Permian Salt in the Holbrook Basin, Arizona

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Includes 6 plates and 21 pages of text (including title page)

Introduction

The current report depicts the general extent and thickness of Permian salt in the Holbrook Basin on two maps and four well-log sections. Plate 1 shows the aggregate thickness of salt and the limits of halite and potash deposition. Plate 2 represents the structural top of the evaporite interval relative to sea level. Plates 3 through 6 are two pairs of well-log sections across the salt basin. One pair trends northeast and includes Plate 3, a structure section, and Plate 4, a stratigraphic section. The other pair trends northwest and includes Plate 5, a structure section, and Plate 6, a stratigraphic section.

The area studied covers about 8000 square miles in east-central Arizona including Townships 10 through 21 North and Ranges 13 through 31 East in Coconino, Navajo and Apache Counties (Figure 1). Salt underlies about 3500 square miles and potash underlies about 600 square miles (Plate 1). Anhydrite and gypsum extend beyond the limit of the halite deposits shown on Plate 1 (Plates 2-6).

The towns of Winslow, Sanders, Springerville, and Heber define the approximate northwest, northeast, southeast, and southwest extent of the study area. Surface elevations are 4900 ft, 5900 ft, 6900 ft, and 6500 ft, respectively.

The area slopes from the pine-covered terrain (Mogollon Rim) between Heber and Springerville on the south to the desert terrain between Winslow and Sanders on the north. This near dip slope is known as the Mogollon Slope. The Black Mesa Basin is north of Winslow. The Defiance uplift is northeast of Sanders.

Wells

The 223 wells correlated for the study include 135 wells drilled for potash in the 1960s and 1970s and 88 wells drilled for oil, gas, or LPG storage. Most of the potash tests were drilled by Arkla Exploration Company and Duval Corporation. Arkla drilled 47 holes and Duval drilled 61. Only 5 of the potash tests were drilled through the entire thickness of salt. Three of the potash tests were abandoned before penetrating salt and 127 were drilled only into the upper 100-300 ft of salt. Only 24 of the oil and gas tests were drilled through the entire thickness of salt within the limits of salt deposition (Holbrook Salt Basin). Most of the potash tests were cored through at least the upper 100 ft of salt and provide good information to "calibrate" the wireline logs for correlation with the oil and gas tests.

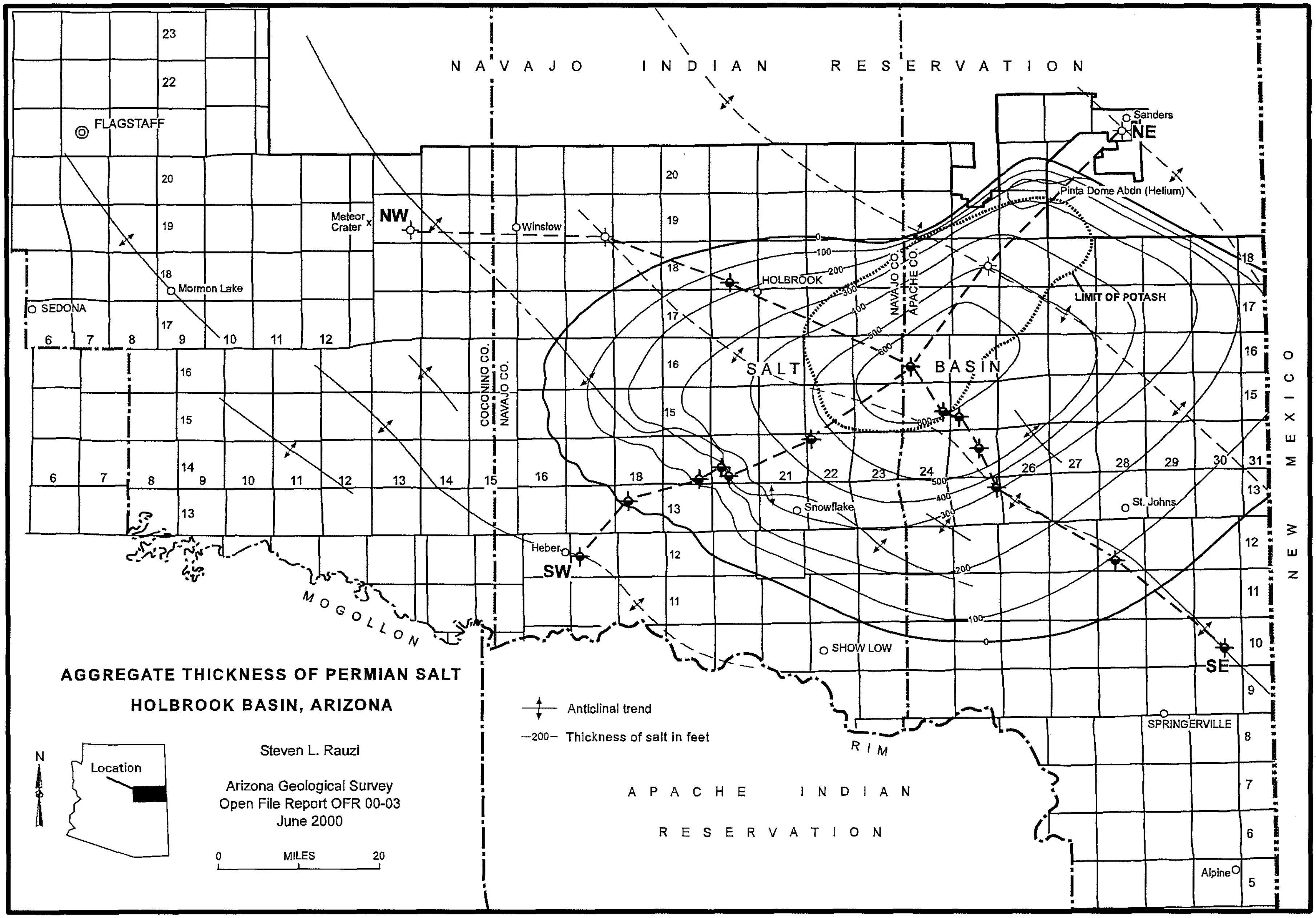

Figure 1. Location map of study area showing limit of Holbrook Salt Basin, aggregate thickness of Permian salt (Plate 1), lines of cross-sections (Plates 3-6), and regional structural trends.

Wireline logs from the 18 wells used in the cross sections show the typical response of the various log types in the Permian strata. These are the best available logs completely penetrating the salt and include gamma ray, neutron, density, sonic, and resistivity logs. The spontaneous potential curve is not useful in the Permian Holbrook Salt Basin or in the underlying pre-Permian carbonate rocks.

