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Nautiloid mass kill and burial event, Redwall Limestone (Lower Mississippian), Grand Canyon region, Arizona and Nevada

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Keywords: Grand Canyon, Redwall Limestone, Anchor Limestone, Whitmore Nautiloid Bed, hyperconcentrated flow.

ABSTRACT

Billions of large orthocone nautiloids occur within an extremely persistent lime packstone bed of the Redwall Limestone through the Grand Canyon region, Arizona and Nevada. The platform facies of the packstone bed is 2 m thick at the top of the Whitmore Wash Member (Osagean Series of Mississippian System). Abundant nautiloids occur within the platform facies of the bed from Marble Canyon, Arizona westward 290 kilometers to Las Vegas, Nevada. The slope facies of the bed, where nautiloids are rare, is 3-to-14-m-thick, light-gray-weathering grainstone occurring northwest of the platform facies in southern Nevada, extreme northwestern Arizona, and southwestern Utah. Both platform and slope facies of the bed are named formally Whitmore Nautiloid Bed (WNB). Bed area exceeds 3 x 10^4 km^2 and bed volume exceeds 100 km^3.

Orthocone nautiloids assignable to the genus *Rayonnoceras* show evidence that bodies occupied the shells during mass kill and burial of an entire population. Shell orientation, inverse grading, outsized coral heads, and water-escape pipes indicate rapid deposition of the platform facies from a high-velocity, laminar, low-cohesion, fluidized dispersion of carbonate sand and silt. This moving dispersion can be called a hyperconcentrated flow (volume concentration sediment ≈ 35%, flow density ≈ 1.6 g/cm^3). Nautiloids and large coral heads were separated within the dispersion being supported as a raft above the highest-density, strongly fluidized, laminar flow. The flow event resembles the process that suspends lithic fragments and pumice clasts within a pyroclastic density current. WNB has internal structure resembling ignimbrite. The hyperconcentrated flow was initiated as a liquefied flow slide, probably in southwest Colorado, and hydroplaned toward southern Nevada at velocity ≈ 5 m/s through the carbonate platform in northern Arizona. When the flow encountered the slope in southern Nevada and southwest Utah, it was transformed into a turbulent, concentrated flow (volume concentration sediment ≈ 25%) depositing most of its sediment mass. Further westward in Nevada the flow lost its hydroplane and became a tractive current. This is the first documentation in the geological literature of a regionally extensive hyperconcentrated sediment gravity flow upon a marine carbonate platform.

INTRODUCTION

John Wesley Powell was the first geologist to encounter the Redwall Limestone within Grand Canyon. On August 9, 1869, Powell observed and described "one great bed of marble a thousand feet in thickness" (Powell, 1875) within what he named Marble Canyon (Fig. 1) on the Colorado River.[†] Powell's reflections on the strata within the river's gorge were prompted that day as he floated past the thick dolomite beds of what we know today as the Whitmore Wash Member of the Redwall Limestone. Soon, G. K. Gilbert (1875) began referring to various exposures within Grand Canyon as "Red Wall Limestone." With an average thickness of 200 m, Redwall Limestone forms the most persistent cliff within Grand Canyon, and, since the time of Powell and Gilbert, has been recognized as a characteristic element of the topography for which the Canyon has become famous.

† Data Repository item, Table DR1 (Locality register for study of Whitmore Nautiloid Bed) and Table DR2 (River log showing study locations of Whitmore Nautiloid Bed within Marble Canyon) accompanies this report.

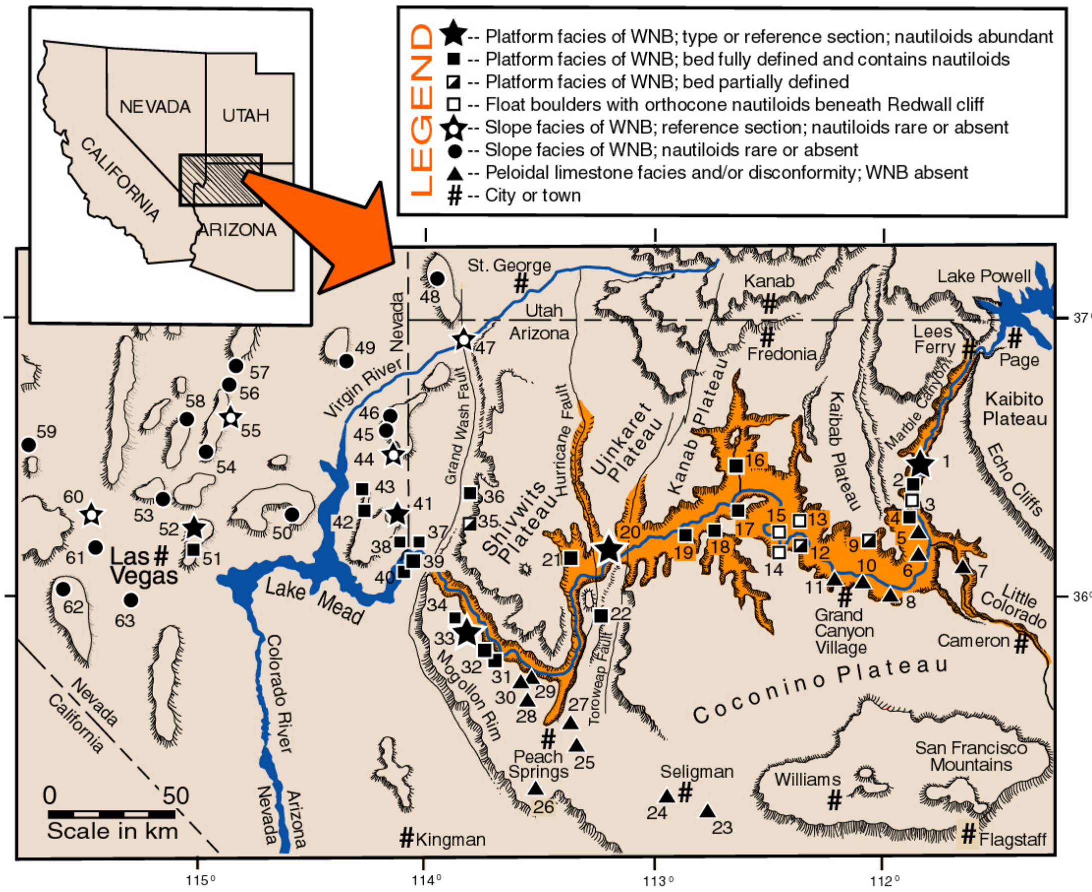

Figure 1. Location map for study of Whitmore Nautiloid Bed and associated strata. The platform facies of Whitmore Nautiloid Bed is defined at the type section and four reference sections: Whitmore Wash type section (location 20), Marble Canyon (location 1), Jeff Canyon (location 33), Garden Wash (location 41), and Sunrise Mountain (location 52). The slope facies of Whitmore Nautiloid Bed is defined at four reference sections: Whitney Pocket (location 44), Virgin River Gorge (location 47), Tungsten Gap (location 55), and Harris Springs Canyon (location 60). A complete locality register describing the type section, reference sections and supplementary sections is found in the Data Repository item, Table DR1.

Redwall Limestone has been given formation status within formal stratigraphic nomenclature. McKee (1963) divided and defined the Redwall Limestone using four members. In ascending order the four divisions within the Redwall are the Whitmore Wash Member, the Thunder Springs Member, the Mooney Falls Member, and the Horseshoe Mesa Member (Figure 2). In their monograph *History of the Redwall Limestone*, Edwin D. McKee and Raymond C. Gutschick (1969) described in detail this Lower Mississippian formation's stratigraphy and sedimentology. Concerning the contact between the Whitmore Wash and Thunder Springs Members within Grand Canyon, McKee and Gutschick (1969, p. 37) wrote, "In most sections the thin beds of alternating chert and limestone of the Thunder Springs Member seem to rest uniformly and evenly upon the uppermost thick bed of the Whitmore Wash Member." McKee informally recognized his "uppermost thick bed of the Whitmore Wash Member," and its composition and texture were generalized with the rest of the dolomite in the Whitmore Wash type section. McKee and Gutschick did not describe this bed's distinctive paleontological content within Grand Canyon.

Gutschick measured numerous stratigraphic sections of Redwall Limestone south of Grand Canyon (McKee and Gutschick, 1969). The Thunder Springs Member looses its abrupt lower boundary of thin-bedded lime wackestone, mudstone and chert south of Grand Canyon. The uppermost bed of the Whitmore Wash Member was uniquely described south of Grand Canyon as a massive oölitic and peloidal limestone as much as 8 m thick. This oölitic limestone measured by Gutschick occurs as a lighter colored zone within a darker gray dolomite sequence. Gutschick recognized oölitic limestone as very persistent in the Chino Valley area extending eastward beneath Williams and Flagstaff into the Little Colorado River drainage. South of Grand Canyon this oölitic limestone was used to define the Whitmore/Thunder Springs boundary. McKee and Gutschick did not describe any nautiloid fossils from the Whitmore Wash Member of Redwall Limestone within Grand Canyon or south of Grand Canyon.

The description and sedimentologic interpretation of McKee and Gutschick's "uppermost thick bed" is the purpose of this research report. We seek to understand the composition, texture, structure, external form and stratigraphic association of the persistent carbonate bed for the purpose of delineating its sedimentary process.

REGIONAL STRATIGRAPHY

Strata equivalent to Redwall Limestone have been recognized in Nevada, California, Utah, Colorado and New Mexico. Stevens et al. (1993) recently revised Lower Mississippian stratigraphic nomenclature for southern Nevada. The Monte Cristo Group of southern Nevada is composed of four formations directly equivalent in sequence and overall composition to Redwall Limestone. Figure 2 depicts regional correlation of Redwall Limestone westward into

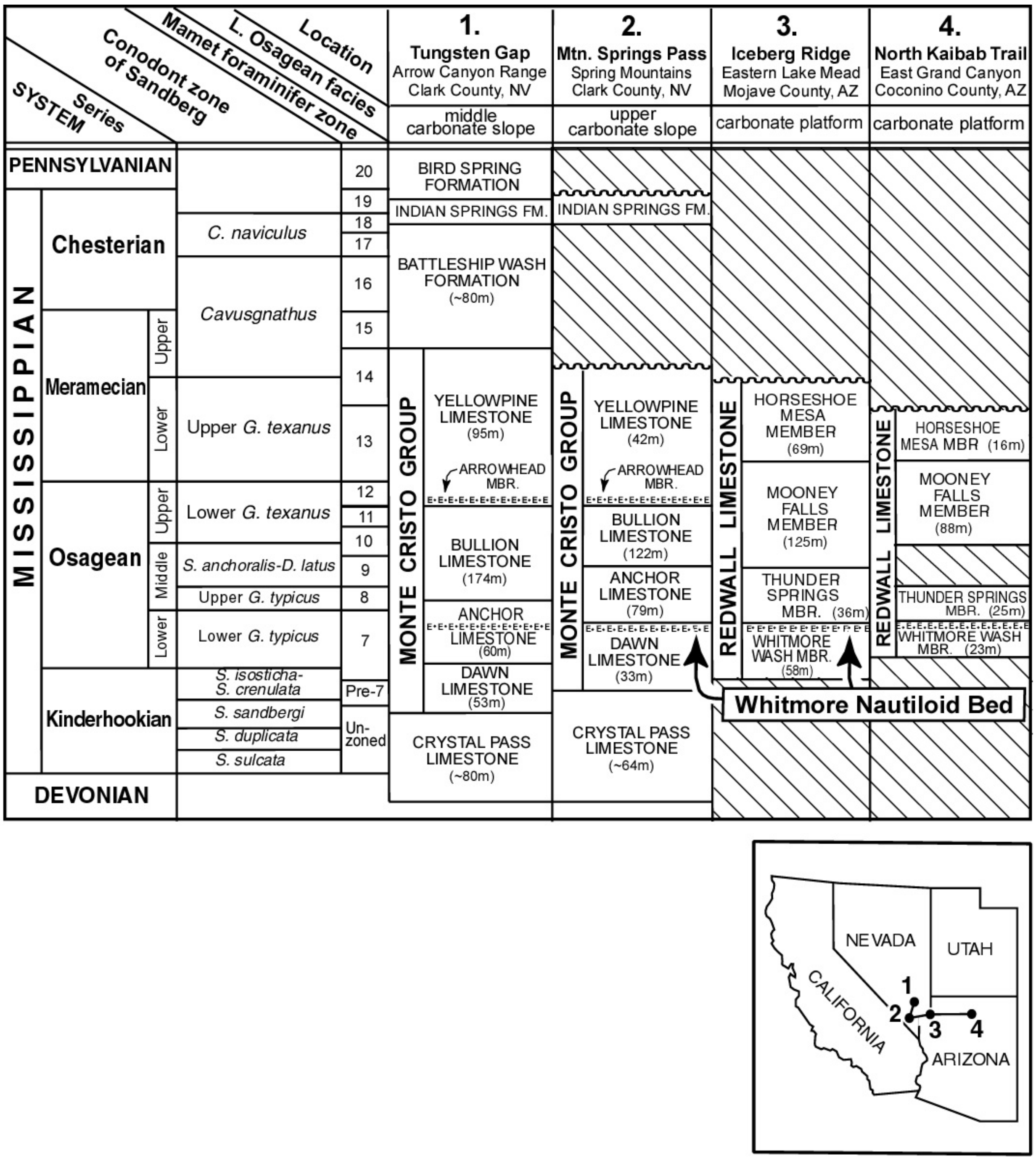

Figure 2. Regional correlation chart for Mississippian strata of northern Arizona with southern Nevada. Two thin but persistent Osagean lithostratigraphic units are the Arrowhead Member and Whitmore Nautiloid Bed. According to facies models of Poole and Sandberg (1991), the lower Osagean strata straddled a carbonate platform deepening westward into a carbonate slope. Nevada strata nomenclature follows revisions of Stevens et al., 1993. Conodont zones are for western U.S. by Sandberg (Poole and Sandberg, 1991) and Foraminifer zones are by Mamet (Mamet and Skip,1970).

Nevada. The distinctive cherty, thin-bedded dolomites or limestones of the Thunder Springs Member in western Grand Canyon have lithostratigraphic correlation to the cherty beds of the Anchor Limestone (formation status in nomenclature of Stevens et al., 1993) in the Lake Mead area of Nevada. The Whitmore Wash Member in western Grand Canyon correlates with the Dawn Limestone (formation status in Stevens et al., 1993) in the Lake Mead area of Nevada.

The upper part of the Whitmore Wash Member of the Redwall Limestone in the Grand Canyon region has been assigned to the Lower Osagean Series of the Lower Mississippian System (Beus, 1989). Conodonts from the upper Whitmore Wash Member indicate the *Gnathodus typicus* biozone of the Osagean on Iceberg Ridge (Ritter, 1983) and on the Kaibab and Bright Angel Trails (Walter, 1976; Beus, 1989). The lower part of the Whitmore Wash Member has conodonts indicative of Kinderhookian (Racey, 1974; Ritter, 1983). The Lower *G. typicus* conodont zone appears in the uppermost bed of the Dawn Limestone at Mountain Springs Pass (Stevens et al., 1993), but the uppermost beds of the Dawn Limestone at Tungsten Gap in the Arrow Canyon Range are Kinderhookian with the *G. typicus* zone occurring in the overlying Anchor Limestone (Pierce, 1969; Pierce and Langenheim, 1974; Poole and Sandberg, 1991).

Two thin but persistent Osagean lithostratigraphic units confirm biostratigraphic correlation between northern Arizona and southern Nevada. These two units are shown in Figure 2. The first is the Arrowhead Member at the base of the Yellowpine Limestone of the Monte Cristo Group (member, formation and group terms of Stevens et al., 1993). The Arrowhead Member of the Yellowpine Limestone is calcareous shale, usually only a few m thick, and contrasts strongly with the very pure carbonate and chert that dominate the Monte Cristo Group. The Arrowhead Member signals an unusual regional appearance, and then disappearance, of siliciclastic sedimentation. The diverse open-marine fauna of the Arrowhead includes Upper Osagean conodonts indicating the *G. texanus* zone and "orthoceratid nautiloids and large gastropods, in addition to large horn corals and Syringopora colonies" (Poole and Sandberg, 1991). In the Virgin River Gorge in extreme northwestern Arizona, Redwall Limestone is described with the Arrowhead Member occurring at the boundary between the Mooney Falls Member and the Horseshoe Mesa Member (Steed, 1980; Hintze, 1986). South of the Virgin River Gorge in the Virgin Mountains of northwestern Arizona, the Arrowhead Member is reported at thickness of 10 m (Bohannon, 1991; Bohannon and Lucchitta, 1991; Bohannon et al., 1991; Williams et al., 1997). Although the Arrowhead Member appears in the Muddy Mountain thrust block in the Lake Mead area in Nevada (Langenheim, 1956), it has not been reported at the northeastern end of Lake Mead in the South Virgin Mountains (Brady et al., 2000) or on Iceberg Ridge, 8 km beyond the west end of Grand Canyon on the Arizona side of Lake Mead (Beus, 1979). Foraminifera of the Redwall Limestone in eastern Grand Canyon have been used to assign the uppermost Mooney Falls Member and entire Horseshoe Mesa Member to the Meramecian Series. Therefore, the Arrowhead siliciclastic interval (Osagean Series, Lower *G. texanus* conodont zone) appears to correlate with strata in the middle Mooney Falls Member of Grand Canyon without obvious lithologic evidence of siliciclastics.

The second regionally persistent Osagean lithostratigraphic unit is "the uppermost thick bed of the Whitmore Wash Member" described in the Grand Canyon by McKee and Gutschick(1969). This bed appears to correlate with the 3-m-thick "pelmatozoan lime packstone" which forms the upper bed of the Dawn Limestone at Mountain Springs Pass in the Spring Mountains of Clark County, Nevada (Belasky, 1988), and the 9-m-thick, light-gray weathering crinoidal grainstone bed ("unit TG M-17") within the middle of the Anchor Limestone at the Arrow Canyon Range in Clark County, Nevada (Pierce, 1969). This later occurrence of a widespread light-gray weathering crinoidal limestone was also distinguished in lithologic description of the Anchor Limestone during mapping of the Arrow Canyon Range (Page, 1992). The correlation between Grand Canyon, Mountain Springs Pass and Arrow Canyon Range is indicated in Figure 2 where this stratigraphic unit is called "Whitmore Nautiloid Bed." Regionally, the bed marks a distinctive change upward within strata from thicker-to-thinner bedding and from coarser-to-finer sediment. The description of this persistent Lower Osagean stratigraphic unit is the purpose of the present report.

