Capitanian as a stage based largely on ammonoid biostratigraphy. The base of the Capitanian is defined by its GSSP in the Pinery Limestone Member of the Bell Canyon Formation at Nipple Hill near the southern end of the Capitan escarpment in the Guadalupe Mountains National Park, Texas (Henderson et al., 2020, fig. 24.6). Its primary signal for correlation

FIGURE 5. Photograph of El Capitan in the Guadalupe Mountains shows the cliff-forming Capitan Formation “reef” above slope-forming strata of the forereef to basinal Delaware Mountain Group. Photograph by Joe Cancellare.

is the FAD of the conodont *Jinogondolella postserrata* within the hypothesized lineage from *J. nankingensis* to *J. aserrata* to *J. postserrata*. Shen et al. (2022) recently provided a detailed description of the base Capitanian GSSP section at Nipple Hill—its lithofacies, biostratigraphy, chemostratigraphy, and radioisotopic geochronology.

PROBLEMS AND PROSPECTUS

In the 2001 annual report of the Subcommission on Permian Stratigraphy, Wardlaw (2001, p. 4) reported that the ICS had accepted (ratified) the GSSPs proposed to define the Guadalupian Series and the bases of its constituent stages and that a “final write-up for Episodes [official publication of the IUGS] was completed and is now in review.” However, that *Episodes* article, a standard facet of all GSSP proposals, was never published (Henderson, 2020). In other words, none of the detailed stratigraphic data and conodont taxonomy necessary to support GSSP definitions were published.

Beginning in 2013, a new effort began to restudy the Guadalupian stage GSSPs (Henderson, 2020). This restudy (Shen et al., 2020, 2022; Yuan et al., 2021) has revealed problems with all three Guadalupian stage GSSPs:

1) The LO (lowest occurrence) of serrated gondolellids (i.e., *Jinogondolella nankingensis*) was considered to be the primary signal of the Roadian (Guadalupian), but such conodonts have been found about 100 m below the level of the base Roadian GSSP at Stratotype Canyon (Shen et al., 2020).
2) The primary signal of the base of the Wordian is supposed to be the LO of *Jinogondolella aserrata*, but conodonts of that species were not recovered by extensive sampling of the GSSP level (Yuan et al., 2021). Instead, the LO of *J. aserrata* at the GSSP is stratigraphically well below the GSSP level, and two morphotypes of *J. aserrata* were recognized by Yuan et al. (2021). Furthermore, those two morphotypes have different LOs. Clearly, the taxonomy of *J. aserrata* is now unclear, as is its stratigraphic range relevant to GSSP

definition. Yuan et al. (2021) concluded that a replacement GSSP for the base of the Wordian is needed, and I agree.

3) The base Capitanian GSSP at Nipple Hill only preserves about 5 m of Capitanian strata above the GSSP level (e.g., Henderson et al., 2020). Therefore, Shen et al. (2022) described what they call the Frijole reference section for the GSSP about 2.9 km to the west of Nipple Hill. At Nipple Hill, the LO of *Jinogondolella postserrata* (primary signal of the GSSP) is about 5 m above the base of the Pinery Member of the Bell Canyon Formation, but at the Frijole section it is about 19 m above the Pinery Member base. This means that either the stratigraphic range of *J. postserrata* at the Frijole section is incomplete or that sedimentation rates vary widely between that section and the section at Nipple Hill. The former seems likely and raises questions about how well and how widely the GSSP level can be correlated, even in a very small area.

Clearly, there is a need to redefine the GSSPs of at least the base of the Roadian and Wordian. The problems with the Guadalupian GSSPs reveal the politics of the ICS (which led to premature and unsubstantiated original definitions) and the relative lack of understanding and agreement on stratigraphic ranges and the taxonomy of the conodonts used as primary signals to define the GSSPs. Such problems have beset many conodont-based GSSPs (Lucas, 2018). Clearly, more work is needed and expected to redefine and refine Guadalupian chronostratigraphy as a part of the Permian timescale.

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