Many of the early oil and gas tests were drilled through the salt with freshwater drilling mud which resulted in large-diameter, washed out holes. As a result, cuttings samples and wireline logs from these wells are not as useful as they could have been in accurately measuring thickness of salt. Salt-saturated mud must be used when drilling salt to obtain good cuttings of salt and maintain in-gauge hole. Otherwise, the salt goes into solution rather than circulating to the surface as good cuttings samples and the hole diameter becomes too large to obtain useful information from neutron, density, and sonic logs.

The Arkla Exploration Company #1 New Mexico and Arizona Land Company (NMA) core test in Sec. 19, T. 16 N., R. 24 E. (Figure 2) penetrated the entire salt interval and may be considered the type log for the Permian Holbrook Salt Basin in east-central Arizona. The thickest interval of halite in the Holbrook Salt Basin is in the Arkla #1 NMA core test, which contains an aggregate 655 ft of salt in 1500 ft of strata and defines the approximate depositional center of the Holbrook Salt Basin (Plate 1). Both pairs of wireline log cross sections intersect in this well (Plates 1-6).

Geologic Setting

Peirce and Gerrard (1966) discussed the general geologic setting and stratigraphy of the evaporite deposits of the Holbrook Basin and presented the broader aspects of evaporite distribution and deposition. They attributed halite deposition in the Holbrook Basin to intermittent restriction of marine waters from the south across a generally southeast-trending barrier approximately coincident with the present Mogollon Rim (Peirce and Gerrard, 1966, p. 9). Blakey (1979), who described the lower Permian stratigraphy of the southern Colorado Plateau, attributed halite deposition in the Holbrook Basin to sabkha and low-energy restricted marine conditions (Blakey, 1979, p. 128). The coastal sabkha and salt pan environments described by Handford (1981) in the Permian lower Clear Fork Formation in the Permian Basin

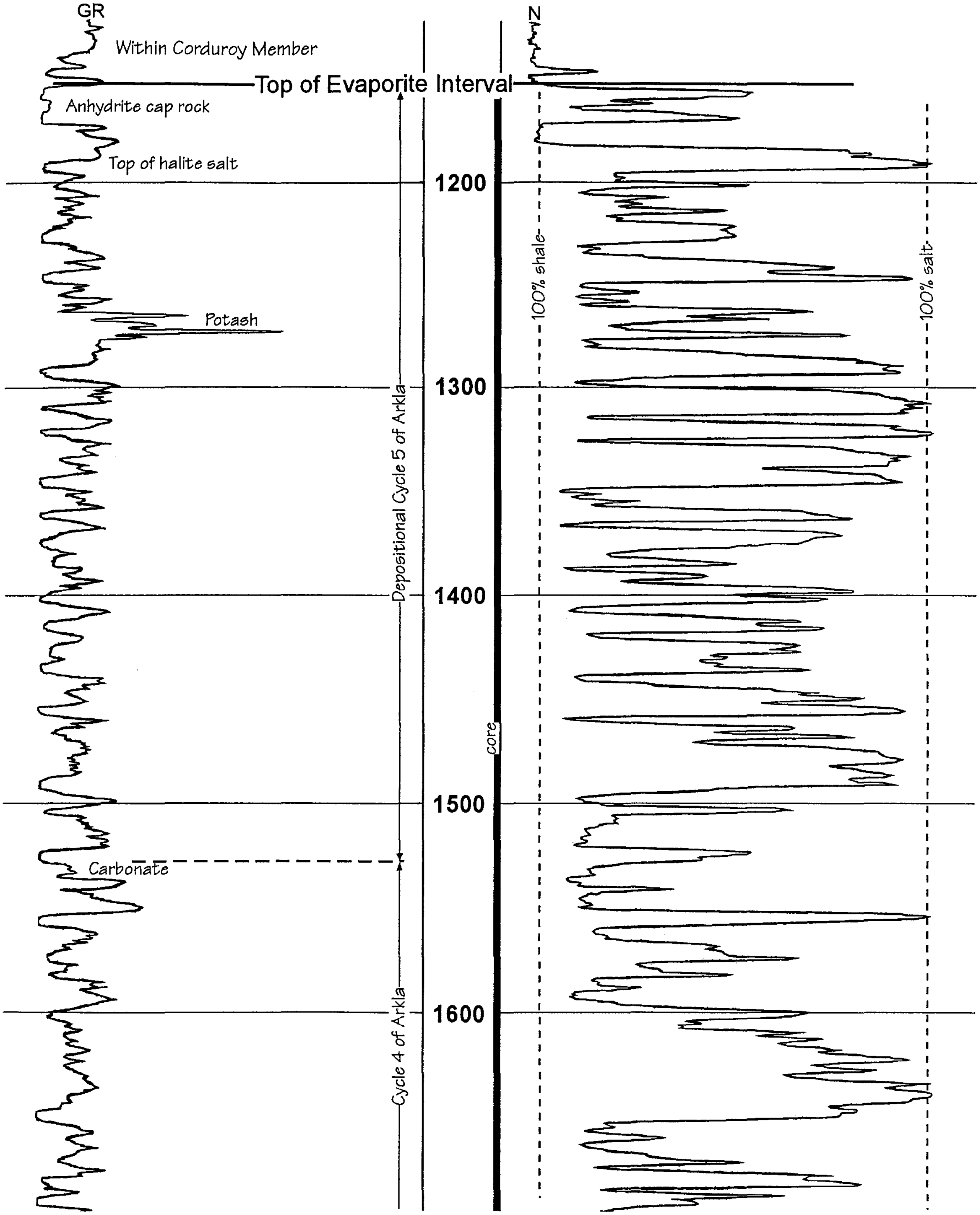

Figure 2. Arkla #1 NMA core test in Sec. 19, T. 16 N., R. 24 E. Typical gamma-ray neutron character of bedded salt in the Permian Supai Formation, Holbrook Salt Basin, Arizona. This well has 655 ft of salt in 1500 ft of section and defines the approximate depositional center of the Holbrook Salt Basin (see Plate 1).