Lower Osagean strata occur in east-central California in the northern Death Valley area. The uppermost beds of the Tin Mountain Limestone contain Lower *G. typicus* conodonts and are abruptly overlain, conformably, by finer-textured and thinner-bedded lime mudstone and wackestone of the new Leaning Rock Formation (Stevens et al., 1993). Jones (1989) measured detailed stratigraphic sections within the Tin Mountain Limestone and documented the occurrence of unidentified nautiloids near the top of the formation. Peck (1951), Gordon (1964) and Russell *et al.* (2001) report the large orthocone nautiloid

Rayonnoceras in the Tin Mountain area, however, these occurrences appear to be within Upper Mississippian strata.

In southwestern Utah, Hintze (1986) adopted McKee's Redwall Limestone terminology for the Beaver Dam Mountains. Northward in west-central Utah a massive and widespread bed of crinoidal grainstone at the top of the Joana Limestone contains Lower *G. typicus* conodonts ("encrinite" of Poole and Sandberg, 1991). The crinoidal limestone bed is 10 m thick in the Silver Island Mountains and 8 m thick in the Deep Creek Mountains, Utah (Poole and Sandberg, 1991). The Joana Limestone is overlain conformably by the finer-grained and thinner-bedded sediments of the Delle Phosphatic Member at the base of the Woodman Formation. The appearance of lime mudstones at the base of the Woodman Formation marks the abrupt onset of the geochemically and petrographically distinctive condition called the "Delle phosphatic event" (Silberling and Nichols, 1991; Jewell et al*.,* 2000).

According to Parker and Roberts (1963), the Osagean cherty carbonate of the Thunder Springs Member is widely traceable on subsurface electric logs from Black Mesa Basin of northeastern Arizona, into Paradox Basin of southeast Utah, and into San Juan Basin of southwest Colorado and northwest New Mexico. In the Paradox and San Juan basins the cherty interval is near the base of what is there called the Leadville Limestone. The cherty interval in the Paradox and San Juan basins overlies carbonate apparently equivalent to the Whitmore Wash Member (Parker and Roberts, 1963). However, north of San Juan Basin in the San Juan Mountains of Colorado, the Whitmore-equivalent strata within the Leadville appear to be missing. In the San Juan Mountains of southwestern Colorado the thin Leadville Limestone is mostly Upper Osagean (Mamet foraminiferal zone 9), whereas strata equivalent to the Whitmore Wash Member (Lower Osagean, Mamet foraminiferal zone 7) appear to be absent (Armstrong and Mamet, 1976; Armstrong and Holcomb, 1989). At Rockwood Quarry north of Durango, Colorado, the Leadville Limestone is 34.8 m thick (Armstrong and Mamet,1976), the lower portion being cherty and correlated with the Thunder Springs Member of the Redwall and the upper portion being correlated with the Mooney Falls Member (Parker and Roberts, 1963). A thin synsedimentary carbonate breccia and a significant disconformity at the base of the Leadville Limestone at Rockwood Quarry may mark what remains of the Lower Osagean in the San Juan Mountains (Armstrong and Mamet, 1976).

Regionally, the Redwall Limestone and Monte Cristo Group have been interpreted as accumulated on a broad marine platform in Arizona that transitioned northwestward into a marine slope or ramp environment (McKee and Gutschick, 1969; Rose, 1976; Gutschick et al., 1980; Stevens et al., 1991; Albright, 1991; Poole and Sandberg, 1991). Measured stratigraphic sections (e.g., Figure 2) and regional isopach maps (Parker and Roberts, 1963; McKee and Gutschick, 1969; Condon, 1995) indicate the overall thickening of Mississippian strata northwestward toward a foreland basin in eastern Nevada and the Antler orogenic highland of central Nevada (Stevens et al*.,* 1991). The zero isopach line of the Mississippian System in southwestern Colorado, east-central Arizona, and northwestern New Mexico is supposed to be near the ancient shoreline (Armstrong and Holcomb, 1989). Numerous authors (McKee and Gutschick, 1969; Rawson and Kent, 1979; Skipp, 1979; Beus, 1989; Poole and Sandberg, 1991) interpreted the Whitmore Wash Member regionally as the first stage of the major southeastward marine transgression across a shallow marine platform. Rawson and Kent (1979) and Beus (2003) supposed that crinoidal packstone beds of the uppermost Whitmore Wash Member in Grand Canyon were deposited by quiet water in a shallow, open-marine shelf or platform at the time of the maximum marine transgression.

WHITMORE NAUTILOID BED (WNB)

McKee defined the Whitmore Wash Member of the Redwall Limestone at an outcrop on the up-thrown side of the Hurricane fault just north of the Colorado River in Whitmore Wash in the central Grand Canyon. The location of the type section is shown in Figure 1 (location 20). McKee described the Whitmore Wash Member as 31 m (101 feet) thick composed of yellowish-gray to light-brownish-gray, finely crystalline, even-grained and very thick-bedded dolomite. The Whitmore Wash Member was defined at its type section as overlain by thin-bedded, rhythmic chert and dolomite that represent what McKee called the Thunder Springs Member.

Definition of Whitmore Nautiloid Bed

Figure 3 shows the uppermost several meters of the Whitmore Wash Member and the lower Thunder Springs Member at the type section studied by McKee. The "uppermost thick bed" of the Whitmore Wash Member is well exposed as a cliff. Because of the paleontological and sedimentological importance of the “uppermost thick bed,” it needs to be recognized specifically and described. The bed is here formally named “Whitmore Nautiloid Bed” (hereafter WNB). This uppermost bed at the Whitmore type section is massive, finely crystalline dolomite, 2 m in thickness. The finely crystalline dolomite replaces the packstone texture of the original lime sediment. The bed weathers to light gray and often medium-gray to purplish-gray strongly mottled with lighter yellowish-gray vertical pipe structures, especially in its upper half. The bed contains three to six stylolites. WNB is here defined at the top of the

Figure 3. Redwall Limestone at the Whitmore Wash type section (location 20 in Fig. 1). Whitmore Nautiloid Bed (WNB) is 2-m thick composed of massive dolomite at the level where the man is standing. WNB is overlain conformably by the lower chert/carbonate rhythmites of the Thunder Springs Member.

Whitmore Wash type section at its boundary with the abruptly overlying thin rhythmite beds composed here of alternating chert and dolomite beds that form the base of the Thunder Springs Member. The generalized description of the stratigraphic interval is shown in Figure 4.

A noteworthy characteristic of WNB is its marine fossil content. Crinoids, corals, brachiopods, gastropods and bryozoans are common, but the most extraordinary fossils are large orthocone nautiloids. Although conditions for observation of nautiloids are generally poor in the cliff of weathered dolomite at the type section (Fig. 3), large, indistinct circles, some more than 10 cm diameter, exposed on the west-facing cliff just north of the type section contain internally the septate structure distinctive of orthocone nautiloids. Septate structure was demonstrated by sawing dolomite through the center of these circular features. These poorly displayed nautiloids occur at a single level within WNB about one meter below the lowest overlying thin, carbonate and chert bed at the type section of the Whitmore Wash Member.

Characteristics of WNB within the type section allow four defining characteristics to be recognized: (1) thick, massive bed with inverse grading in lower half, (2) position below a thin-bedded carbonate rhythmite interval, (3) vertical to subvertical pipe structures in upper half of bed, and (4) orthocone nautiloids occurring along a nearly coplanar horizon within the bed. These four defining characteristics allow the platform facies of the bed to be located elsewhere.

In central Grand Canyon east of the type section, WNB was observed in outcrop in National Canyon (location 19), Havasupai Canyon (location 18), Matkatamiba Canyon (location 17), and Kanab Canyon (location 16). Orthocone nautiloids assignable to *Rayonnoceras* occur in concentrations often 2 fossils per m^2 on a single coplanar horizon within the bed. Nautiloids longer than 1 m length are not uncommon. The bed maintains remarkable constancy in thickness at 2.0 ± 0.1 m.

In several side canyons within central Grand Canyon the lower Redwall Limestone is exposed as the characteristic cliff inaccessible to direct observation. Float boulders containing mottled pipe structures, stylolites, and large orthocone nautiloids were observed below the Redwall cliff in Kanab Canyon (location 16), Elves Chasm (location 14), Blacktail Canyon (location 15), and along the North Bass Trail (location 13). An extraordinary display of float boulders with mottled color and large orthocone nautiloids occurs in Blacktail Canyon. The large alcove with Redwall cliff has supplied the lower drainage within Blacktail Canyon with more than 20 dolomite boulders observed with mottled color and large nautiloids. The most interesting float boulder was found in the drainage channel below the Great Unconformity in lower Blacktail Canyon. The 2-m-diameter dolomite boulder displays densely packed pipe structures in its upper half, 5 bedding-parallel stylolites, and 7 coplanar nautiloids around its perimeter. Because a very broad cliff supplies float boulders to the drainage channel, nautiloids must be widely distributed within the cliff in Blacktail Canyon.

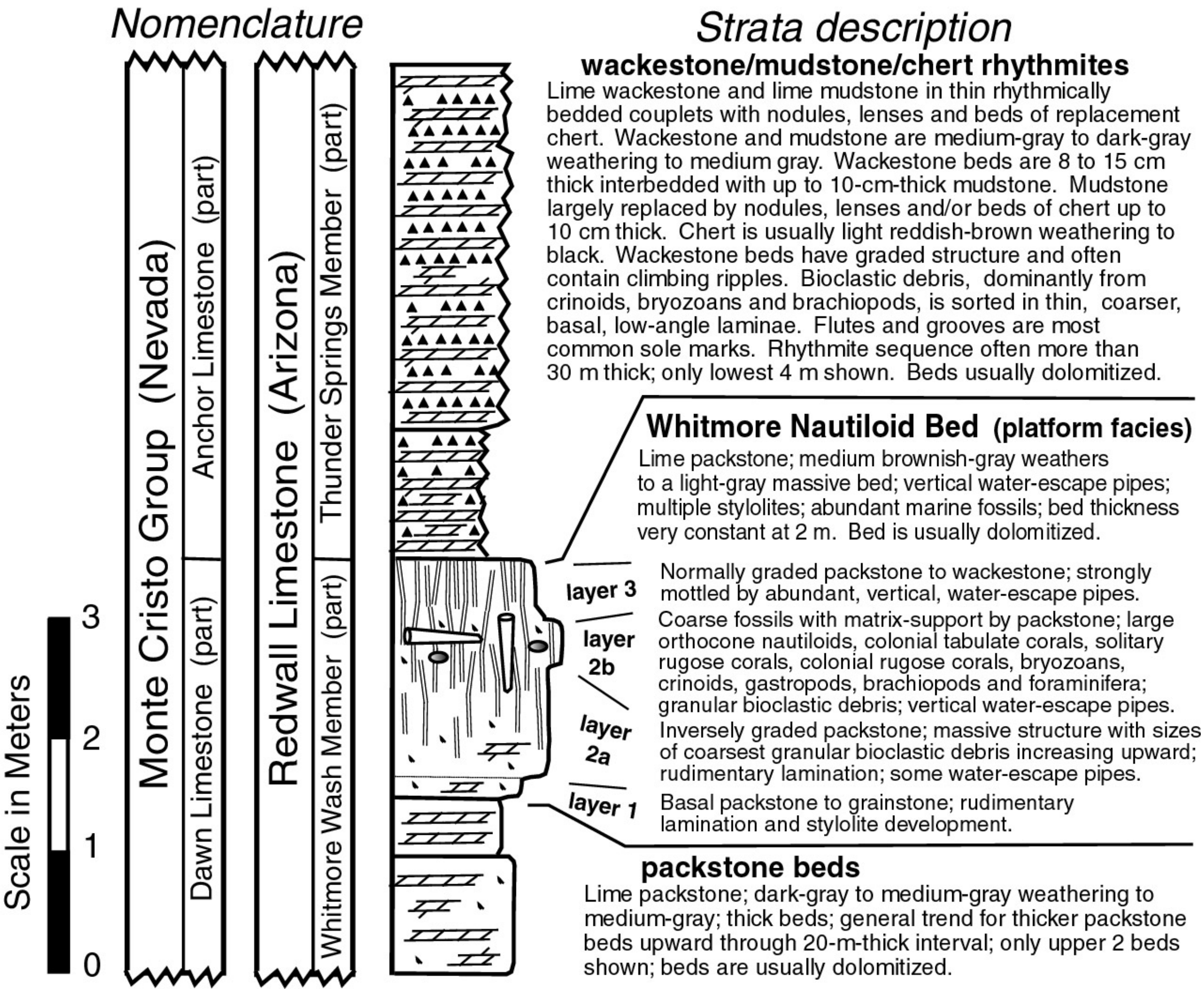

Figure 4. Stratigraphic section of the platform facies of Whitmore Nautiloid Bed generalized at the type section (Whitmore Wash) and four reference sections (Marble Canyon, Jeff Canyon, Garden Wash and Sunrise Mountain).

Platform Facies of Whitmore Nautiloid Bed

Defining characteristics at the type section of Whitmore Nautiloid Bed (WNB) in Whitmore Wash can be recognized elsewhere in Grand Canyon of northern Arizona, westward into southern Nevada, and northward into southern Utah. In addition to the type section at Whitmore Wash in central Grand Canyon, four other reference sections for Whitmore Nautiloid Bed are designated by the star symbol in Figure 1. These reference sections are Marble Canyon in eastern Grand Canyon (location 1), Jeff Canyon in western Grand Canyon (location 33), Garden Wash within the South Virgin Mountains north of Lake Mead (location 41), and Sunrise Mountain northeast of Las Vegas (location 52). The type section, the four reference sections, and the associated supplementary sections (Fig. 1) define the platform facies of WNB.

During May 1966 a party of Colorado River rafters first discovered nautiloids within WNB at an obscure side canyon within Marble Canyon (Breed, 1969). The side canyon is now enshrined on river logbooks as Nautiloid Canyon (Fig. 1, location 1). Eighty large orthocone nautiloids lie on a nearly coplanar surface of 320 m^2 within the massive dolomite bed on the water-polished floor of the canyon. However, the exposure of nautiloids is not optimum across a significant portion of the 320-m^2 surface. Where the exposure is optimum, the average density within the bed is greater than 2 nautiloids per m^2. The nautiloids occur within Nautiloid Canyon along a coplanar surface about 0.2 m below the top of the 2-m-thick bed.

The display of nautiloids within Marble Canyon is much more extensive than just the water-polished floor of Nautiloid Canyon.† At Marble Canyon in eastern Grand Canyon, WNB is well exposed on numerous flood-scoured ledges along the Colorado River beginning just downstream of "Little Redwall Cavern" (river mile 33.9) to beyond Nautiloid Canyon (river mile 34.8). High density of nautiloid fossils was observed, typically on a coplanar horizon about 0.7 m below the top of the bed. Weathered outcrops above the zone of flood scour within Marble Canyon have recognizable nautiloids extending downstream of Thirty-six Mile Rapid (river mile 36.1). These observations indicate that fossil density within the dolomite bed in Marble Canyon is greater than 1 orthocone nautiloid per m^2 along the course of the river through a distance of 3.5 km. High densities of nautiloids are also known from Buck Farm Canyon (location 2), a side canyon farther south within Marble Canyon.

In the western Grand Canyon excellent exposures in Jeff Canyon on the Hualapai Reservation are designated as a reference section. Remarkably, WNB is again a 2-m-thick massive bed. Here the bed is composed of limestone with the original packstone texture largely altered by diagenetic process and replaced by coarse sparry calcite. This limestone occurrence allows better field observations of both bed structure and fossil content than the more-common dolomite occurrences elsewhere in Grand Canyon. Concentration of coarser fossil material is especially evident within the Jeff Canyon limestone exposures. The coarsest material is dominated by crinoid columnals and occurs as a 0.4-m-thick zone near the middle of WNB. Large heads of the colonial corals (both syringoporoid and lithostrontionoid varieties) have a diameter sometimes over 20 cm. Solitary rugose corals resembling *Zaphrentites* are also common with some more than 5 cm long. Spiriferid brachiopods, gastropods, ammonoids and fragments of bryozoans are also present. The largest fossils observed, however, are orthocone nautiloids. These occur within Jeff Canyon at a horizon about 1.2 m from the top, always as a single, coplanar horizon within the bed. More than one hundred nautiloid fossils have been observed in Jeff Canyon with packing often exceeding 1 nautiloid per m^2 within the bed. Vertical, tubelike structures within the upper half of the bed create the distinctive mottled appearance.

Along the shore of Lake Mead on the Arizona-Nevada border, WNB is usually well exposed. On Iceberg Ridge (Fig. 1, location 39) the west-facing slope exposes the 50˚-east-dipping Redwall Limestone. At Iceberg Ridge the dolomite bed is exposed in cross section with nautiloids being poorly exposed in transverse cross section as indistinct circles. However, on the east-facing slope of nearby Boundary Point (location 37) just north of Iceberg Ridge, the east-dipping dolomite bed exposes bedding-parallel views with a stylolite surface displaying nautiloids prominently in longitudinal cross sections.

North of Lake Mead in the South Virgin Mountains of Nevada, WNB can be identified as the uppermost bed of the Dawn Limestone of the Monte Cristo Group. Here the thin chert and carbonate beds of the Anchor Limestone of the Monte Cristo Group overlie the bed abruptly. Within Garden Wash (Fig. 1, location 41) at the north end of Azure Ridge in the South Virgin Mountains, WNB is exposed within a strike valley as a persistent dolomite bed dipping eastward at 60°. Again the massive bed is a 2-m-thick dolomite, dominated by vertical pipe structures, and possesses the distinctive horizon of nautiloids, here about 0.7 m from the top of the bed. A stylolite within the bed aids in the extraordinary bedding-surface exposure of nautiloids. Corals are also well displayed at the horizon of the nautiloids. More than 250 nautiloid fossils were observed within WNB through the 350-m-long, strike-valley portion of Garden Wash.

At Frenchman Mountain (Fig. 1, location 51) and Sunrise Mountain (location 52) on the east side of Las Vegas, WNB displays its typical structure and composition. A good exposure within an unnamed canyon on the west side of Sunrise Mountain is designated as a reference section for the platform facies of WNB. Nautiloids are abundant having both vertical and horizontal orientations along a coplanar surface about 0.7 m below the top of the bed. Corals are also abundant, and the bed's internal structure appears very similar to exposures in Garden Wash and Lime Wash.

† Data Repository item, Table DR1 (Locality register for study of Whitmore Nautiloid Bed) and Table DR2 (River log showing study locations of Whitmore Nautiloid Bed within Marble Canyon) accompanies this report.