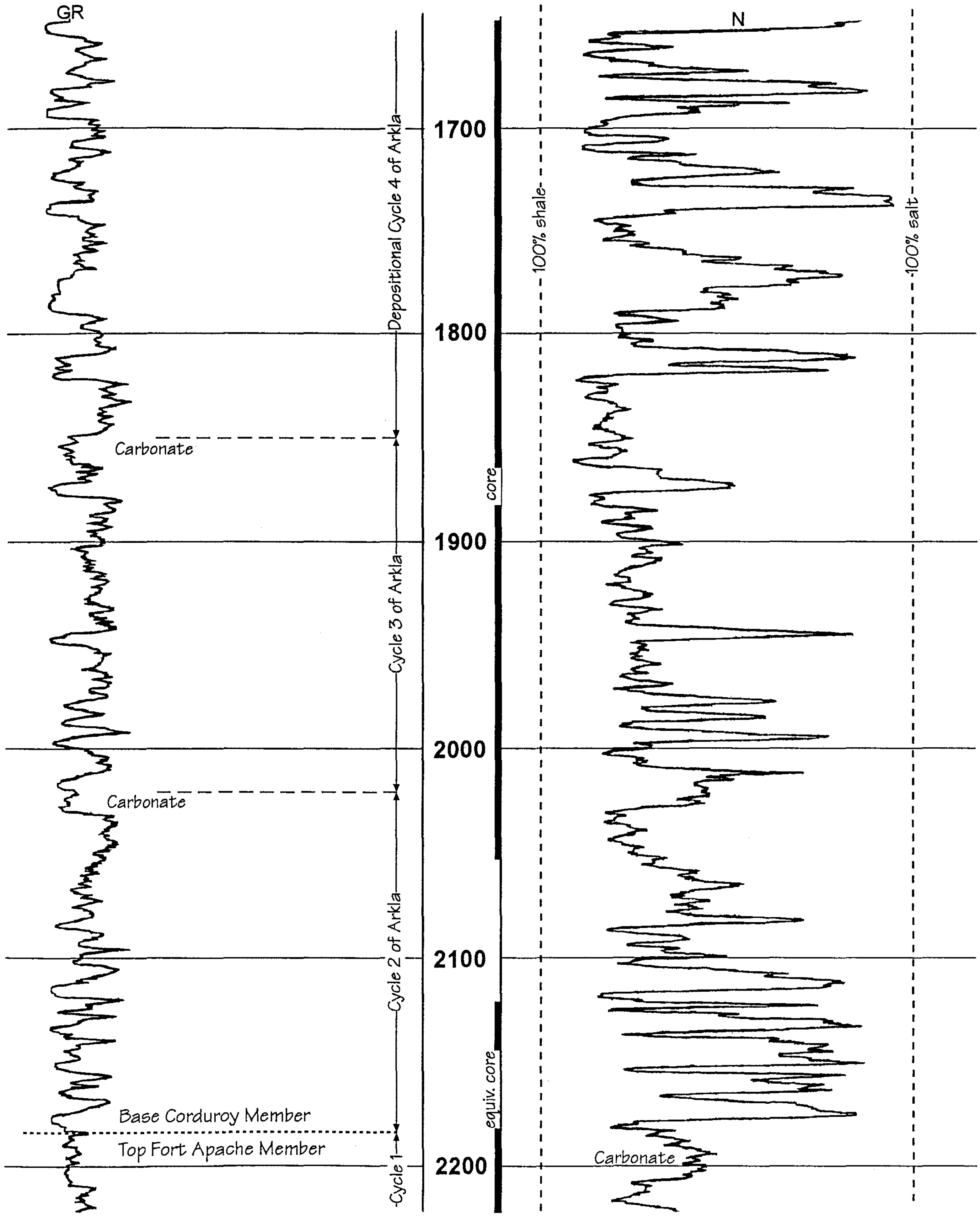

Figure 2 (continued). Arkla #1 NMA core test in Sec. 19, T. 16 N., R. 24 E. Typical gamma-ray neutron character of bedded salt in the Permian Supai Formation, Holbrook Salt Basin, Arizona. This well has 655 ft of salt in 1500 ft of section (See Table 1).

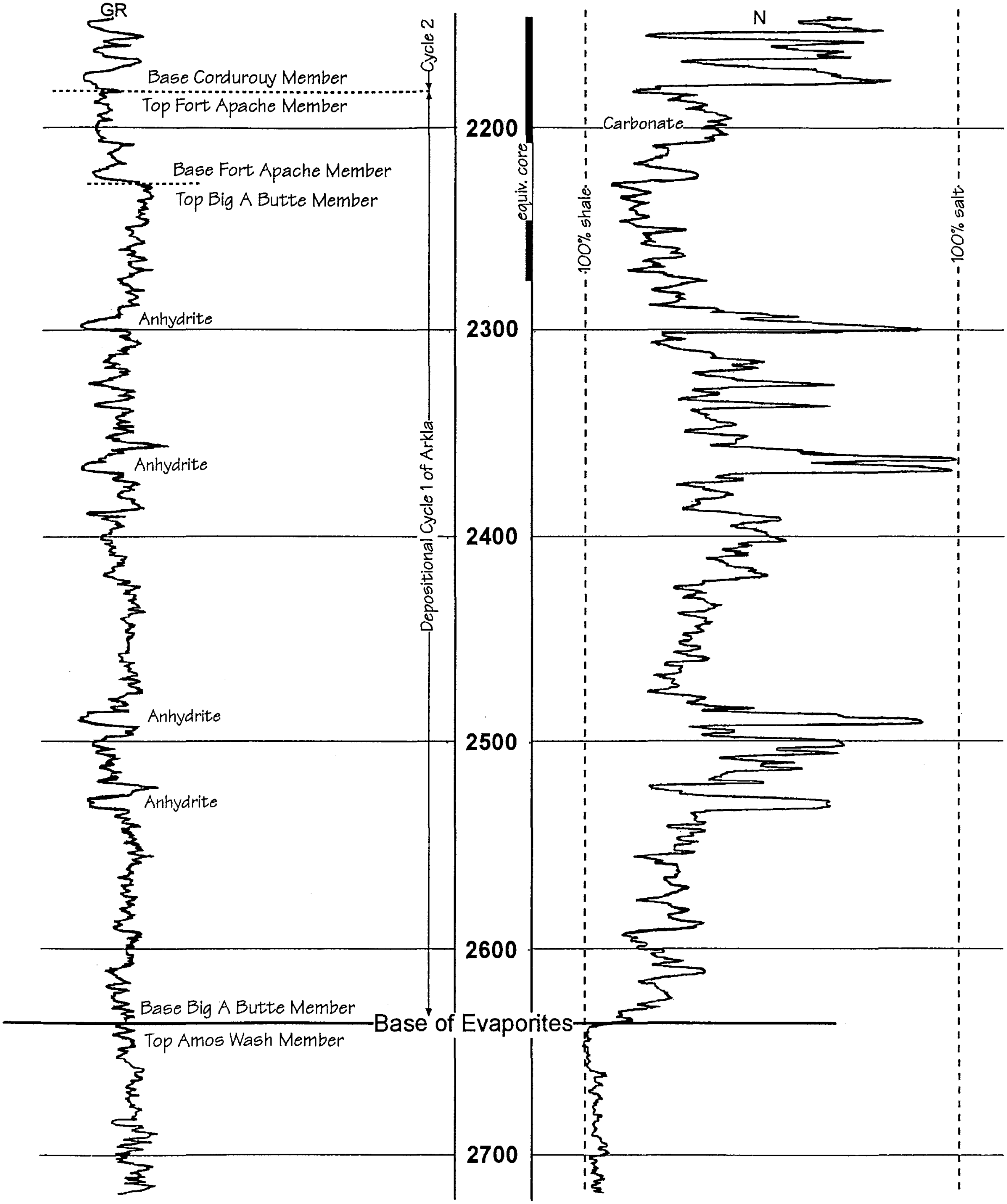

Figure 2 (continued). Arkla #1 NMA core test in Sec. 19, T. 16 N., R. 24 E. Typical gamma-ray neutron character of bedded salt in the Permian Supai Formation, Holbrook Salt Basin, Arizona. This well has 655 ft of salt in 1500 ft of section (See Table 1).