Slope Facies of Whitmore Nautiloid Bed

West of the platform facies of WNB, the bed thickens and its structural and compositional characteristics change significantly. This defines what can be called the slope facies of WNB. The slope facies of WNB is defined at four reference sections (Fig. 1, locations 44, 47, 55 and 60), one reference section being in extreme northwestern Arizona, and three being in Clark County in southern Nevada. Figure 5 shows the excellent exposure of WNB in Virgin River Gorge blasted from unweathered limestone in the road cut of Interstate

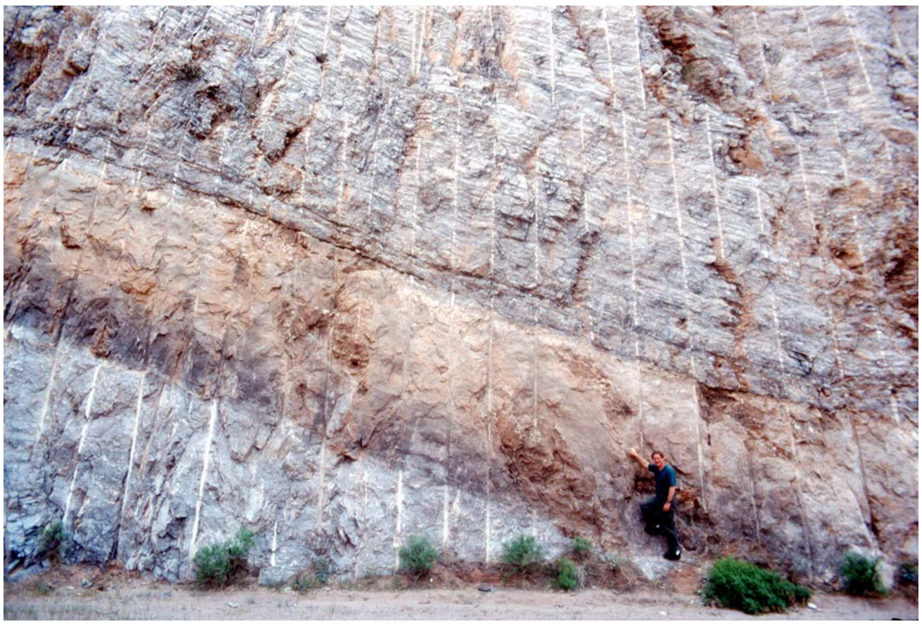

Figure 5. Slope facies of Whitmore Nautiloid Bed at the Interstate Highway 15 road cut within Virgin River Gorge in northwestern Arizona (location 47). Here the slope facies is a normally graded, 3.5-m-thick, lime grainstone bed at the level where the man is standing. The massive limestone bed at the top of the Whitmore Wash Member is overlain conformably by chert/limestone rhythmites of the Thunder Springs Member.

Highway 15 (Arizona mile marker 13.5) in extreme northwest Arizona (location 47). Here WNB is a massive, 3.5-m-thick, lime grainstone bed, with dispersed bioclastic material throughout the bed, and vertical water-escape pipes in its uppermost 0.5 m. Thin chert/limestone rhythmites here overlie the bed abruptly. Within Virgin River Gorge WNB displays normal grading and some internal lamination, with the largest coral fragments occurring at the base of the bed. The bed differs from the platform facies, however, by lack of the coarse fossil zone midway within the bed, and the bed lacks the inverse grading in its lower half. Sorting of grains increases producing grainstone rather than packstone. Consolidation lamination and possibly dish structure (Hurst and Cronin, 2001) may be common within the slope facies at Virgin Gorge, but these sedimentary structures are rare or lacking within the platform facies. No nautiloids were observed within the bed in Virgin River Gorge, but very rare nautiloids were encountered in float boulders on the north side of the river. The slope facies of WNB at the Virgin River Gorge resembles the 3-m-thick, light-gray-weathering packstone bed at the top of the Dawn Limestone at Mountain Springs Pass (location 62) originally described by Belasky (1988). The bed at Mountain Springs Pass contains rare orthocone nautiloids.

On the west face of the Virgin Mountains just north of Whitney Pocket (Fig. 1, location 44), WNB maintains its distinctive position just below the chert/carbonate rhythmites. However, here the slope facies of WNB is 8 m thick composed of three superimposed, massive, flow subunits, each superimposed flow subunit bearing abundant water-escape pipes in its upper half. These three subunits are each normally graded or massive, not showing the inverse grading characteristic of the platform facies of WNB. The slope facies at the Virgin Mountains resembles the several-m-thick, multiple beds just below chert/carbonate rhythmites in the Beaver Dam Mountains in southwestern Utah (location 48). These multiple flow units in the Beaver Dam Mountains occur at the top of the Whitmore Wash Member as described by Hintze (1986). No nautiloids were observed at these locations.

The slope facies of WNB occurs as thick, lighter-gray-weathering, multiple-flow units of 8-m thickness within the lower portion of the Anchor Limestone in the Muddy Mountains (Fig. 1, location 50). Northwestward from the Muddy Mountains, WNB establishes its position as light-gray-weathering grainstone within medium-gray-weathering limestone near the middle of the Anchor Limestone (e.g., locations 53, 55, 56, 57, 58 and 60). At the reference section in Tungsten Gap in the Arrow Canyon Range (location 55), the slope facies of WNB is represented by the persistent 9-m-thick, light-gray-weathering crinoidal grainstone ("unit TG M-17" of Pierce, 1969, and Pierce and Langenheim, 1974). The grainstone appears to be multiple flow units of uniform lithology, possesses indistinct internal lamination, lacks inverse grading, lacks outsized clasts, and lacks nautiloid fossils. The light-gray-weathering grainstone stands out among the darker-gray-weathering and thinner-bedded limestone immediately above and below. Aerial observation shows this light-gray grainstone is persistent within the Arrow Canyon Range. The grainstone thickens slightly northward being 10.5 m thick at Arrow Canyon (location 56) where it is also characterized by multiple, normally graded subunits. Persistent light-gray-weathering grainstone is 11.5 m thick northward in the Meadow Valley Mountains (location 57) and is distinctive enough to be described by Webster and Lane (1987) informally as the entire "middle member" of the Anchor Limestone. Thinner light-gray-weathering grainstone within the middle of the Anchor Limestone also occurs in the Las Vegas area, the excellent outcrop in Harris Springs Canyon (location 60) being designated a reference section. Normal grading of subunits characterizes these occurrences of the slope facies of WNB. No inverse grading, no outsized clasts and no nautiloids were observed at these locations.

Disconformity and Marginal Peloidal Limestone Facies

The southern boundary of the platform facies of WNB appears to be a significant disconformity. South from Marble Canyon to Nankoweap Canyon (Fig. 1, locations 1 to 4), WNB maintains its typical thickness and structure. However, south of Nankoweap at Sixtymile Canyon (location 5), the bed is not present at the top of the Whitmore Wash Member and evidence of pronounced disconformity occurs. Figure 6A shows the northern side of Sixtymile Canyon where WNB is missing and a disconformity with about 5 m relief occurs at the Whitmore/Thunder Springs boundary. Evidences of pronounced, large-scale disconformity were observed at Hermit Canyon (location 11) and Bridge Canyon (location 29) near the southern boundary of WNB. At Bridge Canyon the Whitmore Wash Member thins from about 19 meters, its normal thickness, to zero, at the same time the Thunder Springs Member thickens dramatically.

South of the area of significant disconformity at the Whitmore/Thunder Springs boundary, dolomite dominates the Whitmore and Thunder Springs Members. Within the dolomite succession a peloidal limestone bed appears as what Gutschick called the upper bed of the Whitmore Wash Member (McKee and Gutschick, 1969). This persistent limestone bed at the top of the Whitmore Wash Member is referred to by McKee and Gutschick as a massive "oölitic limestone" up to 8 meters thick. Because peloids are more common than oöids and bioclastic debris, this bed should best be called "peloidal limestone." This bed is very widespread, being especially evident in Chino Valley, where it thickens southward (McKee and Gutschick, 1969). Figure 6B shows Gutschick's drawing of the "oölitic limestone" southwest of Seligman (near location 23). Here the limestone bed occurs in its normal dolomite sequence with significant disconformity above and below the bed. A similar peloidal limestone bed up to 5 m thick occurs on the Grandview Trail just north of Horseshoe Mesa (location 8). At this location the Whitmore Wash Member is abnormally thin (≈10 m, locally usually more than 25 m) with the peloidal limestone comprising most of the Whitmore Wash Member, and the Thunder Springs Member is abnormally thick (≈45 m, locally usually 25 m). Evidently, significant disconformity occurs in association with the massive peloidal limestone where it occurs as the uppermost bed of the Whitmore Wash Member. The two bounding disconformities associated with the peloidal limestone bed would seem to argue that the massive peloidal limestone is coeval with WNB to the north.

Lithofacies and Isopach Map

Figure 7 is a restoration of displaced WNB in the Basin and Range Province (west of Grand Wash fault) to its Mississippian position relative to the Colorado Plateau (east of Grand Wash fault). The restoration removes compressional deformation during the Sevier orogeny and extensional faulting during the Cenozoic. Up to 15 km of westward extension is removed for different blocks within the South Virgin Mountains (Brady et al., 2000). The Frenchman

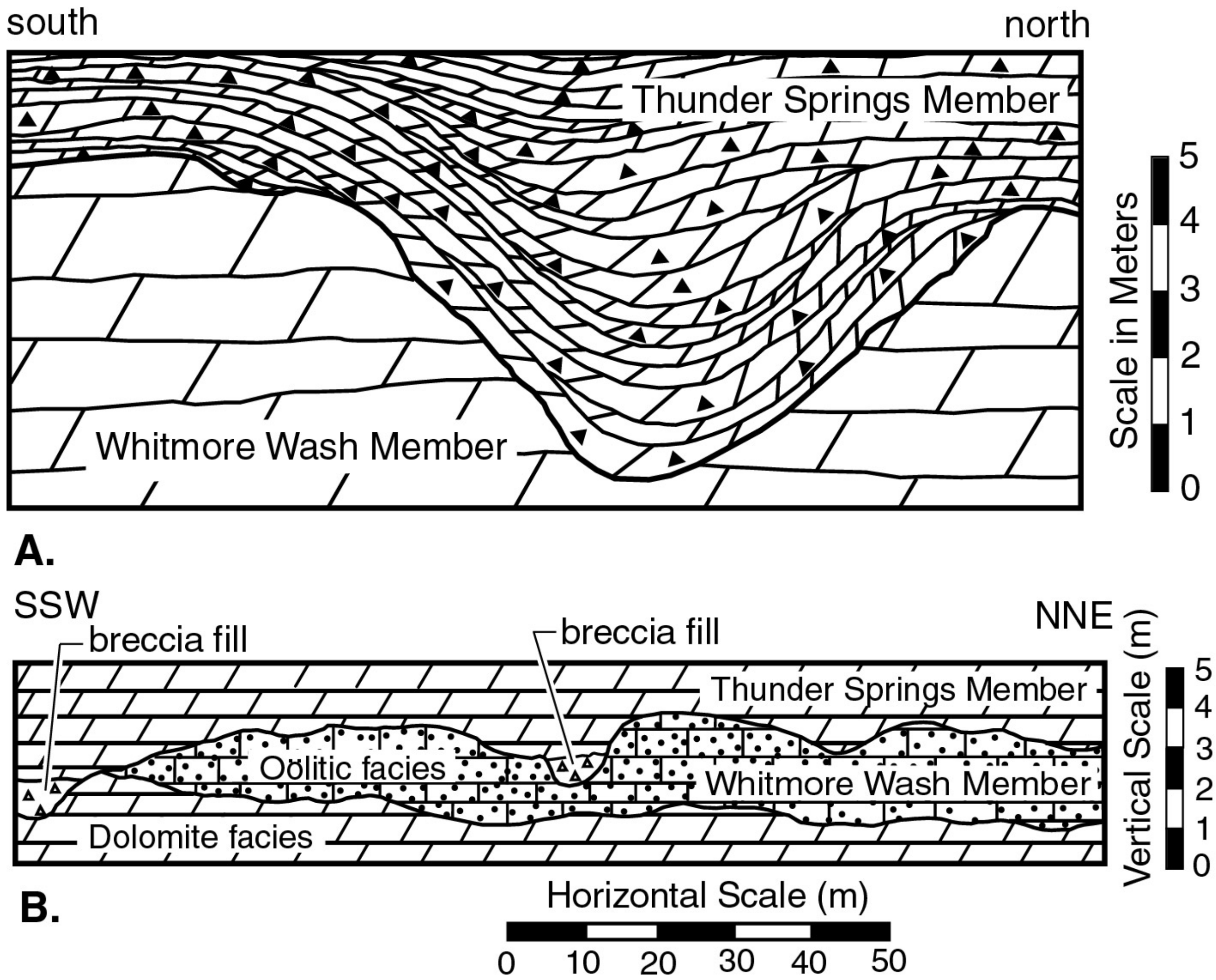

Figure 6. Disconformity at the position of Whitmore Nautiloid Bed in extreme eastern Grand Canyon and south of Grand Canyon. WNB is missing at these locations. **A** shows significant evidence of disconformity at Sixtymile Canyon (location 5) in extreme eastern Grand Canyon (no vertical exaggeration, after unpublished drawing by Kurt P. Wise). **B** shows disconformities above and below the widespread peloidal and oölitic limestone near Picacho Butte (near location 23) within a dolomite sequence (significant vertical exaggeration, after McKee and Gutschick, 1969, p. 32).

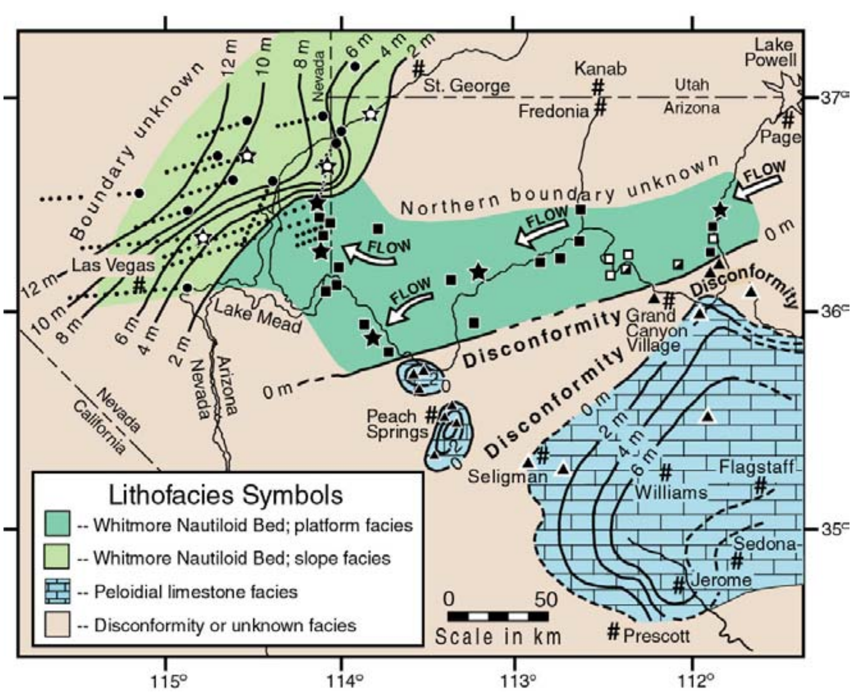

Figure 7. Lithofacies and isopach map of the stratigraphic interval associated with Whitmore Nautiloid Bed. Nevada locations have been restored to what is believed to be their original Mississippian positions relative to Colorado Plateau. Map location symbols defined in Figure 1. Distribution of peloidal limestone facies modified from isopach map of McKee and Gutschick (1969, p. 35).

Mountain block is restored ENE about 85 km to its original position just north of the South Virgin Mountains (Rowland et al., 1990; Duebendorfer et al., 1998). Restorations of the North Virgin and Muddy Mountains, as well as the Sevier orogenic belt, are more complex, most involving both compression and extension (Axen, 1984; Wernicke et al., 1988; Axen et al., 1990; Duebendorfer et al., 1998).

Figure 7 indicates lithofacies and isopach after the Mississippian restoration for the Basin and Range is completed. The platform facies of WNB after restoration extends westward a distance of 200 km from Marble Canyon, Arizona to South Virgin Mountains, Nevada. The north-south extent of the platform facies of WNB exceeds 75 km, extending from at least Squaw Canyon (location 36) on northern Grand Wash cliffs southward to Hindu Canyon (location 31) on the Hualapai Reservation. However, the northern boundary of WNB is likely concealed in the subsurface north of Grand Canyon and north of Grand Wash cliffs. The areal distribution of the platform facies of WNB, therefore, appears to exceed 1.5×10^4 km^2 (1.5×10^{10} m^2). With a density of nautiloids approaching 1 fossil per m^2, billions of nautiloid fossils are likely to occur within WNB throughout the Grand Canyon region. Because bed thickness is 2 m through an area in excess of 1.5×10^{10} square meters, the volume of the platform facies of WNB is at least 3×10^{10} m^3 (30 km^3). The massive-to-very-thick-bedded slope facies of the bed, where nautiloids are rare or absent, is 3-to-14-m thick, and occurs northwest of the platform facies in southern Nevada, extreme northwestern Arizona, and southwestern Utah. The slope facies of WNB occupies an area > 1.5×10^4 km^2 and a volume ≥ 75 km^3. The volume of this deposit could be much greater because the northwestern boundary of the slope facies has not yet been located. The southern, massive peloidal limestone facies, within which nautiloids are rare or absent, is up to 8 m thick, and forms the uppermost bed of the Whitmore Wash Member in southeastern Grand Canyon extending southward into central Arizona (area ≈ 1.5×10^4 km^2, volume ≈ 60 km^3). Together the three facies (platform facies, slope facies and adjacent peloidal limestone facies) occur though an area of > 4.5×10^4 km^2 in Arizona, Utah and Nevada. The two facies of WNB have volume > 100 km^3, and adding the adjacent peloidal facies, the total sediment volume in this stratigraphic interval is > 150 km^3.

DATA RELEVANT TO SEDIMENTARY PROCESS

Three types of data on WNB were obtained for the purpose of characterizing the sedimentary process that formed the bed: (1) the morphology, size and orientation of nautiloids, (2) the characteristics of water-escape pipes, and (3) the internal layered structure of the bed.

Nautiloid Morphology

Observations and measurement were made on more than one thousand nautiloid fossils within WNB. Figures 8 shows representative specimens of large, orthocone nautiloids that are abundant within the platform facies of WNB. Nautiloids were studied in cross sections and weathered outcrops of both dolomite and limestone. Internal anatomy is best studied on longitudinal surfaces sawed from blocks of limestone. Using photographs from the water-polished surface in Nautiloid Canyon, Flower (cited by Breed, 1969) tentatively identified the nautiloid as *Rayonnoceras*, the genus name introduced by Croneis (1926) from study of large cephalopods from the Fayetteville Shale (Upper Mississippian) of Arkansas.

A.


B

C.

Figure 8. Three examples of the nautiloid *Rayonnoceras* from WNB. **A** shows three-dimensional form of shell inclined within the bed (Garden Wash), **B** displays longitudinal section with rare occurrence of preservation of body cavity on left (Marble Canyon), and **C** shows siphuncle that is penetrated by the central canal with subspherical connecting rings and mural calcite (Marble Canyon).

Morphology of the septate portions of the shells indicates a single species of *Rayonnoceras* generalized in Figure 9. The siphuncle is generalized from displays of connecting rings seen in longitudinal cross sections. The conch is circular in cross section expanding at moderate rate, typically a 1 to 7 ratio with the siphuncle being subcentral. Camerae near the apical end are only partially filled with cameral calcite. Long siphuncular connecting rings have length-to-diameter ratios usually ranging from 1.0 (spherical) to 1.3, higher than all species of *Rayonnoceras* described from central and eastern North America as well as Europe (Turner, 1951; Gordon 1957, 1964). Mineralized connecting rings have only been observed in the apical ends of shells less than about 10 cm diameter. Either the animal did not make mineralized connecting rings in the oral chambers within shells greater than 10 cm diameter, or these larger connecting rings were destroyed by decay or rupture of the siphuncle. The body chamber, the non-septate and oral end of the conch, is usually collapsed or exploded, suggesting that the post-depositional decay of the tissue resident within the cavity usually caused rupture of the shell. Often when the apical end is crushed, horizontal shortening is evident, arguing that during burial the gas-filled chambers imploded while the tissue mass was still filling the siphuncle. According to Croneis (1926), the body chamber of *Rayonnoceras* is about one third of the length of the septate portion of the shell. Turner (1951) measured *Rayonnoceras* and found the body chamber length to be from 23 to 45% of the septate length of the conch.

Nautiloid Sizes

Sizes of nautiloids are best observed on bed-parallel surfaces. Because nautiloids are sometimes inclined to the surfaces of the bed, maximum length of shells is often not observed. Maximum measured shell diameter is a better indicator of the size of the shells. Figure 10 is the maximum-diameter histogram from measurements of 403 fossils. The mean maximum shell diameter measured is about 9.6 cm, with standard deviation of 4.3 cm. If shells enlarge at a ratio of 1 to 7, the mean diameter equates to a mean length of more than 0.6 m. These measured maximum diameters probably provide significant underestimates of the mean maximum diameter for three reasons. First, the maximum diameter is not always displayed on the outcrop, especially where fossils are observed on two-dimensional surfaces that pass randomly through the fossils. Second, the body cavity of the largest end of the shell is usually not preserved, usually being ruptured during compaction in the sediment. Third, fossils sometimes occur as broken segments with the larger section of the shell unavailable for measurement. These factors indicate the mean length of the original shells is about 0.8 m. The typical *Rayonnoceras* reconstructed in Figure 9 assumes the mean length of 0.8 m and a body chamber equivalent to 25% of the length of the shell. Because the largest nautiloid shells observed are more than 25 cm diameter, the largest fossils probably approach a length of 2 m. A lognormal probability density function seems to describe the maximum diameters in Figure 10 and suggests an entire "life assemblage" of nautiloids. These fossils could be thought of as indicative of a mass-kill event involving an entire population of a single species of nautiloids.

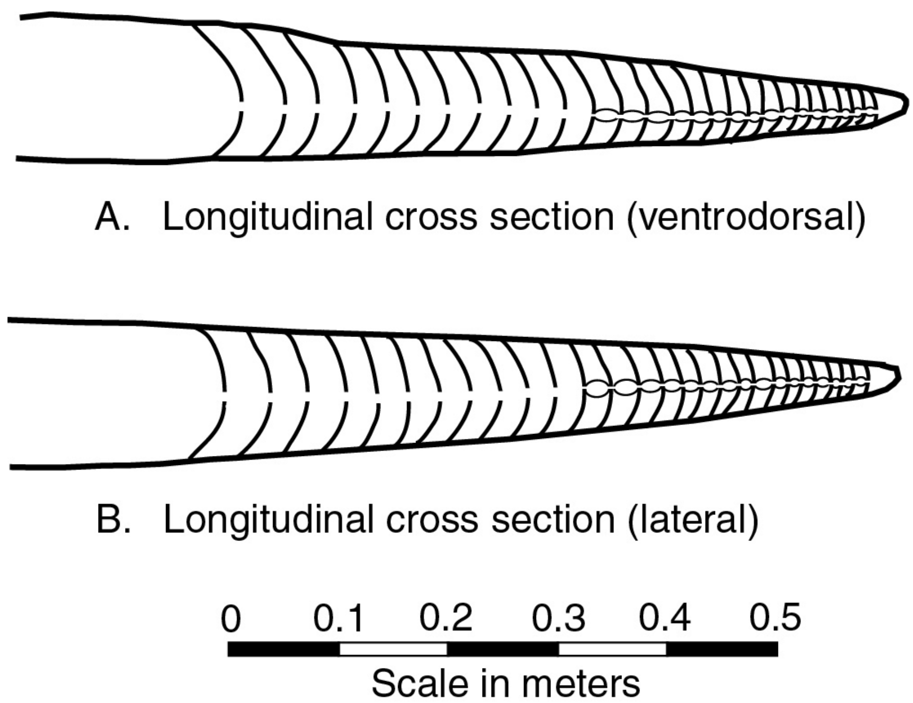

Figure 9. Reconstruction of a typical *Rayonnoceras* from Whitmore Nautiloid Bed. Longitudinal cross sections indicate the septate structure within the shell and the mineralized connecting rings surrounding the siphuncle.

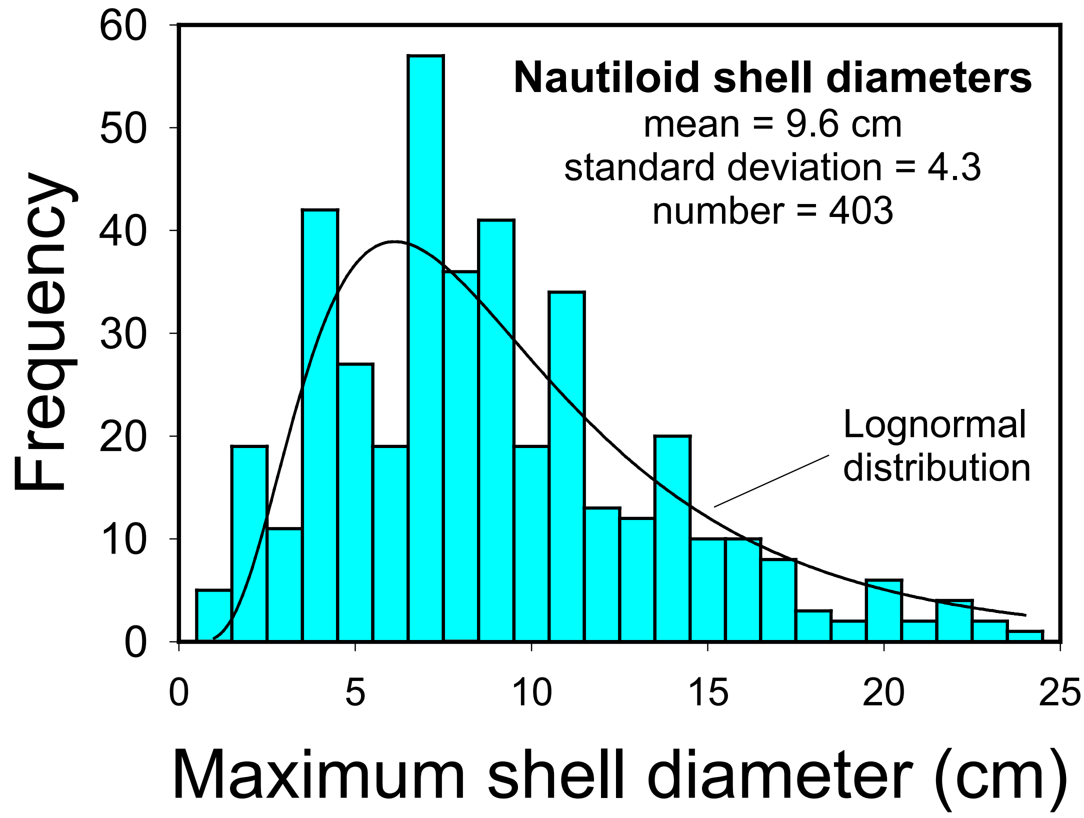

Figure 10. Size histogram of nautiloid shells from diameters measured in cross sections. The histogram was constructed from measurements of 403 shells from Marble Canyon, Jeff Canyon and Garden Wash.

Nautiloid Orientations

Orientations of nautiloids in both the horizontal and vertical planes were studied at Jeff Canyon, Marble Canyon and Garden Wash. Figure 11 shows a map of 21 nautiloids on a 9-m^2 horizon within WNB at Jeff Canyon. This exposure appears to be typical of nautiloid orientations within the coplanar horizon of the bed. About 75% (16 of 21 specimens in Fig. 11) have long axes approximately parallel to the horizon of WNB. Of those 16 nautiloids whose axes are along the horizon of the bed, there appears to be a deficiency of nautiloids with apical ends pointing southwest. Only one (specimen 15) has apical end pointing into the southwest quadrant, that specimen being a stubby, broken segment of a conch without a body cavity. About 25% of nautiloids (5 of 21 specimens in Fig. 11) are significantly inclined relative to the horizon with about 10% (nautiloids 6 and 13) being oriented about 45° to bedding, and about 15% (nautiloids 10, 11 and 20) being oriented perpendicular to bedding. One of the three vertical fossils (nautiloid 20) shows enough three-dimensional exposure to prove that it was embedded within the limestone with its apical end pointed downward within the bed.

Orientations of nautiloids relative to the horizontal and vertical planes of the bed were studied in detail at Marble Canyon and Garden Wash for the purpose of detecting an orientation pattern. The direction of the apical end of the shell was recorded relative to the plane of the bed. For orientations in the horizontal plane, nautiloid lengths at least twice the widths were chosen for measurement. In Marble Canyon (Fig. 12A) and Garden Wash (Fig. 12B) a total of 337 orientations were measured. Of that total, 288 nautiloids (85%) have plunge of the long axis of the shell less than 10° relative to the horizon of bedding, and 49 nautiloids (15%) have plunge greater than 10° relative to bedding. For the 49 nautiloids with plunge greater than 10° relative to the bed, more than 75% have plunge greater than 80° relative to the bed. In the cases where the vertical and near-vertical nautiloids displayed enough internal structure of septae, each showed apical end downward within the bed. None was observed with apical end upward. For Marble Canyon (Fig. 12A) the rose diagram shows 163 orientations in the horizon of the bed. For Garden Wash (Fig. 12B) the rose diagram shows 125 orientations in the horizon of the bed. Chi-squared statistical test of orientations in the horizon of the bed demonstrates the pattern shown in the rose diagrams is strongly nonrandom. For Marble Canyon the rose diagram shows a pronounced deficiency of nautiloids with apical ends pointing southwest. For Garden Wash there is a pronounced deficiency of nautiloids pointing west-northwest. The horizontal orientations appear to be tripolar. To these rose diagrams must be added the significant number of fossils with vertical orientations, apical ends downward. Four dominant directions of orientation (what can be called “quadrapolar orientation”) are evident at Marble Canyon and Garden Wash. The four directions are depicted next to the rose diagrams (Fig. 12).

What is the significance of the quadrapolar orientation pattern of nautiloids? This pattern contrasts strongly with the bipolar nautiloid orientation pattern of orthocone nautiloids from Morocco (Wendt, 1995). The bipolar orientation of nautiloids was interpreted as caused by shoaling of shells under the influence of a bi-directional current as could occur on a beach (Seilacher, 1973; Grahn, 1986). Theoretical and experimental studies show that elongate conical objects easily orient with long axes parallel to a unidirectional current, with apical ends upstream (Ferretti and Kriz, 1995). Laboratory flume studies of cones (Loubere, 1977) model the hydrodynamic and buoyancy characteristics of orthocone nautiloids allowing a tripolar orientation pattern in the horizontal to be produced by a unidirectional flow. Loubere’s studies showed cones weighted in their apical end tended to point with apical end into the current, whereas cones with the same density in both ends tended to align perpendicular to the same current. Loubere’s observations appear to be especially relevant to *Rayonnoceras* because it is observed to have cameral calcite deposits, especially at its apical end. Tripolar orientation of nautiloids in the horizon of bedding was reported by Grahn (1986) to be common in Ordovician limestones of Sweden. His term for the pattern was “polymodal,” and he showed it to be nonrandom by chi-squared statistics, interpreting the pattern as evidence of a unidirectional current in deeper water.

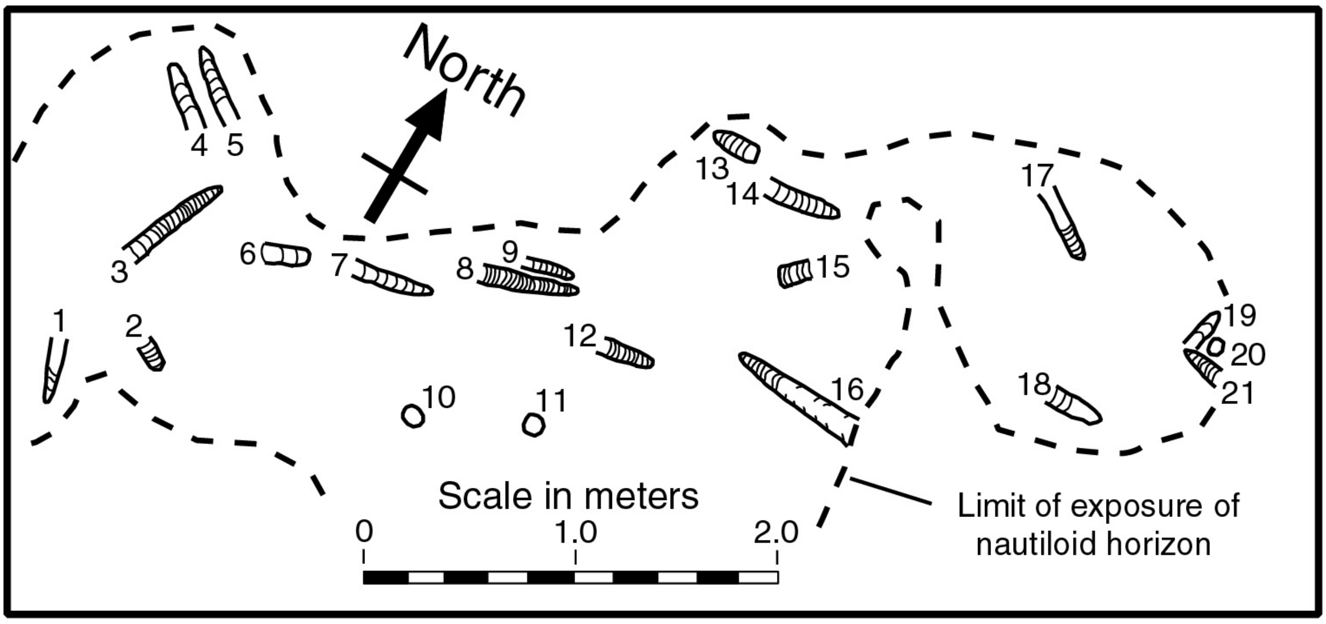

Figure 11. Map depicts the locations and orientations of 21 nautiloids on a 9-m^2 horizon within Whitmore Nautiloid Bed in outcrop on a stream channel at Jeff Canyon (location 33). This outcrop is representative of nautiloid abundance and orientation within the platform facies.

Zangerl et al. (1969) observed that the majority of *Rayonnoceras* in the Fayetteville Shale (Mississippian) of Arkansas are oriented at high angles to the bedding, all with apical end downward. Vertical orientations of *Rayonnoceras* in Fayetteville Shale indicated to Zangerl et al. (1969) that positively buoyant bodies were inside the shells creating a significant displacement of a shell's center of buoyancy from its center of gravity. An excellent petrographic case was made using concretions indicating bodies were within shells at the time of burial. Zangerl et al. (1969) supposed very rapid deposition allowed sediment to freeze capturing many large *Rayonnoceras* in the body-cavity-upright position. Quinn (1977) also reported vertical orientations of *Rayonnoceras* from the Fayetteville Shale. He recognized that most *Rayonnoceras* from the Fayetteville Shale lack a living chamber or preserve only a portion. Preservation of gut contents indicated to Quinn that body decay generated enough gas after burial to explode the living chamber ejecting body fragments. Quinn attributed upright orientation of *Rayonnoceras* to an abrupt thixotropic transition during a rapid, clay-rich, high-concentration sedimentation event.

The quadrapolar orientation pattern of nautiloids in WNB appears to be best explained by a unidirectional flow of very high sediment concentration that moved westward or southwestward. As the high sediment concentration flow deposited sandy calcite sediment, it produced abrupt freezing allowing about 15% of the nautiloids, those with positively buoyant body cavities and negatively buoyant apical ends, to remain oriented vertically with apical ends downward. WNB, being composed of sandy calcite sediment, has virtually no clay content, and so, unlike Fayetteville Shale, has significantly reduced thixotropic property during sedimentation.