of west Texas may be comparable to environments of salt deposition represented in the Permian Supai Formation in the Holbrook Basin of east-central Arizona.

Stratigraphy

The stratigraphic names used by Winters (1963, p. 9) to define the widely exposed Supai Formation in the Fort Apache region adjacent to the south are used in this report. Winters' nomenclature is readily applied to subsurface wireline log correlation of the Supai Formation in the Holbrook Basin. From the top, the Supai Formation consists of the Corduroy, Fort Apache, Big A Butte, and Amos Wash Members. This interval is correlative with the Yeso and underlying Abo Formation equivalents in adjoining New Mexico.

Blakey (1979 and 1990), Elston and DiPaolo (1979), and Peirce (1989) developed other nomenclature for Permian rocks in east-central Arizona based on regional interpretations and correlation of the Hermit Formation of the Grand Canyon region with units in east-central Arizona. Blakey (1979, Figure 3) correlated the Hermit Formation with the Amos Wash Member, which he renamed the upper Supai Formation (Blakey, 1990, Figure 2). Elston and DiPaolo (1979, Plate 1) correlated the Hermit Formation with the uppermost clastic interval of the Big A Butte Member of Winters. Peirce (1989, Figures 4 and 5) interpreted the Hermit Formation to pinch out between the Esplanade Sandstone and overlying Coconino Sandstone southeast of the Grand Canyon.

The Permian Coconino Sandstone consists of light-colored, mostly fine-grained cross-bedded sandstone and overlies the Supai Formation throughout the Holbrook Basin. The top of the Coconino Sandstone was used as the datum for the stratigraphic sections (Plates 4 and 6) because it is easily and consistently identified in subsurface wireline logs by almost all well operators or stratigraphic investigators. The base of the Coconino Sandstone is not easily identified in subsurface wireline logs. The base of the Coconino as picked by different well operators and stratigraphic investigators varies by as much as several hundred feet. The base of the Coconino in the current study was picked at the first distinct shale break on gamma ray and lithologic logs below which there is an increase in interstitial clay and interbedded red to orange very fine-grained sandstone, siltstone and shale (Plates 3-6).

The Supai Formation consists largely of red to reddish-brown clayey siltstone and halite with anhydrite, gypsum, and carbonate. Halite grades laterally into anhydrite, gypsum, and mudstone at the perimeter of the basin and ultimately into fine-grained clastic strata beyond the perimeter of the salt basin. The Supai Formation overlies the Naco Formation (Pennsylvanian) throughout the Holbrook Basin and onlaps structurally high Precambrian granitic and metamorphic rocks to the east (Plates 3-6; see also Rauzi, 1996a).

Salt

Arkla Exploration Company identified 5 cycles of halite deposition in the Supai Formation based on regionally extensive carbonate beds (Figure 2, Table 1). Each cycle starts with deposition of halitic mudstone and halite and ends with a fining upward sequence of siltstone and shale overlain by carbonate, which could represent flooding of the marginal and inner sabkha by marine water. Cycle 1 starts at the base of the Big A Butte Member and ends with deposition of the Fort Apache Member. Cycles 2 through 4 start at the base of the Corduroy Member and end with deposition of what Arkla referred to as the first regionally extensive dolomite below the top of the evaporite strata. Cycle 5 starts at the top of the first dolomite and ends with the deposition of regionally persistent anhydrite beds that cap the evaporite strata (Figure 2, Plate 2).

The main body of salt in the Holbrook Salt Basin occurs in the Corduroy Member of the Supai Formation (Figure 2, Plates 3-6). Salt beds in the Corduroy Member are most commonly 1-5 ft thick but range in thickness from inches up to 30 ft and are interbedded with mostly red to brown clayey siltstone and shale, some gray to brown carbonate, and white to gray anhydrite. Black carbonaceous shale and dark-brown to black dolomite are reported in some core descriptions. Aggregate thickness of salt in the Corduroy Member ranges up to 530 ft.

Salt in the Corduroy Member grades from very clear to muddy. Clay in muddy salt grades from finely disseminated clay to small to large irregular blebs, stringers, and bands of clay. Interbedded clay and silt generally contain thin to very irregular bands and inclusions of fine to medium crystalline salt and small anhydrite blebs. Halite generally fills fractures in the interbedded clay and silt. Anhydrite generally occurs as small to medium to occasional very large blebs and stringers in the salt. Lithologic logs of the American Stratigraphic Company (Amstrat) record numerous salt casts in the sample cuttings of interbedded clay, silt, carbonate, and anhydrite from the oil and gas tests drilled with freshwater drilling mud.

The Fort Apache Member is a distinctive carbonate marker unit in the Supai Formation that can be traced throughout central and east-central Arizona (Winters, 1963, p. 10; Gerrard, 1966, p.

Table 1. Cycles of halite deposition in the Permian Supai Formation, Holbrook Basin, Arizona, as identified from core data by Arkla Exploration Company.