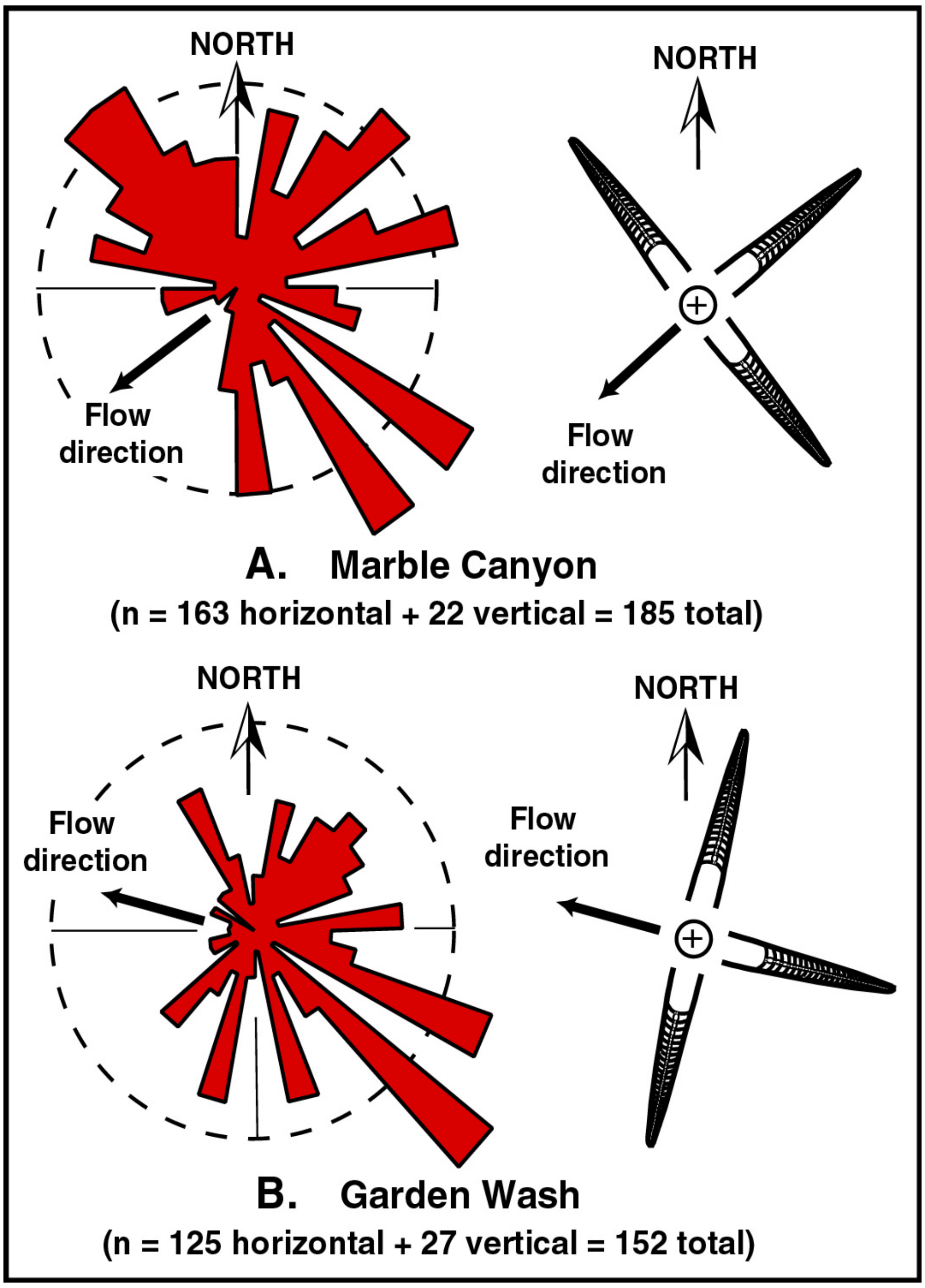

Figure 12. Rose diagrams show the orientations of the apical ends of nautiloids observed on river-scoured ledges within Marble Canyon and in weathered outcrop within Garden Wash. Binning is by 10-degree sectors with dashed circles indicating eight nautiloids.

Water-escape Pipes

Pipe structures are the most widespread and easily recognized features of WNB, both within the platform and slope facies. Densely packed vertical to subvertical pipe structures dominate the upper half of the platform facies of WNB. In thick exposures of the slope facies pipe structures often occur at multiple levels within the bed. Pipe structures average about 1.5 cm diameter, are rather uniformly spaced, and penetrate upward often more than 1 m within the platform facies and sometimes 0.5 m within the slope facies. Pipe structure distinctive of the upper half of the platform facies of WNB is best studied on slightly weathered outcrops and water-polished float boulders. On the outcrop individual pipes typically weather to lighter gray within the medium gray matrix. Usually weathering causes the pipes to acquire a light yellowish-gray color, whereas the matrix often acquires a medium purplish-gray color. This produces the distinctive mottling seen in both limestone and dolomite outcrops.

Figure 13A shows a slightly weathered surface of the top of WNB with vertical pipes reaching the upper surface of the bed. The strong color contrast, especially evident at the top of the bed, is produced by coarser texture sediment (lithified carbonate sand) that composes pipes within a host matrix of finer and more poorly sorted sediment (lithified fine sand with a significant fraction of carbonate silt). Figure 13B shows pipe structure on a water-polished surface vertical through the bed. Although most pipes are vertical, those that are subvertical often branch and reconnect in an anastomosing pattern unlike animal burrows. Pipe structures of WNB resemble those attributed to fluid escape in rapidly deposited sediments such as high-density turbidite sandstones (Lowe, 1975; Lowe and Guy, 2000), mudflow deposits (Best, 1989) and ignimbrites (Cas and Wright, 1987). Recently, several workers use the words "water-escape pipes" to describe these structures in sediments (Cas and Wright, 1991; Pauley, 1995; Lowe and Guy, 2000; Hurst and Cronin, 2001; Roche et al., 2001). Their terminology is adopted here.

Many researchers have conducted laboratory experiments on particle settling within high-concentration dispersions of sediment in water (e.g., Weiland et al., 1984; Batchelor and van Rensburg, 1986; Druitt, 1995; Roche et al., 2001; Marr et al., 2001). Experiments by Druitt (1995) and Roche et al. (2001) are especially relevant to WNB because they document formation of water-escape pipes by sedimentation from concentrated dispersions of poorly sorted, sand-size particles in water. At low sediment concentration (≈10% solids by volume) the sandy dispersion settled to form a normally graded deposit without water-escape pipes (Druitt, 1995). At high sediment concentration (from as little as 45% to as high as 65% solids by volume) particle segregation was suppressed causing the dispersion to settle *en masse* to form an ungraded bed without pipe structures. At intermediate sediment concentration (25% to as much as 55% solids by volume), however, the sandy dispersion experienced hindered settling, produced a self-fluidized condition, and allowed particles to segregate assembling vertical channels with coarse particles falling and finer particles rising with expelled water within pipes (Druitt, 1995). The highest contrast between sediment in pipes and matrix occurred at volume concentrations above 30% (Batchelor and van Rensburg, 1986). The elutriation process flushed silt-size particles from the lower portion of the bed through pipes to the upper surface of the bed. Pipes as much as 2 cm wide and 15 cm high were generated in, or just above, the aggrading bed and propagated upward at the same rate as movement of the depositional interface (Druitt, 1995; Roche et al., 2001). Water and finer sediment continued to be transmitted through pipes below the rising depositional interface within the compacting bed. Pipes retained coarser texture than their surrounding matrix. These experiments indicate that WNB water-escape pipes were generated by rapid deposition from a sandy dispersion with about 25 to 45% solids by volume (dispersion density ≈ 1.4 to 1.8 g/cm^3).

A.


B.


Figure 13. Water-escape pipes in Whitmore Nautiloid Bed. **A** shows pipes on the weathered uppermost surface of WNB parallel to bedding. **B** shows pipes on water-polished surface perpendicular to bedding from the horizon of the nautiloids (indicated by finger) to 1 m stratigraphically below the nautiloids (bottom of photo).

Internal Structure of the Bed

Figure 4 generalizes internal bed structure for the platform facies showing the bed's three subdivisions or layers. The layered organization of the platform facies of WNB is similar in both structure and texture to that generalized from ignimbrite, the class of welded or nonwelded, pumiceous, ash-rich deposits accumulated from "pyroclastic density currents" (Druitt, 1998; Freundt et al., 2000). The idealized ignimbrite structure has layers 1, 2a, 2b and 3 (Sparks et al., 1973), thought to form by progressive aggradation of a single, fast-moving, high-density, pyroclastic density current (Druitt, 1998; Freundt et al., 2000). The same layer terminology for the ideal ignimbrite is adopted here for the platform facies of WNB. Although significant differences exist between the subaerial, gas-fluidized, volcanic flows and subaqueous, high-concentration, water-fluidized flows, the similarities are significant (Kneller and Branney, 1995; Freundt and Bursik, 1998). Six characteristics of WNB that are strongly represented in ignimbrites are: (1) thin basal layer, (2) inverse grading just above the basal layer, (3) outsized clasts near the middle of the bed, (4) orientation of clasts near the middle of the bed, (5) fluid-escape pipes, and (6) finer sediment at the top of the bed with some indication of normal grading.

Field observations of WNB show bed structure to be better displayed in limestone than dolomite. The best display of bed structure was found at the limestone cliff at Jeff Canyon (location 33). Layer 1 (see Fig. 4) is packstone to grainstone that forms the lowest division within the platform facies of WNB. It is always less than 0.25 m thick and forms the base of the bed without obvious disconformity with underlying packstone beds. It shows crudely developed lamination and, as a zone, possesses strong stylolite development. Fluid-escape pipes are absent. Layer 1 could represent mechanical shear created within or in front of the head of the flow. It might be supposed that the flow moved so fast that it hydroplaned, but, as the aggradation of the bed began, laminar shear developed as the thin basal layer of the bed was deposited.

Layer 2a (see Fig. 4) is massive packstone that forms the main mass of WNB. It is inversely graded (coarse-tail grading) with the sizes of the granular bioclastic debris increasing slightly upward within a uniform packstone matrix. Water-escape pipes are not very abundant, but they appear to have their bases rooted at this level within the bed. Consolidation lamination and dish structures (Hurst and Cronin, 2001) are not evident. Large fossils are *not* characteristic of this division. In the central and eastern Grand Canyon and in Lake Mead region, layer 2a appears to comprise the major volume of the bed, usually being thicker than 1.0 m. In the southwestern Grand Canyon, layer 2a is often reduced in thickness, sometimes being thinner than 1.0 m. If WNB is a sandy sediment flow, layer 2a might represent high-density, laminar flow characteristic of the main body of the flow. It would be analogous to inversely graded layer 2a of the ideal ignimbrite (Sparks et al., 1973) and to the highly fluidized "quick bed" formed by gravitational compaction of a high sediment concentration flow in a laboratory flume (Middleton, 1967). A high-density, laminar flow could not carry larger fossil fragments *within* the laminar flow, but would suspend corals and nautiloids above it (Legros and Marti, 2001). The laminar flow process may, therefore, explain the unusual sorting of the bioclastic debris and the inverse grading within layer 2a.

Layer 2b is the packstone interval with very coarse fossil material, the coarsest debris within the bed. It sits on top of layer 2a with transitional boundary. Within layer 2b large heads of colonial corals up to 20 cm diameter and nautiloids up to 1.5 m long are suspended within packstone matrix possessing texture resembling layer 2a. This division is usually about 0.4 m thick and is strongly mottled by the vertical water-escape pipes. This division may reflect the transition or boundary between high-density, laminar flow and low-density, laminar flow. Two processes could promote the separation of a sandy raft or plug containing coarse, oriented nautiloids at the top of a high-density flow: (1) hindered settling, and (2) laminar shear at a flow boundary. Druitt (1995) conducted hindered-settling experiments and showed that fluidization pipes are characteristic of high sediment concentration flows that have about 40% by volume sediment (dispersion density ≈ 1.6 g/cm^3). He described experiments showing how fluidized pumice clasts separate within a nonshearing, sandy dispersion to form a raft above the aggrading fluidized bed. Branney and Kokelaar (1992) considered how grain fabrics would be acquired by shear within a progressively aggrading, laminar flow. Grain fabric in layer 2b of ignimbrites is attributed to "laminar flow within the sustained depositional boundary layer of a stratified flow" (Branney and Kokelaar, 1992). Thus, the coarse fossil fabric within layer 2b of WNB is analogous to the outsized and flow-oriented clasts of pumice and lithics from layer 2b of ignimbrites. It seems reasonable to suppose that the fabric of coarse fossils within layer 2b of WNB was not acquired by deposition as a rigid plug *en masse*, but as a raft separated by hindered settling that, while still in a fluidized boundary layer, sustained laminar shear. Because a high-density, laminar flow would likely make the transition to low density laminar flow during its passage over any point only once, there would be just one raft of coarse material assembled within the bed. This process could explain why the nautiloids are remarkably coplanar within WNB.

Layer 3 forms the uppermost division of WNB. It is normally graded packstone, of finer grain size, usually dolomitized, and has the dense packing of water-escape pipes that creates the unusual mottled appearance especially evident at the top of the bed. Finer texture of layer 3 is caused by added fine sand and silt elutriated from the underlying layers. Normal grading within layer 3 represents the last settling of sediment from the low-density, turbulent tail of the flow. The thickness of layer 3 ranges greatly from less than 0.2 m (Nautiloid Canyon, Squaw Canyon, Havasupai Canyon) to over 1.0 m (Jeff Canyon).

SEDIMENTARY MODEL

WNB appears to have been deposited from a sandy, subaqueous, hyperconcentrated, sediment gravity flow. Structural and textural characteristics of WNB provide strong evidence for deposition from a high-concentration dispersion of sediment in water. First, the bed's massive appearance, poor sorting and inverse grading of basal layers are features deposited by concentrated dispersions such as debris flows and pyroclastic density currents. Second, large coral heads and other outsized clasts in the middle of the bed require that the lower half of the bed was in a concentrated dispersion denser than the coral heads that the dispersion supported. Third, rapid freeze of the dispersion is required in order to capture vertical orientations of orthocone nautiloids within the bed. Fourth, water-escape pipes are similar to those generated in lab experiments on deposition from dispersions containing 25 to 45% by volume sandy sediment. Internal structure within WNB, especially the bed's similarity to ignimbrite, provides evidence of a fast-moving flow that accumulated layers quickly by progressive aggradation of the bed, not by abrupt freezing of the sediment flow *en masse*.

Definition of Hyperconcentrated Flow

Field observation (Lowe, 1982; Cao, 1992), laboratory experiments (Middleton, 1966, 1967; Postma et al, 1988; Hallworth and Huppert, 1998), and numerical modeling (Norem et al., 1990; Straub, 2001) are used to study high-concentration, fast-moving, sand-rich, non-cohesive, subaqueous sediment flows. What short name should be given to these flows? Postma (1986) observed, "…there are too many flow descriptions for laminar, high-concentration, cohesionless flow." Mulder and Alexander (2001) replaced confusing terminology for these high-concentration, subaqueous flows with a rather simple rheological classification. Volume % sediment allows three rheological types of non-cohesive sediment gravity flows to be recognized: turbidity currents (≤9%), concentrated density flows (9% to ≈27%), and hyperconcentrated density flows (≈27% to ≈70%). According to Mulder and Alexander (2001), hyperconcentrated density flows are "non-cohesive," and, therefore, are distinct from debris flows. A quadratic rheological model for hyperconcentrated flow confirms low yield strength for low shear rates (Julien and Lan, 1991), making this flow distinct from debris flows. Hyperconcentrated density flows have rheological properties (laminar flow, matrix support, and quick freeze) that differ from concentrated density flows (turbulent flow, grain interactions, and steady aggradation). The critical sediment volume concentration of slightly less than 30% appears to divide the two rheological domains (Middleton, 1967; Hallworth and Huppert, 1998). Sedimentary structures and textures of the platform facies of WNB place it within the classification "hyperconcentrated density flow." The terminology of Mulder and Alexander (2001) is adopted here.

Figure 14 is a cartoon depicting a sandy, hyperconcentrated flow within a carbonate platform environment. Photographs of high-concentration sediment gravity flows generated in the laboratory (Postma et al., 1988) show structure resembling Figure 14. Zone A in Figure 14 is the horizon of intense bed shear probably associated with the hydroplane surface beneath the head of the flow. Zone B is the region of high-velocity, high-density laminar flow where larger, heavier objects such as corals move upward within the dispersion. Nautiloids, corals and brachiopods were supported above the hyperconcentrated region in a lower-density, possibly laminar flow in zone C. The low-density, turbulent flow in zone D has low enough density and velocity to allow larger objects like nautiloids to fall through it. Zone D represents the upper surface and tail of the sediment flow. The model supposes that nautiloids were swept over the top of the hyperconcentrated flow, then smothered by being swallowed up in the wake of the sediment-charged slurry, and then buried rapidly as the density of the sediment slurry declined. Large coral heads and dense rugose corals are like the outsized clasts carried near the middle of the sediment flow created in the laboratory by Postma et al. (1988).

Numerical Flow Model

The hyperconcentrated flow depicted in Figure 14 can be modeled numerically. Benjamin (1968) developed principles for a 2-D model for sediment gravity flows, and Kranenburg (1978) applied them specifically to shallow water flows. The motion of the dispersion was modeled assuming uniform, steady, subcritical flow over a level ocean floor. The 2-D model solves equations for conservation of mass, conservation of momentum and conservation of energy. Energy loss was assumed to be very low because WNB traversed the 200 km distance through the carbonate platform between Marble Canyon and Lake Mead with no thickness change and little internal structure and texture change. These persistent physical characteristics of the platform facies of WNB argue that the flow was an "autosuspension current" (Pantin, 2001), a particle-driven gravity flow that could persist indefinitely without an external supply of energy. Flow velocities on a carbonate platform for different flow thicknesses and flow concentrations are calculated by the method of Kranenburg (1978, equation 9). Solutions for flow velocity, assuming water depth of 30 m, are shown graphically as a nomograph in Figure 15.

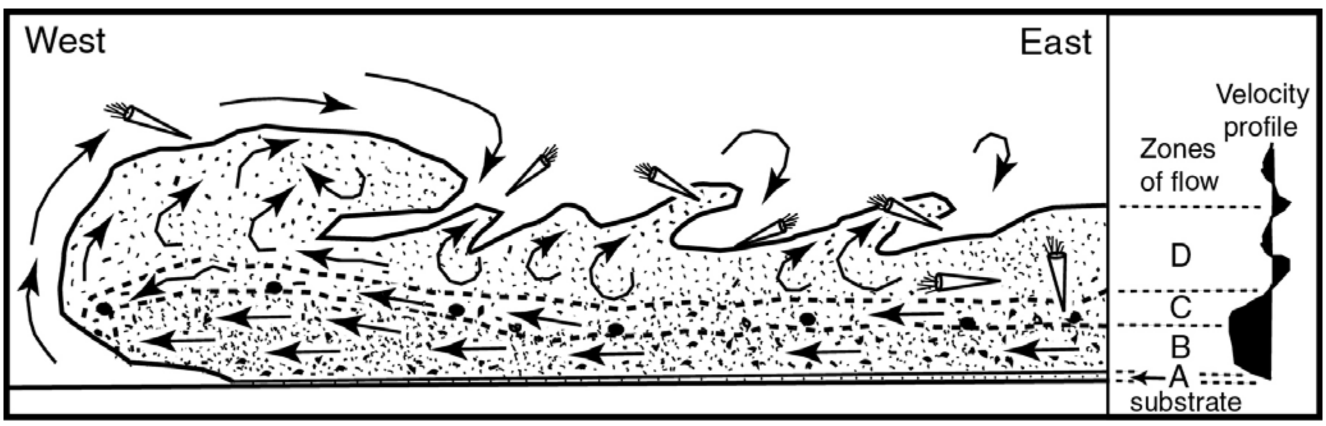

Figure 14. Hyperconcentrated flow model for the origin of the platform facies of Whitmore Nautiloid Bed. Coral heads (black circles) and nautiloids were supported as a raft above the high-density, sandy, laminar dispersion and were buried by the low-density tail of the sediment gravity flow.