WELL	CYCLE 1		CYCLE 2		CYCLE 3		CYCLE 4		CYCLE 5		TOTAL	
	ft	%	ft	%	ft	%	ft	%	ft	%	ft	%
Arkla #1 (19-16n-24e)												
Interval	2180-2638		2017-2180		1846-2017		1530-1846		1138-1530		1138-2638	
Sandstone	30	6.5									30	2.0
Siltstone	254	55.4	53	32.5	87	50.9	136	43.0	82	20.9	612	40.8
Carbonate	38	8.3	12	7.4	23	13.4	8	2.5	0	0	81	5.4
Anhydrite	10	2.2	2	1.2	16	9.3	32	10.1	62	15.8	122	8.1
Halite	126	27.5	96	58.9	45	26.3	140	44.3	248	63.3	655	43.7
Total	458	99.9	163	100.0	171	99.9	316	99.9	392	100.0	1500	100.0
Arkla #56 (30-16n-24e)												
Interval									1004-1388		1004-1388	
Sandstone									0	0.0	0	0.0
Siltstone									94	24.5	94	24.5
Carbonate									0	0.0	0	0.0
Anhydrite									58	15.1	58	15.1
Halite									232	60.4	232	60.4
Total									384	100.0	384	100.0
Arkla #3 (18-14n-25e)												
Interval	2034-2541		1873-2034		1690-1873		1358-1690		885-1358		885-2541	
Sandstone	26	5.1									26	1.6
Siltstone	284	56.0	47	29.1	101	55.2	171	51.5	133	28.1	736	44.4
Carbonate	50	9.9	11	6.8	23	12.6	8	2.4	0	0.0	92	5.5
Anhydrite	27	5.3	15	9.3	13	7.1	29	26.2	124	26.2	208	12.6
Halite	120	23.6	88	54.7	46	25.1	124	37.3	216	45.6	594	35.9
Total	507	99.9	161	99.9	183	100.0	332	99.9	473	99.9	1656	100.0
Arkla #4C (28-14n-25e)												
Interval	1947-2447		1785-1947		1600-1785		1261-1600		794-1261		794-2447	
Sandstone	22	4.4									22	1.3
Siltstone	248	49.6	57	35.2	96	51.9	175	51.6	167	35.8	743	44.9
Carbonate	48	9.6	11	6.8	25	13.5	8	2.4	0	0.0	92	5.6
Anhydrite	31	6.2	17	10.5	16	8.6	65	19.2	110	23.5	239	14.4
Halite	151	30.2	77	47.5	48	25.9	91	26.8	190	40.7	557	33.7
Total	500	100.0	162	100.0	185	99.9	339	100.0	467	100.0	1653	99.9

2441; Conley, 1977, Map G-7; Peirce, 1989, p. 366). In the subsurface, the base of the Fort Apache Member is easily picked in well logs from the western margin of the Holbrook Salt Basin between Winslow and Heber, Arizona, to western Catron County, New Mexico, because it is characterized by a distinctive gamma ray log curve break. The base of the Fort Apache Member is an important subsurface correlation horizon in east-central Arizona and western Catron County, New Mexico (Figure 2, Plates 3-6; see also Rauzi, 1999, Plates 1-3).

The Fort Apache Member consists of an upper anhydrite and lower dolomite up to 108 ft thick in the St. Johns-Springerville area. It grades to a thin, 10 ft thick carbonate with some anhydrite and gypsum to the northwest in the Townsend well west of Winslow in Sec. 26, T. 19 N., R. 13 E. To the northeast, the Fort Apache Member pinches out as a distinct carbonate unit southwest of Sanders in the Brown & Associates #2 Chambers Sanders well in Sec. 27, T. 21 N., R. 28 E. (Plates 5 and 6; see also Gerrard, 1966, p. 2444).

Salt in the Big A Butte Member of the Supai Formation is usually muddy and interbedded with mostly red-brown siltstones and shale and lessor very fine-grained sandstone, gray-brown carbonate, and several thin but persistent beds of anhydrite. Aggregate thickness of salt in the Big A Butte Member ranges up to 151 ft (Table 1). The base of the evaporite interval defines the base of the Big A Butte Member in the Holbrook Basin of east-central Arizona (Figure 2, Plates 3-6).

The Amos Wash Member of the Supai Formation consists of red to maroon to brown mudstone, siltstone, and very fine-grained sandstone. The dashed correlation line within the Amos Wash Member on Plates 3-6 is close to the top of the conspicuous chocolate-brown claystone where Peirce and Wilt (1970, p. 61-66; Plate 15) placed the questionable top of the Pennsylvanian system in the lower Supai Formation in east-central Arizona.

Potash

A zone of potash minerals (sylvite, carnallite, and polyhalite), which underlies about 600 square miles and ranges up to 38 ft thick, is present near the top of cycle 5 salt in the Corduroy Member (Figure 2). The area underlain by potash is nearly coincident with the approximate depositional center of the Holbrook Salt Basin (Plate 1). Scattered blebs and traces of potash are reported up to 30 ft below the main potash "pay zone." Even though potash was the subject of considerable exploration in the 1960s and 1970s, there has been no commercial production or solution mining of potash. This may be because the nearly 16.5 townships underlain by potash are approximately centered under the southern part of the Petrified Forest National Park.

Sylvite is generally described in conventional core reports as clear to pink to milky, red-rimmed small to large irregular blebs and makes up to 39% of salt in the "pay zone." Carnallite is generally described as maroon in color and makes up to 80% of salt in the "pay zone." Polyhalite is generally described as pink blebs.

Plate 1 shows that deposition of potash was confined to the northern and northeastern part of the Holbrook Salt Basin where the salt reached its maximum aggregate thickness. Desiccation of saline mud flats and salt pans of the inner sabkha may have had its greatest effect in the area outlined by the potash deposits.

Thickness of Salt

The aggregate thickness of salt in Plate 1 was determined by comparing cuttings samples with lithologic, electrical, radioactivity, and sonic logs. Mud salinity and the caliper curve were important correlation tools in the early oil and gas test holes that were drilled with freshwater mud, which became salty during drilling.

Salt becomes increasingly muddy and thinner bedded in the western part of the Holbrook Salt Basin, suggesting lateral transition into saline mud flats around the western perimeter of inner sabkha salt pans. Cycle 5 salt cored in the upper 103 ft of the Corduroy Member of the Supai Formation in the Duval #56 State in Sec. 2, T. 16 N., R. 18 E. has an aggregate thickness of 42 ft and is described as muddy halite and halitic mudstone. The thickest halite bed reported in the Duval #56 core is 4 ft thick.

Cycle 5 salt cored in the upper 105 ft of the Corduroy Member in the Duval #54 State in Sec. 2, T. 16 N., R. 20 E. has an aggregate thickness of 77 ft and is described as halite to locally dirty halite to dirty halite. The thickest halite bed reported in the Duval #54 core is 18 ft thick.

Amstrat lithologic logs for the Pan American Petroleum Company (Pan Am) wells #B-1 Aztec Land & Cattle in Sec. 9, T. 16 N., R. 18 E. and #A-1 Aztec Land & Cattle in Sec. 5, T. 16 N., R. 20 E. report salt casts about 280 ft above the first reported salt bed. The first reported salt casts in the Pan Am #B-1 correlates with cored salt in the Duval #56 State, which is 2 miles northwest of the #B-1. The first reported salt casts in the Pan Am #A-1 correlate with the large diameter, washed-out hole on the caliper curve and with cored salt in the Duval #54 State, which is 3 miles east of the #A-1 hole.