What are the boundary conditions for stability of a particle-driven sediment gravity flow hydroplaning within a shallow-water, platform environment? Figure 15 attempts to describe what can be called the "stability window" for high concentration flows like the one that deposited WNB. Laboratory studies show that high-concentration, fast-moving, shallow-water sediment flows are very susceptible to hydroplaning (Mohrig et al., 1998; Mohrig et al., 1999; Marr et al., 2001). Hydroplaning is caused by a thin layer of ambient water that slips under the head of a sediment flow when the dynamic pressure generated in the water in front of the head approaches or exceeds the submerged weight per unit area beneath the sediment in the head of the flow. Because of high sediment concentration and silt content, this flow is relatively impermeable, not allowing pressure to be dissipated by upward flow. Thus, conditions for hydroplaning are promoted. According to Mohrig et al. (1998), a densimetric Froude number greater than 0.4 describes the hydroplaning flow regime. That boundary parameter (Fr_d = 0.4) defines the lower right edge of the stability window in Figure 15.

High sediment concentration and high flow thickness promote hyperconcentrated flow, driving the dispersion through ambient seawater by the force of gravity. However, very high sediment concentration causes high resistance to shear at high strain rates. Experiments by Hallworth and Huppert (1998) and rheological modeling by Julien and Lan (1991) show that hyperconcentrated flows with 27.5% to 40% sediment by volume have the greatest mobility. Experimentalists have had problems producing and maintaining dispersions above 45% solids by volume (Middleton, 1967; Hallworth and Huppert, 1998). Therefore, the sediment friction regime defines the upper left boundary of the stability window for a hydroplaning flow in Figure 15.

A sandy hyperconcentrated flow may have significant permeability especially if it has lower sediment concentration with deficiency in silt- and clay-size particles. The high dynamic pressure at the head of a thin, lower-concentration flow would cause it to inflate with water loosing its velocity and potential to hydroplane. Therefore, the lower left boundary of the stability window in Figure 15 appears to define a water inflation regime.

A subaqueous hyperconcentrated flows must displace the water through which it travels. This displacement is especially important for a shallow-water sediment gravity flow because the return water flow cannot be supercritical (Froude number cannot be greater than 1.0). For water depth of 30 m, sediment gravity flow thicknes of about 10.4m.

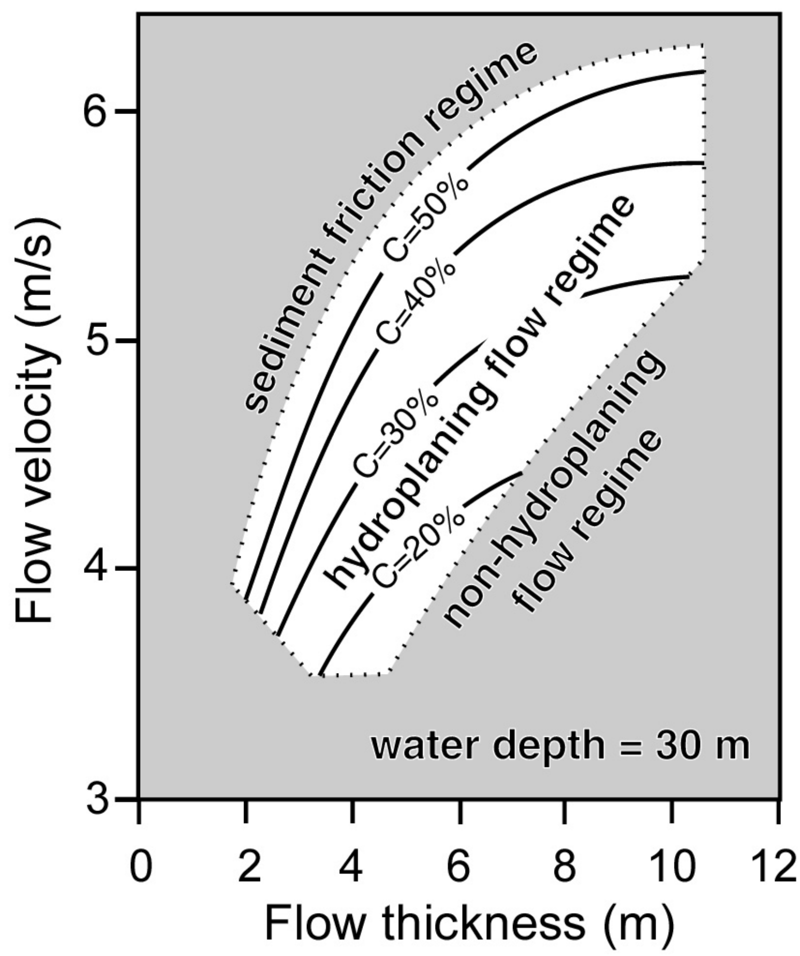

Figure 15. Nomograph illustrating the stability window for a hydroplaning sediment gravity flow at 30 m depth on a marine platform. (about 1/3 of water depth). Kranenburg (1978) describes this flow thickness limitation that defines the upper right side of the stability window for hydroplaning flow in Figure 15.

Flow Model Applied to Whitmore Nautiloid Bed

Numerical modeling of shallow-marine sediment flows indicates the existence of a hydroplaning density flow regime that can explain the unusual sedimentary textures and structures of the platform facies of WNB. If we assume that the hyperconcentrated density flow that deposited the platform facies of WNB in Arizona had a thickness of 8 meters and a sediment concentration of 35% by volume, Figure 15 indicates a flow velocity over the carbonate platform of more than 5 m/s. In order for the hyperconcentrated flow to traverse the distance of at least 200 km (Marble Canyon to South Virgin Mountains), the sediment slurry had to exist in a fast-moving, strongly fluidized condition upon a marine platform, resting on a hydroplane, for a period of several hours. Although difficult to visualize on so large a scale, such a process appears to be a reasonable application of the sediment gravity flow model to WNB.

What happened when the hyperconcentrated flow encountered the deeper water of the marine slope environment westward in southern Nevada and southwestern Utah? It appears that the *laminar* hyperconcentrated flow ($C \approx 35\%$) was transformed into a *turbulent* concentrated density flow ($C \approx 25\%$). Such a process is known as "flow transformation" (Fisher, 1983; Sohn, 2000). It can be supposed that the slope increase off the platform promoted flow acceleration, leading to increased dynamic pressure at the flow front, increased turbulence at the flow boundary, and bringing about breakdown of laminar flow (a "body transformation" upon increase in slope in the classification of Fisher, 1983). Dilution of a hydroplaning laminar flow probably occurs most effectively by detachment and disintegration of the flow front to form a turbulent flow (Sohn, 2000). A $C \approx 35\%$ *turbulent* flow with velocity of ≈ 6 m/s could not support its sediment over a low slope, and, would, through significant deposition, be altered into a *C*≈25% concentrated flow. The evidence of flow transformation to a concentrated density flow (*C*≈25%) is seen in the abrupt change to thicker bed, better sorting, and normal grading. Turbulence within the newly formed concentrated flow continued to entrain silt and fine sand within the dispersion allowing only coarser sand to be deposited. Flow transformation explains why platform packstone gives way to slope grainstone within WNB in association with the abrupt thickening of the bed. The abundance of water-escape pipes is significantly reduced in the slope facies. Absent from the slope facies of WNB in Nevada and southwest Utah are outsized clasts in the middle of the bed and inverse grading, the normal characteristics of the platform facies. Thus, flow acceleration at the platform margin in response to slope increase is the likely cause of breakdown of the laminar flow condition.

That the flow deposited more sediment in Nevada than in Arizona is seen in the abrupt thickness increase in WNB westward (Fig. 7) at the approximate platform margin (Rose, 1976; Stevens et al., 1991; Poole and Sandberg, 1991). Up to seven-fold thickness increase occurs westward from the platform to the slope. Most sediment was transported through the platform environment (hyperconcentrated flow regime) and was deposited in the slope environment (concentrated flow regime). As Figure 15 suggests, even a concentrated flow less than 20% by volume sediment might hydroplane. Loss of sediment (or inflation with water), however, would increase flow permeability, would allow excess fluid pressure to dissipate upwards through the flow, and would defeat hydroplaning. Without hydroplaning the flow would enter a new friction-dependent regime with its bed. If the head of the concentrated flow inflated with water, it could loose its coherence (Marr et al., 2001). After inflation, dynamic pressure could break it apart producing multiple, stacked, normally graded beds with better sorting than their inversely graded, hyperconcentrated counterpart within the platform facies. Thus, sediment deposition and flow infiltration are the likely causes of breakdown of the concentrated flow.

Distal portions of the slope facies of WNB argue for breakdown of the hydroplaning flow. At the northern end of the Las Vegas Range (Fig. 1, location 58) large-scale, west-dipping cross-stratification occurs within very coarse crinoidal grainstone. Near Indian Springs in the northern Spring Mountains (location 59) significant scour structures occur at the base of the bed. These distal occurrences indicate breakdown of the hydroplane and formation of a tractive current, the large-scale cross-stratification indicating westward velocity of more than 2 m/s (Ashley, 1990).

DISCUSSION

What are the primary causes of shelf sediment flows? According to Hampton et al. (1996), three classes of instability produce modern shelf landslides: (1) *gravity loading* caused simply by the continued accumulation of sediment, (2) *seismic loading* due to vertical and horizontal accelerations during earthquakes, and (3) *storm wave loading* induced by horizontal shear stress and pressure pulse on a shallow ocean floor. Historic events and flume experiments on liquefaction failure on low slopes show that shelf landslides are initiated abruptly by a trigger event. A variety of conditions or events have been proposed for generating shelf sediment gravity flows: (1) earthquakes, (2) storms, (3) tsunami, (4) hyperpycnal sediment-laden river floods, (5) extreme low tides, (6) spontaneous failure within rapidly accumulated sediment, and (7) human disturbances in coastal areas (Bornhold et al., 1994). Flume experiments demonstrate that after a liquefaction event, moving sandy sediment does not entrain much water and has a strong tendency to remain in motion as a laminar, high-sediment-concentration flow (Van der Knapp and Eijpe, 1968; Stoutjesdijk at al., 1998; Van den Berg et al., 2002). These fluidized mass movements of sandy sediment on very low slopes have been called “flow slides” (Stoutjesdijk at al., 1998). According to the flume tests, only a small portion of the moving mass generated by the flow slide turns into a low-density turbidity current.

Submarine mass movements in historic times have generated sediment gravity flows within continental shelf environments on nearly level surfaces. Documented examples of modern shelf submarine sediment gravity flows include the 1663 Saguenay Fjord earthquake (Syvitski and Schafer, 1996), the 1975 Kitimat event (Prior et al., 1984), the 1980 Klamath River delta earthquake (Field, 1993), the 1989 Bute Inlet events (Bornhold et al., 1994), the 1991 Middle Atlantic Bight storm (Wright et al., 1994), the 1993 Louisiana shelf event (Wright et al., 2001), and the 1998 Eel River flood event (Traykovski et al., 2000). The Klamath River delta earthquake of 1980 (M = 7.2) initiated liquefaction failure and flow on a 0.25° slope off the coast of northern California along a 20-km-long, 1- to 4-km wide zone, less than 15 m thick in 60-m water depth (Field, 1993). The Klamath delta event, as well as other recent landslide events, did not produce blanketlike sand flows, but local lobelike sand flows stacked on top of each other. The Eel River event of January 1998, also off the northern California coast, involved high river sediment discharge accompanied by large storm waves. A thin, dilute, across-shelf, hyperpycnal flow of clay and silt apparently was sustained by turbulence added from storm waves, penetrated the Eel River open mid-shelf environment to more than 60 m depth, and produced up to 13 cm of deposit (Traykovski et al., 2000; Wheatcroft, 2000). These historic examples of shelf gravity-driven sediment flows on very low slopes did not possess high enough flow volume, flow density, or flow kinetic energy to achieve conditions of autosuspension and/or hydroplaning, and, therefore, could not maintain across-shelf transport of sand. These historic events contrast markedly with the catastrophic flow event that deposited the blanket of sandy sediment of WNB across a Mississippian marine carbonate platform.

Shelf sediments associated with the Cretaceous-Tertiary (K-T) boundary are among the most thoroughly studied within the stratigraphic record. In the northwestern Gulf of Mexico region the K-T boundary is marked by a persistent sequence of graded sandstone beds averaging 1 to 3 meters thick variously interpreted as tractive current caused by the tsunami from the Chicxulub impact (Smit et al., 1996), by sediment gravity flows initiated by the Chicxulub impact (Bohor, 1996), and by non-catastrophic marine transgression (Ekdale and Stinnesbeck, 1998). The shelf facies of the K-T boundary deposit on the Campeche marine platform in southeastern Mexico (southwest of the Chicxulub structure) is described as multiple beds of calcareous sandstone and siltstone up to 6-m thick at the top of a very thick succession of limestone breccia and reworked ejecta with breccia (Grajales-Nishimura et al., 2000). The shelf facies of the boundary sand deposit in Alabama and Texas is also distinctly bedded, occupies erosional channels, and is not described as possessing the characteristics of a high-sediment-concentration gravity flow (Smit et al., 1996). Elsewhere in the Gulf of Mexico region K-T boundary carbonate sands are described as off-shelf gravity flow deposits (e.g., western Cuba by Takayama et al., 2000; northeastern Mexico by Soria et al., 2001). In the Pacific margin of Baja California a K-T boundary deposit is contained in a 15-km-long, coastal-marine paleovalley including local massive sandstones deposited by “high-density turbidity currents” (Busby et al., 2002). In northeastern Brazil the K-T boundary deposit contains a massive, 50-cm-thick, normally graded carbonate packstone bed with intraclasts up to 9 cm diameter persisting along a distance of at least 30 km (Albertão and Martins, 1996). This packstone was interpreted as reworked by tsunami waves on a carbonate ramp at a water depth of 100 to 200 m (Albertão and Martins, 1996).

Other shelf sediment gravity flows within the stratigraphic record are still poorly understood. Ancient sandy tempestites (storm-deposited beds on continental shelves) are unusually thick compared to modern deposits, indicating much greater ancient cross-shelf sand transport (Myrow and Southard, 1996). Graded sand layers within some ancient tempestites indicate gravity-driven shelf sediment gravity flows, but these are much thinner and are much less extensive than WNB (Myrow et al., 2002). The Fayetteville Shale (Upper Mississippian, Arkansas) is interpreted as a storm-dominated, muddy shelf deposit with southward paleoslope of about 0.1° (Handford, 1986). Large *Rayonnoceras* fossils in vertical orientation within Fayetteville Shale indicate rapid freezing of sediment and argue for some type of fine-grained, shelf sediment gravity flow (Zangerl et al., 1969; Quinn, 1977). A 3-m-thick lime packstone unit called the Crow Creek Member of the Pierre Shale (Upper Cretaceous) extends 300 km from northeastern Nebraska to central South Dakota, and is thought to be a catastrophic marine shelf deposit associated with the Manson impact structure of Iowa (Izett et al., 1998). However, the Crow Creek Member cannot be a sediment gravity flow throughout most of its extent because it contains sedimentary structures diagnostic of tractive current (thin bedding, hummocky cross-stratification, and large ripples). The Alamo Breccia (Upper Devonian, southern Nevada) covers about 1×10^4 km^2 of a carbonate platform with coarse carbonate breccia overlain by as many as five sequentially thinner, normally graded, sandy carbonate beds (Warme and Kuehner, 1998). The breccia was interpreted as impact-generated debris flows with the overlying sandy beds representing turbidite deposition from tsunami backwash (Warme and Kuehner, 1998). Resurge gullies associated with Lockne crater (Ordovician, Sweden) contain localized channels with matrix-supported breccia supposedly deposited within a shelf sea by hyperconcentrated flow (Von Dalwigk and Ormö, 2001). The Lower Muschelkalk (Triassic, Germanic Basin) is an epicontinental carbonate sequence hundreds of km wide, containing several event beds, each up to 3.7 m thick, composed of mud-supported conglomerates and associated slide blocks (Föhlisch and Voigt, 2001). Numerous slumps and debris flows were initiated by large earthquakes within the Muschelkalk, but plastic behavior, not strongly fluidized condition, characterized these flows (Föhlisch and Voigt, 2001).

WNB is extraordinary within the geologic literature. What makes the process that deposited WNB distinctive among shelf sediment gravity flows reported in the literature is its regional extent, high sediment concentration, and strongly fluidized condition. Together the platform and slope facies of WNB indicate a bed area of more than 3×10^4 km^2 and bed volume of more than 100 km^3. Allowing original porosity of 30% for the bed, the calcite sediment of WNB had a volume of 70 km^3 and mass of 1.9 x 10^{14} kg. With the added 65%-by-volume seawater, the hyperconcentrated flow had a volume of about 200 km^3, density of 1,600 kg/m^3, and mass of 3.2 x 10^{14} kg. Kinetic energy of the hyperconcentrated flow, assuming velocity of 5 m/s, is estimated to have been 4 x 10^{15} joules. For energy comparison, 1.9 x 10^{14} kg of sediment falling just 2.1 m at the earth's surface releases 4 x 10^{15} joules. Liquefaction shelf failure in a flow-slide event, therefore, is a very energy-efficient process that could convert a major part of the gravitational potential energy of shoreface and inner-shelf sediment into a hyperconcentrated flow on a carbonate platform at a depth of about 30 m. The process is much more energy efficient than the process generating a turbidity current because only a small volume of seawater needs to mix with the sandy sediment flow. What is hard to imagine is the huge scale of the shelf sediment liquefaction event that would be required to initiate the hyperconcentrated flow. Nautiloid orientations and the associated southeastern boundary of WNB within Grand Canyon indicate that the hyperconcentrated flow came from the northeast. The closest source for more than 100 km^3 of sandy carbonate sediment appears to be southwestern Colorado where the lower Leadville Limestone north of Durango is thin and lacking the lower Osagean (Armstrong and Mamet, 1976; Armstrong and Holcomb, 1989).

What is the relationship between WNB and its adjacent and overlying sediments? Could the adjacent disconformities and peloidal limestone facies south of WNB (see Figs. 6 & 7) be related to large-scale shallow marine erosion and redeposition associated with big sea waves initiated by movement of the hyperconcentrated flow? If the peloidal facies is a reworked shelf deposit, it might be similar to "homogenite," the residual sediment created by bed shear and pressure pulse from passage of a tsunami (Cita et al., 1996). Could the wackestone/mudstone/chert rhythmites overlying WNB be deposited from thinner gravity-driven sediment flows simultaneous with back-surge of big sea waves after the main deposition event? Similar rhythmites have been described in the sedimentary rock record and have been interpreted as "wave-modified turbidites" (Myrow et al., 2002). These questions are worthy of further study.