Both of the Pan Am wells were drilled with freshwater mud that dissolved salt for about 280 ft before the mud became salty enough to circulate good salt cuttings to the surface. The gamma ray-neutron and caliper curves indicate that the actual top of the halite in the 2 Pan Am wells is at or above the first reported salt casts in the Amstrat lithologic logs.

Neal (1999) described numerous sinks and related solution-collapse structures just east of Chevlon Creek near the western limit of salt deposition in Township 16 North and Ranges 16 and 17 East (Plate 1). The Eisele #1 McCauley well just west of Chevlon Creek in Sec. 1, T. 16 N., R. 16 E. was drilled with freshwater mud that became salty and is reported to contain about 20 ft of salt at a depth of 1500 ft. The McCauley well defines the approximate western limit of the Holbrook Salt Basin. The evaporite strata of the Supai Formation grade laterally into fine grained clastic rocks west of the McCauley well (Plates 5 and 6).

Bahr (1962, p. 119) described a regionally retreating collapse front just south of the Holbrook Anticline near the southwestern limit of salt deposition in Townships 13 and 14 North and Ranges 18 to 20 East. Cycle 5 salt is noticeably thin south of the surface trend of the Holbrook Anticline in the California Oil #1 State in Sec. 12, T. 14 N., R. 18 E, Taubert & Steed #1 Babbitt Brothers in Sec. 35, T. 14 N., R. 19 E., and Webb Resources #29-1 Federal in Sec. 29, T. 14 N., R. 20 E. The wavy thickness contours, which suggest dissolution of salt through this area (Plate 1), generally parallel the northern boundary of the internal drainage pockmarked with numerous sinks and related solution-collapse structures south of the Holbrook Anticline that Bahr (1962, p. 118) attributed to the dissolution of Permian salt.

A saltwater plume in the overlying Coconino Sandstone that extends northward from the area of internal drainage, sinks, and related solution features to Holbrook is further evidence of dissolved salt on the southwestern margin of the Holbrook Salt Basin (Mann, 1976, Plate 3). Mann (1976, p. 17) attributed the high concentration of sodium and chloride in the plume to solution as fresh groundwater moved down the Mogollon Slope through the halite beds in the uppermost part of the Supai Formation. Neal, Colpitts, and Johnson (1998) report more than 500 sinkholes, fissures, depressions, and other evaporite karst features along the dissolution front at the southwestern margin of the Holbrook Salt Basin.

Salt commonly grades into gypsum and anhydrite to the south and southeast. This suggests lateral transition into a sulfate brine pan in a marginal sabkha environment. Sample examination compared with Amstrat lithologic logs and gamma ray-neutron log character in the Pan Am #1A NMA in Sec. 12, T. 13 N., R 25 E., Pan Am #1B NMA in Sec. 25, T. 12 N., R. 23 E., Sumatra Energy #1-17 Santa Fe in Sec. 17, T. 12 N., R. 26 E., and Tenneco #1B Federal in Sec. 4, T. 10 N., R. 24 E. indicates that gypsum and anhydrite have largely replaced halite in the Corduroy Member in the southern and southeastern part of the Holbrook Salt Basin as was noted by Peirce and Gerrard (1966, p. 8).

Aggregate thickness of salt in the Tenneco #1B Federal well is primarily muddy salt to shale with intergrowths of salt in the Big A Butte Member of the Supai Formation. Salt thickness of 95 ft in the Tenneco well on Plate 1 is based on increased thickness of the Big A Butte Member, increase of freshwater mud salinity to 80,000 ppm chloride, salt casts recorded in the Amstrat lithology log, and clean gamma ray curve opposite large-diameter hole or washouts in the Big A Butte Member.

Handford (1981, p. 771-772) described marginal-sabkha facies forming low, natural barriers that impeded drainage of water from the inner sabkha. A low, east-west barrier or marginal sabkha environment between the inner salt pans of the Holbrook Salt Basin and basins to the south appears to have been located about 5 miles south of the Tenneco #1B Federal well. The marginal sabkha barrier is defined by the close correlation of anhydrite and interbedded clastic beds in the Big A Butte Member in the Tenneco #1X Fort Apache well southwest of Show Low in Sec. 31, T. 10 N., R. 21 E. and the Eastern Petroleum #1A Coyote Creek north of Springerville in Sec. 27, T. 10 N., R. 30 E., a distance of about 70 miles. Difference in thickness of the Big A Butte Member between the Tenneco #1X and Eastern #1A wells is only 90 ft.

In contrast, the Big A Butte Member in the Tenneco #1B Federal has gained 238 ft in thickness just 5 miles north of the east-trending barrier defined by the Tenneco #1X well (Figure 3). The gain in thickness in the #1B well is attributed to sabkha deposition of salt and halitic mudstone between interbedded anhydrite and clastic beds. Thickness of the Corduroy Member between the #1B and #1X wells differs by only 22 ft.

The Tenneco #1B Federal well is located very close to the southern limit of salt deposition in the Holbrook Salt Basin. It records the onset of sabkha salt deposition in saline mud flats and salt pans on the southern margin of the Holbrook Salt Basin across a barrier with possibly other salt