CONCLUSION

Billions of large orthocone nautiloids occur within an extremely persistent lime packstone bed of the Redwall Limestone through the Grand Canyon region, Arizona and Nevada. The platform facies of the packstone bed is 2 m thick at the top of the Whitmore Wash Member (Osagean Series of Mississippian System). Abundant nautiloids occur within the platform facies of the bed from Marble Canyon, Arizona westward 290 kilometers to Las Vegas, Nevada. The slope facies of the bed, where nautiloids are rare, is 3-to-14-m-thick, light-gray-weathering grainstone occurring northwest of the platform facies in southern Nevada, extreme northwestern Arizona, and southwestern Utah. Both platform and slope facies of the bed are named formally Whitmore Nautiloid Bed (WNB). Bed area exceeds 3 x 10^4 km^2 and bed volume exceeds 100 km^3.

Corals, brachiopods, crinoids, gastropods, bryozoans, ammonoids, Foraminifera and conodonts occur in WNB, but the most abundant large fossils are orthocone nautiloids assignable to the genus *Rayonnoceras*. Nautiloids occur with large coral heads along a nearly coplanar horizon above the inversely graded lower half of the bed. Sizes of nautiloids are lognormal with mean length ≈ 0.8 m. Nautiloid fossils appear to average more than 1 per m^2 through the platform facies of the bed. Orientations of nautiloids are non-random indicative of westward flow. About 15% of the nautiloids stand vertical within the bed with apical end downward.

WNB appears to have been deposited from a sandy, subaqueous, hyperconcentrated, sediment gravity flow. Structural and textural characteristics of WNB provide strong evidence for deposition from a high-concentration dispersion of sediment in water with about 35% by volume carbonate sediment. First, the bed's massive appearance, poor sorting and inverse grading of basal layers are features deposited by concentrated dispersions such as debris flows and pyroclastic density currents. Second, large coral heads and other outsized clasts in the middle of the bed require that the lower half of the bed was in a concentrated dispersion denser than the coral heads that the dispersion supported. Third, rapid freeze of the dispersion is required in order to capture vertical orientations of orthocone nautiloids within the bed. Fourth, abundant water-escape pipes are similar to those generated in lab experiments on deposition from dispersions containing 25 to 45% by volume sandy sediment.

Internal structure within WNB, especially the bed's similarity to ignimbrites, provides evidence of a fast-moving flow that accumulated layers quickly by progressive aggradation of the bed, not by abrupt freezing of the sediment flow *en masse*. The hyperconcentrated flow hydroplaned westward, probably out of southwestern Colorado, toward southern Nevada at velocity approximately 5 m/s across the carbonate platform in northern Arizona. A large population of living nautiloids was swept up, smothered within, and buried by the flow. Layer 1, the basal few cm of the bed, represents the shear zone at the front of the flow in association with the hydroplane. Layer 2a, the main mass of the deposit, accumulated from a moving quick bed as a strongly fluidized, very high-sediment-concentration dispersion characterized by laminar flow. Layer 2b, the coarsest fossil debris, was assembled as a raft above the quick bed, so it's deposition was delayed until passage of the bulk of the flow. A coplanar horizon with abundant nautiloid fossils was produced. Layer 3 represents the final stage of the flow when fines elutriated from the main sediment mass were accumulated probably from lower-density, turbulent suspension. When the flow encountered the slope in southern Nevada and southwestern Utah, it was transformed into a turbulent, concentrated flow (volume concentration sediment approximately 25%). Nautiloids are *not* characteristic of this slope facies. At its far western occurrences in Nevada, the bed's sedimentary structures and the erosional base indicate lack of a hydroplane, but, instead, a tractive current moving westward more than 2 m/s.

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Data Repository item:
Locality register for study of Whitmore Nautiloid Bed

Localities for study of Whitmore Nautiloid Bed (WNB) are numbered from 1 to 63 in Figure 1. Details of these study localities are included in Table DR1 and Table DR2. Slot canyons and other severe terrain features sometimes prevented or significantly degraded GPS measurements. Each location listed contains an estimate of position error.

WNB is defined at the type section and eight reference sections in Arizona and Nevada. The type section is in Whitmore Wash (location 20). The four reference sections for the platform facies are Marble Canyon (location 1D), Jeff Canyon (location 33A), Garden Wash (location 41) and Sunrise Mountain (location 52). The four reference sections for the slope facies are Whitney Pocket (location 44), Virgin River Gorge (location 47A), Tungsten Gap (location 55), and Harris Springs Canyon (location 60).

Table DR1. LOCALITY REGISTER FOR STUDY OF WHITMORE NAUTILOID BED.

Location number and location name	Latitude Longitude[†]	Description of outcrop
Location 1A Marble Canyon (river mile 33.90 east) at rock wall just downstream of "Little Redwall Cavern"	N 36° 28.893′ W 111° 50.761′ GPS and topo (error ± 10 m)	First appearance of WNB platform facies on dolomite rock wall on east bank of Colorado River; large nautiloid observed in cross section at lowest river water level; WNB abruptly overlain by thin beds of Thunder Springs Member; bottom of bed not visible.
Location 1B Marble Canyon (river mile 33.98 west) at sloping west bank of Colorado River	N 36° 28.831′ W 111° 50.817′ GPS and topo (error ± 10 m)	WNB platform facies; upper half of bed exposed as dolomite slope at very low water level; one large orthocone nautiloid and one large, fully coiled cephalopod.
Location 1C Marble Canyon (river mile 34.17 west) beneath distinctively white, abraded rock slope	N 36° 28.671′ W 111° 50.772′ GPS and topo (error ± 10 m)	WNB platform facies exposed beneath polished slope of Thunder Springs Member.
Location 1D Marble Canyon (river mile 34.19 west) at entry of small slot canyon Reference section for WNB	N 36° 28.650′ W 111° 50.768′ GPS and topo (error ± 10 m)	WNB platform facies fully exposed as 2-m-thick bed on prominent ledges on west bank of Colorado River; 38 nautiloids measured on coplanar surface upstream and downstream of slot canyon; coarse fossil debris at level of nautiloids is not very abundant.
Location 1E Marble Canyon (river mile 34.20 east) at "Square Hole Ledge"	N 36° 28.674′ W 111° 50.721′ GPS and topo (error ± 10 m)	Large, river-scoured ledge of WNB platform facies with 49 nautiloids measured. Many vertical nautiloids.
Location 1F Marble Canyon (river mile 34.29 west) at large boulder delta beneath slot canyon	N 36° 28.583′ W 111° 50.728′ GPS and topo (error ± 10 m)	WNB platform facies exposed as ledge and within slot; 8 nautiloids measured within dolomite bed.
Location 1G Marble Canyon (river mile 34.35 east) at "Five Caves Ledge"	N 36° 28.536′ W 111° 50.641′ GPS and topo (error ± 10 m)	WNB platform facies occurs as very wide ledge with 69 nautiloids measured; vertical nautiloids common.
Location 1H Marble Canyon (river mile 34.46 west) at "Hanging Spring Terrace"	N 36° 28.433′ W 111° 50.641′ GPS and topo (error ± 10 m)	WNB platform facies exposed as high ledge of dolomite with 12 nautiloids measured.
Location 1J Marble Canyon (river mile 34.50 east) at 130-m-high, vertical rock face	N 36° 28.439′ W 111° 50.547′ GPS and topo error ± 10 m)	WNB is 2-m thick exposed in cliff on east side of Colorado River; cross section of large chert/dolomite mound structure in Thunder Springs Member occurs above WNB.
Location 1K Marble Canyon (river mile 34.63 east) at "Railroad Tie Ledge"	N 36° 28.349′ W 111° 50.460′ GPS and topo (error ± 10 m)	WNB platform facies exposed on narrow, river-scoured alcove with 3 nautiloids measured.

[†] Latitude and longitude of each study site (degrees/minutes/decimal minutes) were measured by Global Positioning System (GPS) and/or topographic maps (topo) with reference to the North American Datum of 1927 (NAD 27). Horizontal error estimate is included.

Location number and location name	Latitude Longitude†	Description of outcrop
Location 1L Marble Canyon (river mile 34.79 east) at Nautiloid Canyon above river rapid	N 36° 27.921′ W 111° 50.176′ GPS and topo (error ± 10 m)	WNB platform facies exposed on 320-m^2 floor of slot canyon; nautiloids occur in dolomite about 0.2 m below the top of the bed; 80 nautiloids measured, but only 2 were observed in vertical orientation. Location originally described by Breed (1969).
Location 1M Marble Canyon (river mile 35.17 east) at hanging slot canyon entered by class 5.6 technical climb	N 36° 27.924′ W 111° 50.173′ GPS and topo (error ± 10 m)	WNB platform facies; hanging slot displays the bed but nautiloids are poorly exposed.
Location 1N Marble Canyon (river mile 35.70) at Bridge of Sighs and river riffle	N 36° 27.423′ W 111° 50.194′ GPS and topo (error ± 10 m)	WNB platform facies exposed in full thickness below natural rock bridge; full thickness of Whitmore Wash Member.
Location 1P Marble Canyon (river mile 35.75 east to 36.01 east) at high but climbable slope	N 36° 27.429′ W 111° 50.064′ GPS and topo (error ± 10 m)	WNB platform facies exposed with weathered nautiloids in weathered dolomite slope.
Location 1Q Marble Canyon (river mile 36.05 east) at Thirty-six Mile Rapid	N 36° 27.136′ W 111° 50.064′ GPS and topo (error ± 10 m)	WNB platform facies; last climbed slope exposure of the dolomite bed.
Location 2 Buck Farm Canyon	N 36° 24.501′ W 111° 53.367 ′ GPS and topo (error ± 15 m)	WNB platform facies; measured 15 nautiloids along coplanar surface about 0.8 m from top of lime packstone bed; coral, brachiopod and crinoid debris uncommon; only one coral head observed; water-escape pipes dominate upper half of bed.
Location 3 Saddle Canyon at prominent talus slope on north side	N 36° 22.034′ W 111° 53.625′ Topo (error ± 25 m)	Float limestone boulders beneath the Redwall Limestone cliff on the north side of the canyon; three large limestone boulders observed to contain 4 nautiloids; limestone color and water-escape pipes are diagnostic of WNB. Mr. Kyle George (personal communication, 2001) explained performing a technical climb on the left side of canyon to a prominent ledge with abundant in situ nautiloid fossils.
Location 4A Nankoweap Canyon, small hanging tributary channel on south side of main canyon	N 36° 17.214′ W 111° 52.903′ GPS and topo (error ± 6 m)	WNB platform facies within narrow slot canyon just above the pour point into the main canyon; limestone with nautiloids occurring about 0.7 m below the top of the bed; bottom of bed not exposed.
Location 4B Little Nankoweap Canyon	N 36° 18.515′ W 111° 52.633′ Topo (error ± 25 m)	WNB platform facies on weathered slope; abruptly overlain by Thunder Springs Member.

Location number and location name	Latitude Longitude†	Description of outcrop
Location 5 Sixtymile Canyon, north side of drainage	N 36° 12.574′ W 111° 49.430′ Topo (error ± 50 m)	Prominent disconformity beneath Thunder Springs Member; WNB is not present; outcrop sketched by Kurt P. Wise (Personal communication, 2001).
Location 6 Temple Butte, west side	N 36° 10.875′ W 111° 50.106′ GPS and topo (error ± 8 m)	Exposure of Whitmore Wash Member in contact with Thunder Springs Member; WNB does not appear; interpreted as a disconformity.
Location 7A Little Colorado River, main canyon, east wall	N 36° 08.7′ W 111° 42.3′ Topo (error ± 200 m)	Eastern wall of canyon exposes Whitmore Wash Member in contact with Thunder Springs Member; WNB does not appear; interpreted as a disconformity.
Location 7B Little Colorado River at entry of Salt Trail Canyon	N 36° 11.125′ W 111° 42.423′ Topo (error ± 100 m)	Large collapse deposit beneath Redwall Limestone cliff exposes Whitmore Wash Member in contact with Thunder Springs Member; WNB does not appear; interpreted as a disconformity.
Location 8A Horseshoe Mesa, north side along Grandview Trail	N 36° 01.997′ W 111° 58.865′ GPS and topo (error ± 30 m)	Exposure of Whitmore Wash Member in contact with Thunder Springs Member; 5-m-thick, massive peloidal limestone occurs within dolomite sequence; WNB does not appear. Section originally measured by McKee and Gutschick (1969, p. 618).
Location 8B Horseshoe Mesa, east side above trail north of Miners Spring	N 36° 01.20′ W 111° 58.21′ Topo (error ± 100 m)	Exposure of Whitmore Wash Member in contact with Thunder Springs Member; massive, light-gray peloidal limestone about 2-m thick occurs within dolomite sequence; WNB does not appear.
Location 9 North Kaibab Trail within Roaring Springs Canyon	N 36° 11.988′ W 112° 02.462′ GPS and topo (error ± 20 m)	The 2-m-thick, mottled, massive, medium-gray dolomite bed has vertical pipes and stylolites, but no nautiloids were seen in 20 m of outcrop. Dust from trail obscures study of the outcrop. Apparently WNB is present. Section measured by McKee and Gutschick (1969, p. 624).
Location 10 South Kaibab Trail	N 36° 04.899′ W 112° 05.243′ GPS and topo (error ± 7 m)	Whitmore-Thunder contact is definable within a dolomite or dolomitic limestone sequence. No evidence of WNB found (no nautiloids, no vertical pipes, poor display of stylolites). No light-gray, massive peloidal limestone observed. Thickness of Whitmore Wash Member is near normal. Apparently the boundary is a paraconformity or slight disconformity. Section measured by McKee and Gutschick (1969, p. 620).

Location number and location name	Latitude Longitude†	Description of outcrop
Location 11 Hermit Trail at Cathedral Stairs	N 36° 05.014′ W 112° 11.781′ GPS and topo (error ± 18 m)	Whitmore-Thunder contact is easily definable. Uppermost Whitmore dolomite bed is widely continuous without erosion. Overlap of chert beds demonstrates disconformity. No evidence of WNB found (no nautiloids, no vertical pipes, poor display of stylolites). No light-gray, massive peloidal limestone observed. Thickness of Whitmore Wash Member is near normal. Apparently the boundary is a significant disconformity. Section measured by McKee and Gutschick (1969, p. 623).
Location 12 South Bass Trail	N 36° 11.926′ W 112° 22.117′ Topo (error ± 30 m)	Weathered dolomite outcrop at top of Whitmore Wash Member apparently displays WNB. Vertical pipes, stylolites and bed structure indicate WNB. No definite nautiloids were seen in weathered outcrop. Outcrop described by Bill Hoesch (Personal communication, 2001).
Location 13 North Bass Trail	N 36° 15.01′ W 112° 18.90′ Topo (error ± 100 m)	Float boulder with nautiloid fossil beneath Redwall Limestone cliff.
Location 14 Elves Chasm, below Redwall Limestone cliff	N 36° 10.98′ W 112° 27.02′ Topo (error ± 200 m)	Float boulder with nautiloid fossil beneath Redwall Limestone cliff.
Location 15 Blacktail Canyon, drainage channel below the Redwall Limestone cliff	N 36° 14.465′ W 112° 28.303′ Topo (error ± 30 m)	Extraordinary display of limestone float boulders with nautiloid fossils beneath Redwall Limestone cliff. Along 2.5 km of the creek channel more than 20 water-polished float boulders were observed with nautiloids, pipes, mottled color, stylolites and bed structure indicative of WNB.
Location 16A Kanab Canyon, main creek channel, 220 m west of Showerbath Spring	N 36° 27.422′ W 112° 38.549′ Topo (error ± 20 m)	WNB platform facies exposed as slope on north side of channel; good bed structure, stylolites and water-escape pipes seen on dolomite slope; poor display of nautiloids.
Location 16B Kanab Canyon, within Scotty's Hollow	N 36° 26.945′ W 112° 38.737′ Topo (error ± 20 m)	WNB platform facies exposed at small tributary stream to Kanab Creek; good nautiloids, bed structure, stylolites and water-escape pipes seen on dolomite floor of stream. Nautiloids occur on horizon about 0.65 m beneath the top of the bed
Location 16C Kanab Canyon, main creek channel, 300 m west of Whispering Falls Canyon	N 36° 25.626′ W 112° 37.984′ Topo (error ± 40 m)	Float boulder of mottled dolomite with two large orthocone nautiloids beneath Redwall Limestone cliff.

Location number and location name	Latitude Longitude†	Description of outcrop
Location 17A Matkatamiba Canyon, within main canyon	N 36° 19.63′ W 112° 39.67′ Topo (error ± 100 m)	WNB platform facies in outcrop with large number of nautiloids. Bed is 2.1 m thick with horizon of nautiloids about 0.13 m from top of bed. Distinctive mottled color and stylolites.
Location 17B Matkatamiba Canyon, within eastern branch canyon	N 36° 19.83′ W 112° 39.37′ Topo (error ± 100 m)	WNB platform facies in outcrop with large number of nautiloids. Density of nautiloids as high as 4 per m^2 in dolomite.
Location 18A Havasu Creek below Mooney Falls at "Steel Ladder Ledge"	N 36° 15.871′ W 112° 42.648′ Topo (error ± 30 m)	WNB platform facies in outcrop as ledge of dolomite with 5 nautiloids about 0.2 m below the top of the bed.
Location 18B Havasu Creek, alcove on east side of canyon	N 36° 16.601′ W 112° 43.270′ Topo (error ± 30 m)	WNB platform facies in outcrop as sloping surface; nautiloids discernable in dolomite slope.
Location 19 National Canyon, first side canyon on left ascending from Colorado River	N 36° 14.74′ W 112° 52.35′ Topo (error ± 100 m)	WNB platform facies; photographs of nautiloids provided by Thomas J. Brownold and description of stratum provided by Andre Potochnik.
Location 20 Whitmore Wash, on upthrown side of Hurricane fault 0.5 km north of the Colorado River Type section of WNB	N 36° 09.364′ W 113° 11.993′ GPS and topo (error ± 10 m)	WNB platform facies type section; uppermost bed of the Whitmore Wash Member; nautiloids occur as indistinct circles on the weathered cliff about 1.0 m below the top of bed; water-escape pipes abundant. Type section originally described by McKee (1963).
Location 21 Andrus Canyon	N 36° 08.839′ W 113° 21.755′ Topo (error ± 200 m)	WNB platform facies in channel of canyon; slope and cliff exposure allowed poor exposure of nautiloids.
Location 22 Granite Park Canyon, on upthrown side of Hurricane fault	N 35° 57.645′ W 113° 13.972′ Topo (error ± 50 m)	WNB platform facies; dolomitic limestone exposed on northwestern slope of Granite Park Wash; good display of vertical pipes, stylolites and coarse horn coral debris; nautiloid horizon about 1.2 m beneath the top of the 2.2-m-thick bed.
Location 23 Picacho Butte	N 35° 13.003′ W 112° 48.571′ GPS (error ± 10 m)	Peloidal limestone with disconformities; light-gray massive bed is locally over 3 m thick. WNB is not present. Section measured by McKee and Gutschick (1969, p. 655).
Location 24 West of town of Seligman on south slope of small hill	N 35° 18.23′ W 113° 00.64′ Topo (error ± 200 m)	Whitmore-Thunder boundary exposed but no evidence of WNB. Chert boundary indistinct. Contact may be a disconformity.
Location 25 Shipley Quarry, north side of road between towns of Peach Springs and Nelson	N 35° 30.802′ W 113° 21.089′ GPS (error ± 10 m)	Whitmore-Thunder boundary exposed but no evidence of WNB. Chert boundary indistinct. Contact may be a disconformity. Sequence described by McKee and Gutschick (1969, p. 687).