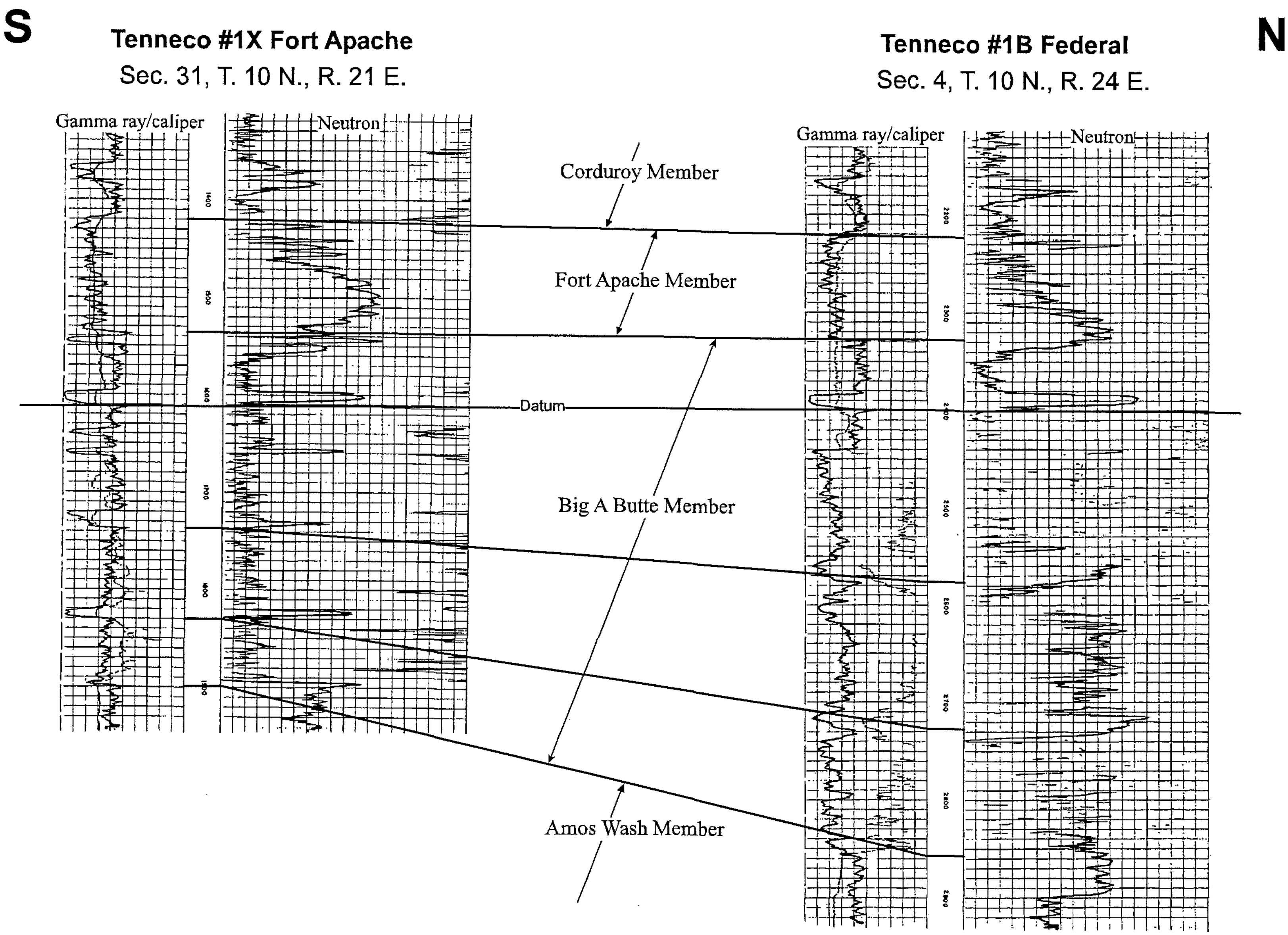

Figure 3. Big A Butte Member of the Supai Formation at the southern boundary of the Holbrook Salt Basin. Increase in thickness of 238 ft in the #1B Federal is attributed to sabkha deposition of salt and halitic mudstone. Note washed-out hole in the #1B where chlorides increased to 80,000 ppm. Thickness of the overlying Corduroy Member varies by only 22 ft between the two wells.

basins to the south (Rauzi, 1996b). In any event, the Tenneco #1B Federal well shows abrupt thickening of the Big A Butte Member on the southern margin of the Holbrook Salt Basin.

The Holbrook Salt Basin extends eastward into New Mexico between Sanders on the north and St. Johns on the south (Plates 1 and 2). Salt was reported in a well drilled south of Zuni Pueblo in western Cibola County, New Mexico, and salt is present at Zuni Salt Lake in western Catron County, New Mexico. Zuni Salt Lake is a shallow saline lake within a maar crater (or diatreme) that is supported by springs that derive salt from the Permian Supai Formation (Bradbury, 1966). Zuni Salt Lake is 34 miles east of St. Johns, Arizona, and 16 miles east of the New Mexico state line.

John Somers, President of High Plains Petroleum, reported salt in the Permian Yeso Formation (equivalent of Supai Formation) in the Burr Oil & Gas #1 Zuni Tribal well in Sec. 34, T. 8 N., R. 20 W. in Cibola County, New Mexico. The Burr Oil & Gas well is 17.5 miles east-northeast of the Duval #38 Santa Fe well in Sec. 27, T. 17 N., R. 29 E., Apache County, Arizona, and 6.5 miles east of the New Mexico state line. Duval cored 259 ft of salt in the upper Corduroy Member of the Supai Formation in its #38 Santa Fe well. Numerous 10-15 ft thick beds of salt are described in the Duval #38 core.

The northeastern margin of the Holbrook Salt Basin is defined by the Duval #21 Santa Fe in Sec. 26, T. 20 N., R. 27 E. and the Duval #17A Santa Fe in Sec. 31, T. 20 N., R. 29 E. No salt is present in these wells (Plate 1).

The northern boundary of the Holbrook Salt Basin in Township 19 North and Ranges 23 through 25 East is defined by the Duval #29 State core test in Sec. 36, T. 19 N., R. 23 E. and the Williams #1 Fee core test in Sec. 8, T. 18 N., R. 24 E. The 297 feet of halite in the Williams #1 has pinched out to zero in the Duval #29, which is only 2.5 miles northwest of the Williams well. The abrupt loss of salt between the Duval #29 and Williams #1 suggests that faulting may have controlled the northern limit of salt deposition in this area.

Salt becomes increasingly thinner bedded and lenticular and is replaced by orange to red siltstone and shale northwest of Holbrook in Townships 17 and 18 North and Ranges 20 and 21 East. The Corduroy Member of the Supai Formation contains 185 ft of increasingly lenticular salt in the Cree #1 Hunt in Sec. 31, T. 18 N., R. 20 E. and the Cree #1 Scorse in Sec. 33. T. 18 N., R. 20 E. suggestive of saline mud-flat and ephemeral salt-pan deposits. Lenticular salt is apparent in the Corduroy Member in the Arrowhead-Besoyan #1 State (Sec. 28, T. 18 N., R. 20

E.), Tucson Oil & Gas #1X Woodman-Federal (Sec. 30, T. 18 N. R. 20 E.), and the Cree #1 Hunt and #1 Scorse wells. Siltstone cored in the Big A Butte Member in the #1 Scorse contains embedded salt crystals interbedded with anhydrite and has only a few very thin beds of salt. This suggests saline mud-flat deposits and very thin, ephemeral salt-pan deposits.

Structure

Several anhydrite beds define the top of the Permian evaporite interval. The most persistent of the capping anhydrite beds can be correlated throughout the Holbrook Salt Basin and was used to construct a structure contour map on the top of the evaporite interval (Plate 2). The structure map is based in part on the structure of the overlying Coconino Sandstone (Conley and Scurlock, 1976) and the base of the Fort Apache Member in the St. Johns-Springerville area (Rauzi, 1999, Plate 1). The first halite usually lies about 5-20 ft below the capping anhydrite bed (Figure 2).