Location number and location name	Latitude Longitude†	Description of outcrop
Location 26 Hill 5730 south of town of Peach Springs, east 2 km from End Water Corral	N 35° 26.750′ W 113° 26.567′ Topo (error ± 20 m)	Whitmore-Thunder boundary exposed but no evidence of WNB. Chert boundary indistinct. Found 4-m-thick "peloidal limestone" in the dolomite sequence described by McKee and Gutschick (1969, p. 648).
Location 27 Mulberry Spring Canyon	N 35° 36.287′ W 113° 21.907′ GPS and topo (error ± 10 m)	Whitmore-Thunder boundary exposed but no evidence of WNB. Chert boundary indistinct at excellent exposure of the dolomite sequence. Contact may be a disconformity.
Location 28 Plain Tank Canyon, long exposure in main channel	N 35° 40.259′ W 113° 34.001′ GPS and topo (error ± 10 m)	Whitmore-Thunder boundary exposed in several excellent outcrops but no evidence of WNB. Chert boundary indistinct within limestone sequence. Contact may be a disconformity.
Location 29 Bridge Canyon, east side above trail	N 35° 43.660′ W 113° 32.849′ Topo (error ± 50 m)	Whitmore-Thunder boundary exposed but no evidence of WNB. Chert boundary indistinct at excellent exposure of the limestone sequence. Peloidal limestone may be present. Contact may be a disconformity. Section described by McKee and Gutschick (1969, p. 639).
Location 30 Hindu Canyon, small tributary canyon on south side	N 35° 42.177′ W 113° 31.785′ Topo (error ± 30 m)	Whitmore-Thunder boundary exposed but no evidence of WNB. Chert boundary indistinct at exposure of the limestone sequence. Peloidal limestone may be present. Found one excellent nautiloid in large float boulder. Contact may contain a disconformity. Section described by McKee and Gutschick (1969, p. 638).
Location 31A Unnamed canyon north of Meriwhitica Canyon, north side	N 35° 49.457′ W 113° 43.679′ GPS (error ± 10 m)	WNB platform facies; both horizontal and upright nautiloids occur about 1.1 m below top of bed.
Location 31B Unnamed canyon north of Meriwhitica Canyon, south side	N 35° 49.538′ W 113° 43.598′ GPS (error ± 10 m)	WNB platform facies; nautiloids occur about 1.1 m below top of bed.
Location 32 Lost Creek, east side of canyon 2.5 km northeast of Clay Tank	N 35° 49.018′ W 113° 47.100′ GPS and topo (error ± 10 m)	WNB platform facies; bed exposed generally as a weathered slope with a few nautiloid fossils observed.
Location 33A Jeff Canyon, channel of main wash at axis of small monocline Reference section for WNB	N 35° 54.524′ W 113° 49.769′ GPS and topo (error ± 10 m)	WNB platform facies; excellent limestone bedding surfaces; bed is 1.98 m thick with horizon of nautiloids about 1.18 m below top of bed; abundant water-escape pipes, stylolites, and coarse fossil debris; the stream bed exposes a 9-m^2 surface displaying 21 nautiloids.

Location number and location name	Latitude Longitude†	Description of outcrop
Location 33B Jeff Canyon, west side slope	N 35° 53.973′ W 113° 50.398′ GPS (error ± 20 m)	WNB platform facies; long orthocone nautiloid with the axis of the fossil being parallel to the limestone cliff exposure.
Location 33C Jeff Canyon, cliff on west side of channel within main canyon	N 35° 53.976′ W 113° 50.663′ GPS and topo (error ± 7 m)	WNB platform facies; exposure of Whitmore Wash Member and overlying Thunder Springs Member is entirely a cliff; excellent internal structure of WNB is seen in limestone; large heads of colonial corals occur in the middle of the bed. No nautiloids seen on this cliff exposure.
Location 33D Jeff Canyon, slope on north side of entry road, 0.8 km southeast of Jeff Tank	N 35° 54.005′ W 113° 50.857′ GPS and topo (error ± 10 m)	WNB platform facies; slope exposes 2-m-thick bed of limestone; coarse middle zone of bed includes crinoids, rugose corals, bryozoans brachiopods and nautiloids.
Location 34 Quartermaster Canyon	N 35° 55.72′ W 113° 51.17′ Topo (error ± 200 m)	WNB platform facies; good bed structure seen in stream channel.
Location 35 Pigeon Wash	N 36° 16.660′ W 113° 49.343′ GPS and topo (error ± 10 m)	WNB platform facies; weathered slope exposure did not allow full definition of bed. Section originally described by McKee and Gutschick (1969, p. 644).
Location 36 Squaw Canyon	N 36° 23.635′ W 113° 48.359′ GPS (error ± 10 m)	WNB platform facies; dolomite bed in fault blocks associated with Grand Wash fault; nautiloids occur about 0.18 m below top of bed; nautiloid abundance low, probably less than one fossil per 10 m^2.
Location 37 Boundary Point on Lake Mead	N 36° 11.666′ W 114° 03.077′ Topo (error ± 20 m)	WNB platform facies exposed along shore of Lake Mead; dolomite bed with nautiloids occurring about 1 m below the top of the bed.
Location 38 Indian Hills Wash	N 36° 12.837′ W 114° 03.642′ Topo (error ± 30 m)	WNB platform facies; dolomite bed is exposed as cliff on north side of wash; nautiloids difficult to observe.
Location 39A Iceberg Ridge, middle section	N 36° 11.190′ W 114° 03.285′ GPS and topo (error ± 10 m)	WNB platform facies; weathered dolomite only visible in cross section. From the reference point traversed 500 m of slope northward. Found weathered circular structures interpreted to be nautiloids. Section described by Beus (1979).
Location 39B Iceberg Ridge, north section	N 36° 11.374′ W 114° 03.156′ GPS and topo (error ± 10 m)	WNB platform facies; weathered dolomite only visible in cross section. Found weathered circular structures interpreted to be nautiloids.
Location 39C Iceberg Ridge, south section on North Howland Cove	N 36° 09.609′ W 114° 04.081′ GPS and topo (error ± 10 m)	WNB platform facies; weathered dolomite only visible in cross section. Faulting prevented observation of continuity of bed.

Location number and location name	Latitude Longitude†	Description of outcrop
Location 40 Sunfish Cove	N 36° 08.203′ W 114° 05.154′ GPS (error ± 10 m)	WNB platform facies; bed outcrops in very short section of canyon 0.2 km from shore of lake.
Location 41 Garden Wash at the north end of Azure Ridge Reference section for WNB	N 36° 19.067′ W 114° 04.719′ GPS and topo (error ± 5 m)	WNB platform facies reference section; uppermost bed of Dawn Limestone; strike valley with 55° eastward-dipping dolomite bed along 350 m outcrop; more than 250 nautiloids occur on coplanar surface about 0.7 m below lowest chert of Anchor Limestone; stylolite position may explain extraordinary exposure; density of nautiloids average more than 2 fossils per m^2.
Location 42 Lime Wash at crossing of Lime Ridge, north side of wash	N 36° 18.806′ W 114° 15.074′ GPS and topo (error ± 10 m)	WNB platform facies; numerous nautiloids including 3 vertical and 1 strongly inclined; middle of bed has large coral heads and abundant rugose corals.
Location 43 North end of Lime Ridge, within unnamed canyon on west side of ridge, north of Lime fault	N 36° 23.396′ W 114° 16.115′ GPS and topo (error ± 12 m)	WNB platform facies; Dawn Limestone at contact with Anchor Limestone well displayed; limestone has water-escape pipes, stylolites and inverse grading of coarse fossils; syringoporid coral heads up to 20 cm diameter; outsized corals and nautiloids occur about 0.2 m below the top of the bed.
Location 44 Whitney Pocket area, stream bed exposure on west side of Virgin Mountains, 5.7 km northwest of Whitney Pocket Reference section for WNB	N 36° 34.261′ W 114° 09.811′ GPS and topo (error ± 19 m)	WNB slope facies exposed as vertical strata in the stream bed at the boundary between Dawn Limestone and Anchor Limestone; 9-m-thick lime grainstone bed has multiple flow units each having normal grading; water-escape pipes observed at three different levels within the bed. Grainstone bed weathers light gray in contrast to the darker-gray-weathering beds above and below. Nautiloid fossils not found.
Location 45 Government Spring on Bunkerville Ridge, slope exposure 500 m northwest of the spring	N 36° 38.866′ W 114° 11.120′ GPS and topo (error ± 10 m)	WNB slope facies; bed weathers light gray among the darker-gray-weathering strata above and below; lime grainstone bed is over 4 m thick with multiple flow units with normal grading; bed has rugose corals and crinoids, but no nautiloids were observed.
Location 46 Bunkerville Ridge at unnamed canyon on west side of ridge	N 36° 39.684′ W 114° 09.176′ GPS (error ± 10 m)	WNB slope facies in unnamed wash; 75°-west-dipping limestone as upper bed of Dawn Limestone exposed in 100 m strike valley; significant weathering; no nautiloids observed; water-escape pipes common.

Location number and location name	Latitude Longitude[†]	Description of outcrop
Location 47A Virgin River Gorge at Interstate Highway 15 northbound road cut (Arizona mile mark 13.45) Reference section for WNB	N 36° 55.309′ W 113° 51.153′ GPS and topo (error ± 10 m)	WNB slope facies; rock wall exposure is darker gray-brown unweathered; lime packstone to grainstone bed is 3.5 m thick; apparently a single normally graded, massive bed; slabs of coral occur at the base of the bed, not at the middle; very distinct boundary with overlying Thunder Springs Member. No nautiloids observed within the bed. Section described by Steed (1980) and Hintze (1986).
Location 47B Virgin River Gorge, north bank of river (at Arizona highway survey mark "P-10")	N 36° 55.368′ W 113° 51.124′ GPS and topo (error ± 15 m)	WNB slope facies; lime grainstone bed is 4 m thick; apparently a single normally graded bed; uppermost 0.5 m displays vertical water-escape pipes; below pipes faint consolidation lamination appears to exist; no dish structure is apparent; very distinct boundary with overlying Thunder Springs Member; one nautiloid was observed within a float boulder but none was observed within the bed; the bed weathers to light gray within darker gray weathering strata sequence.
Location 48 Beaver Dam Mountains on north side of Horse Canyon	N 37° 11.618′ W 113° 53.558′ GPS (error ± 10 m)	WNB slope facies; uppermost bed of Whitmore Wash Member is 6 m thick grainstone composed of multiple flow units; abundantly fossiliferous, but no nautiloids observed.
Location 49A Mormon Mountains, ridge with radio tower, near north end of ridge	N 36° 51.116′ W 114° 18.118′ GPS and topo (error ± 9 m)	WNB slope facies; middle bed of the Anchor Limestone is 6-m-thick, light gray, lime grainstone; no water-escape pipes, no nautiloids and no outsize clasts observed in the middle of the bed.
Location 49B Mormon Mountains, ridge with radio tower, south end of ridge just north of road	N 36° 50.373′ W 114° 18.008′ GPS and topo (error ± 9 m)	WNB slope facies; small outcrop shows light-gray, 6-m-thick grainstone within Anchor Limestone. Sequence under bed not exposed.
Location 50 Bitter Spring Gap, east side	N 36° 18.868′ W 114° 33.075′ GPS and topo (error ± 9 m)	WNB slope facies; light-gray, 9-m-thick grainstone occurring about 4 m above the base of the Anchor Limestone. Section measured by Langenheim (1956).
Location 51 Frenchman Mountain, north end of mountain, 370 m south of Lake Mead Boulevard	N 36° 11.858′ W 114° 59.537′ GPS (error ± 10 m)	WNB platform facies; nautiloids occur about 1.0 m below top of dolomite bed; coarse fossil debris includes large syringoporoid corals, large rugose corals, brachiopods and one gastropod.

Location number and location name	Latitude Longitude†	Description of outcrop
Location 52 Sunrise Mountain, unnamed canyon on west side of mountain. Reference section for WNB	N 36° 13.462′ W 114° 58.942′ GPS (error ± 10 m)	WNB platform facies reference section; uppermost bed of Dawn Limestone; lime packstone about 2.2 m thick is abundantly fossiliferous; numerous coplanar nautiloids with some standing vertical; coarse fossil debris with nautiloids is 0.3 m thick zone about 0.8 m below top of bed; rugose corals abundant; colonial corals up to 20 cm diameter; inverse grading with abundant water-escape pipes.
Location 53 Las Vegas Range, south end of range, 5.6 km east of June Bug Mine	N 36° 22.097′ W 115° 06.443′ GPS and topo (error ± 5 m)	WNB slope facies; middle of Anchor Limestone contains 10.5-m-thick, light-gray grainstone.
Location 54 Hidden Valley on west side of Arrow Canyon Range	N 36° 32.274′ W 114° 54.780′ GPS (error ± 8 m)	WNB slope facies; middle of Anchor Limestone contains thick, light-gray, lime grainstone.
Location 55 Tungsten Gap in Arrow Canyon Range Reference section for WNB	N 36° 38.867′ W 114° 48.593′ GPS and topo (error ± 20 m)	WNB slope facies; 9.5-m-thick, light-gray weathering, coarse grainstone; bed contains individual flow sublayers with normal grading or massive appearance; coarsest fossils are crinoids and rugose corals. Bed numbered "TG M17" in section described by Pierce (1969, p. 108) and noted by Page (1992).
Location 56 Arrow Canyon	N 36° 44.725′ W 114° 47.741′ GPS and topo (error ± 3 m)	WNB slope facies; middle of Anchor Limestone is 10.5-m-thick, light-gray-weathering grainstone with abundant crinoid columnals. Fossil debris is sorted into several rudimentary subunits within the bed; coarsest fossil debris is up to 3.5 cm.
Location 57 Meadow Valley Mountains, south end of mountains	N 36° 46.468′ W 114° 47.412′ GPS and topo (error ± 7 m)	WNB slope facies; middle of Anchor Limestone is 10.5-m-thick, light-gray-weathering grainstone in darker-gray weathering strata sequence. Section originally described by Webster and Lane (1987).
Location 58 Las Vegas Range, north end	N 36° 39.306′ W 114° 56.517′ GPS and topo (error ± 10 m)	WNB slope facies; lower-middle section of Anchor Limestone is 9-m-thick, light-gray-weathering, coarse grainstone in darker-gray weathering, finer-texture strata sequence. Most of the bed is composed of giant cross beds with the coarsest bioclastic fragments up to 1.5 cm.
Location 59 Indian Springs, Smith Mountain, northwest side	N 36° 31.265′ W 115° 43.714′ GPS and topo (error ± 8 m)	WNB slope facies; thick Anchor Limestone contains 14-m-thick, light-gray-weathering grainstone. Erosional and deformational structures occur within the bed. Section originally described by Belasky (1988).

Location number and location name	Latitude Longitude†	Description of outcrop
Location 60 Harris Springs Canyon, ridge on south side of drainage Reference section for WNB	N 36° 18.015′ W 115° 22.760′ GPS and topo (error ± 10 m)	WNB slope facies; middle of the Anchor Limestone contains bed of light-gray-weathering grainstone approximately 4-m thick..
Location 61 Lone Mountain, southeastern side	N 36° 14.278′ W 115° 18.703′ GPS and topo (error ± 10 m)	WNB slope facies; 4-m-thick, light-gray-weathering grainstone; weathered slope with Anchor Limestone section above bed well exposed, but base of bed and below covered or faulted.
Location 62 Mountain Springs Pass	N 36° 01.514′ W 115° 30.573′ GPS and topo (error ± 5 m)	WNB slope facies; uppermost bed of Dawn Limestone Member is 3-m-thick, light-gray-weathering grainstone. Section described by Belasky (1988).
Location 63 Sloan Quarry, first ridge west of main quarry	N 35° 56.961′ W 115° 13.046′ Topo (error ± 100 m)	WNB slope facies; thin, light-gray-weathering grainstone.

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Table DR2. RIVER LOG OF STUDY LOCATIONS FOR WHITMORE NAUTILOID BED WITHIN MARBLE CANYON.

Location name or feature	River mile†	Geologic description
Redwall Cavern (south buttress of overhang)	33.05 east	Mound structure in upper Thunder Springs Mbr.
"Little Redwall Cavern"	33.85 east	Lowest beds of Thunder Springs Mbr.
Rock wall at very low water	33.90 east	First appearance of WNB; one large nautiloid fossil exposed in cross section of dolomite
River bank at very low water	33.98 west	WNB with large cephalopods (1 coiled and 1 straight)
Rock slope, distinctively white, abraded, unweathered	34.18 west	Full thickness of Thunder Springs Mbr. overlying WNB
Small slot canyon with river ledges on both sides	34.19 west	Ledges expose full 2-m thickness of WNB with 38 nautiloids measured
"Square Hole Ledge"	34.20 east	Large, river-scoured ledge of WNB with 49 nautiloids measured
"Big Boulder Beach and Delta"	34.29 west	WNB as ledge and slot with 8 nautiloids measured
"Five Caves Ledge"	34.35 east	Wide ledge with 69 nautiloids measured
"Hanging Spring Terrace"	34.46 west	High ledge of WNB with 12 nautiloids measured
Vertical rock face, 130-m-high	34.50 east	Cross section of large chert/dolomite mound structure in Thunder Springs Mbr. above WNB
"Railroad Tie Ledge"	34.63 east	WNB on narrow, river-scoured alcove with 3 nautiloids measured
Nautiloid Canyon above river rapid	34.79 east	WNB exposed on 320-m^2 floor of slot canyon with 80 nautiloids measured
Hanging slot canyon entered by class 5.6 technical climb	35.17 east	Hanging slot canyon displays WNB, but nautiloids are poorly exposed
Bridge of Sighs and river riffle	35.70 west	Full thickness of Whitmore Wash Mbr. exposed below natural bridge
High but climbable dolomite slope	35.75 east to 36.01 east	Full thickness of Whitmore Wash Mbr. with weathered slope and nautiloids in WNB
Thirty-six Mile Rapid	36.05 east	Last climbed slope exposure of WNB

† Locations are given as conventional Colorado River miles downstream from Lees Ferry.