The top of the evaporite interval in the northeastern part of the area shows a lot of differential "puckering" or settling over the approximate center of inner sabkha salt pan deposition. This indicates flowage of salt, as do core descriptions of "schistose" salt, high-angle contacts, slickensides on fracture planes, well developed slickensides, bedding-plane faults, and strong flowage. The contact between the capping anhydrite and salt dips at 30° in some wells.

The top of the evaporite interval in the southern part of the area is consistent with the regional north to northeast dip of the Mogollon Slope, which generally dips less than 1° northeast with local variations of 1-5° north or south. The regional northeast dip of the Mogollon Slope is profoundly interrupted northwest of Snowflake by the asymmetrical Holbrook Anticline, which can be traced west-northwest for more than 45 miles. Bahr (1962, p. 119) showed that the reversal of northeast dip is the result of salt dissolution.

The southwest-trending cross sections (Plates 3 and 4) show that the axis of the Holbrook Anticline, which is prominently displayed in the Coconino Sandstone at the surface and the top of the evaporite interval (Plate 2), does not persist below the base of the Fort Apache Member (see also Peirce and Wilt, 1970, Plate 8 and Conley, 1977, Map G-7). Cycle 5 salt in the Corduroy Member is noticeably thin in the Webb Resources #29-1 Federal in Sec. 29, T. 14 N., R. 20 E. The structure section on Plate 3 shows an anticline at the top of the Naco Formation just south of the surface axis of the Holbrook Anticline.

Subsurface Storage

Liquefied petroleum gas (LPG) is stored in caverns leached into cycle 5 salt of the Corduroy Member of the Supai Formation just north of the railroad in Sec. 8, T. 18 N., R. 24 E. The caverns range from 120-220 ft in height with a maximum radius of up to 118 ft. Cavern volumes are sufficient to store 6 to 9.6 million gallons of LPG. Good potential exists for additional salt cavern development along the extent of the railroad in east-central Arizona.

Subsurface Pressure

High subsurface pressures were reported below the capping anhydrite in several of the stratigraphic wells drilled to delineate potash deposits in the 1960s and 1970s.

The Kern County Land #1 State in Sec. 2, T. 18 N., R. 24 E. blew gas for 26 hours. The blow was not diminished at the time of control. Analysis of the gas indicated 6.22% methane, 4.09% helium, and 95.10% nitrogen.

The New Mexico and Arizona Land Company #3 Fee in Sec. 28, T. 17 N., R. 22 E. blew out at a depth of 1040 ft while coring. The gas was reported to contain helium.

The Arkla Exploration #22 NMA in Sec. 23, T. 17 N., R. 23 E. blew air while coring. A drill stem test of the interval 1342-1523 ft recovered 480 ft of drilling mud. The tool was opened with a strong blow. Both initial and final flowing pressure was 243 pounds. Initial shut-in pressure was 338 pounds. Final shut-in pressure was 243 pounds.

The Arkla Exploration #37 NMA in Sec. 25, T. 16 N., R. 22 E. blew out at 821 ft in the straight hole and at 816 ft and 818 ft in the side track hole. A drill stem test of the interval 779-819 ft recovered 270 ft of mud and drilling fluid. Initial flowing pressure was 175 pounds and final flowing pressure was 175 pounds. Initial shut-in pressure was 240 pounds and final shut-in pressure was 175 pounds.

The Arkla Exploration #68 NMA in Sec. 19, T. 16 N., R. 23 E. blew out at 896 ft and 970 ft. All drill fluid was lost both times.

The Arkla Exploration #10 NMA in Sec. 27, T. 16 N., R. 23 E. blew fluid out at 940 ft, 959 ft, and 1007 ft. The gas tested 2.4% helium at the Kerr McGee lab at Navajo, Arizona.

The Arkla Exploration #7 State in Sec. 10, T. 15 N., R. 23 E. blew out while drilling.

These higher pressures may be due to salt flowage, with the main mass of salt acting as a pump accumulating pressure and fluids in stratigraphic traps in the Holbrook Salt Basin. Most of the synclines, anticlines, and domes in the Holbrook Salt Basin and along the Mogollon Slope have not yet been drilled. They may hold commercial amounts of oil or gas.

Shows of oil and gas

Bahr (1962, p. 121), Peirce and Wilt (1970, Table D), and Conley and Giardina (1979, Tables D, E, and F) published compilations of reported oil and gas shows in wells drilled in the Holbrook Basin. Shows of oil and gas were reported in several of the potash tests.

Helium shows from a drill stem test of the interval 1009-1021 ft were reported in the New Mexico and Arizona Land Company #3 in Sec. 27, T. 17 N., R. 22 E.

Oil stained dolomite from 1660-1670 ft was reported in the New Mexico and Arizona Land Company #2 in Sec. 24, T. 15 N., R. 22 E.

Moderate oil stain and black carbonaceous blebs were reported throughout the core of a gray-brown, dense dolomite from 2050-2086 ft in the Arkla Exploration #2 NMA in Sec. 23, T. 15 N. R. 24 E. A drill stem test of the interval 2054-2086 ft recovered 20 ft of drilling mud. Low final flowing and shut-in pressures indicated that the zone was tight.

Several shows were reported in the L.M. Lockhart #1 Aztec Land & Cattle Company well in Sec, 33, T. 14 N., R. 20 E. A drill stem test of the Fort Apache from 1678-1742 ft blew for 18 minutes. Analysis of the gas indicated 23.8% methane, 3.2% ethane, 70.7% nitrogen, and 0.267% helium. The gas had a calculated BTU value of 357.

Arkla Exploration described the Fort Apache Member from 2034-2091 ft in its #3 NMA (Sec. 18, T. 14 N., R. 25 E.) as sucrosic, dark gray-brown dolomite specked with tarry substance and having good oil stain and saturation. Black shale laminations were reported in siltstone underlying the Fort Apache Member. Slight stain and approximately 20 units of gas were reported throughout a dolomite from 1700-1705 ft, about 330 ft above the Fort Apache Member.

Any change in permeability is important when strata are as flat as those in the Holbrook Basin, especially in light of the many reported shows of oil and gas. Synclines, monoclines, flanks of synclines and anticlines, and even flat-lying strata become as prospective for commercial accumulations of oil and gas as do the anticlines. As a result, there is good potential for not only potash development and additional storage of LPG but for stratigraphic traps of oil or gas in the many undrilled synclines, anticlines, and domes throughout the Holbrook Basin and all along the Mogollon Slope between Flagstaff and the New Mexico state line. Most of the Mogollon Slope along the southern limit of salt deposition in the Holbrook Basin has not been drilled for oil or gas.

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