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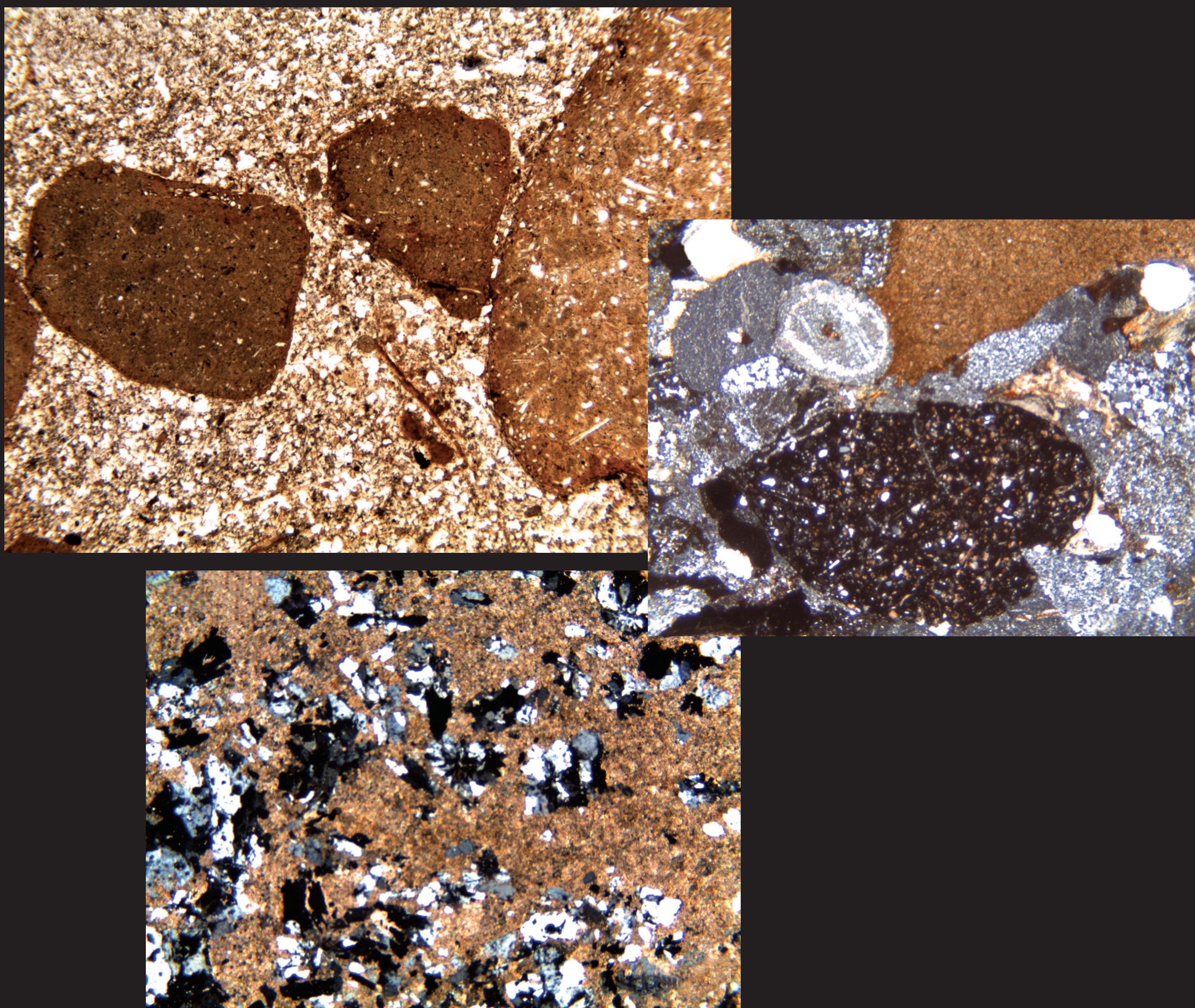
Mid-Permian Phosphoria Sea in Nevada and the Upwelling Model



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U.S. Department of the Interior
U.S. Geological Survey

Mid-Permian Phosphoria Sea in Nevada and the Upwelling Model

By Keith B. Ketner

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By Keith B. Ketner

Abstract

The Phosphoria Sea extended at least 500 km westward and at least 700 km southwestward from its core area centered in southeastern Idaho. Throughout that extent it displayed many characteristic features of the core: the same fauna, the same unique sedimentary assemblage including phosphate in mostly pelletal form, chert composed mainly of sponge spicules, and an association with dolomite. Phosphoria-age sediments in Nevada display ample evidence of deposition in shallow water. The chief difference between the sediments in Nevada and those of the core area is the greater admixture of sandstone and conglomerate in Nevada. Evidence of the western margin of the Phosphoria Sea where the water deepened and began to lose its essential characteristics is located in the uppermost part of the Upper Devonian to Permian Havallah sequence, which has been displaced tectonically eastward an unknown distance. The relatively deep water in which the mid-Permian part of the Havallah was deposited was a sea of probably restricted east-west width and was floored by a very thick sequence of mainly terrigenous sedimentary rocks. The phosphate content of mid-Permian strata in western exposures tends to be relatively low as a percentage, but the thickness of those strata tends to be high. The core area in and near southeastern Idaho where the concentration of phosphate is highest was separated from any possible site of upwelling oceanic waters by a great expanse of shallow sea.

Introduction

The Phosphoria Formation and its local correlatives, the Shedhorn Sandstone, and the Park City Formation, are well-studied deposits of the mid-Permian Phosphoria Sea centered in southeastern Idaho. The northern, eastern, and southeastern extensions of the Phosphoria Sea are quite well known, but its western and southwestern extent, the nature of its western margin, and the nature of its western sediments are commonly left to the imagination.

The Upwelling Model

Many published accounts express the belief that the Phosphoria Formation was deposited at the continental margin beneath upwelling waters as summarized in the following statement authored by several eminent authorities:

> "Comparison with modern phosphorite occurrences has led many workers to conclude that most if not all ancient phosphorite giants were laid down beneath upwelling depocenters. This has remained a particularly attractive scenario, especially for deposits that developed, as today, along western continental margins (e.g. Permian Phosphoria Formation…)" Glenn and others (1994, p. 772).

Actually, a large body of new and old evidence indicates the Phosphoria in its core area was deposited hundreds of kilometers from any possible site of oceanic upwelling. Apparently the Phosphoria was not alone in this regard. The following statement regarding the Tethyan phosphate deposits was included in the same report by Glenn and others (1994).

> "Yet Glenn and Arthur (1988) stressed that upwelled waters are rapidly depleted of nutrients, that productivity is greatly diminished within relatively short distances of the locus of upwelling, and that some of the Tethyan deposits were laid down beneath relatively shallow waters that were apparently tens to hundreds of kilometers removed from the open Tethyan margin to the north."

Published and unpublished data dispel most of the mystery concerning the area west of the depocenter of the Phosphoria, (fig. 1) and the present report seeks to bring the relevant facts and sources together in a brief outline.The plan of the present report is to briefly describe the Permian stratigraphy at several localities in Nevada and to document the nature of the mid-Permian phosphatic sediments by means of descriptions and illustrations. Some of the localities described are known to the author only through published reports, but most are known from first-hand observation in the field and laboratory.

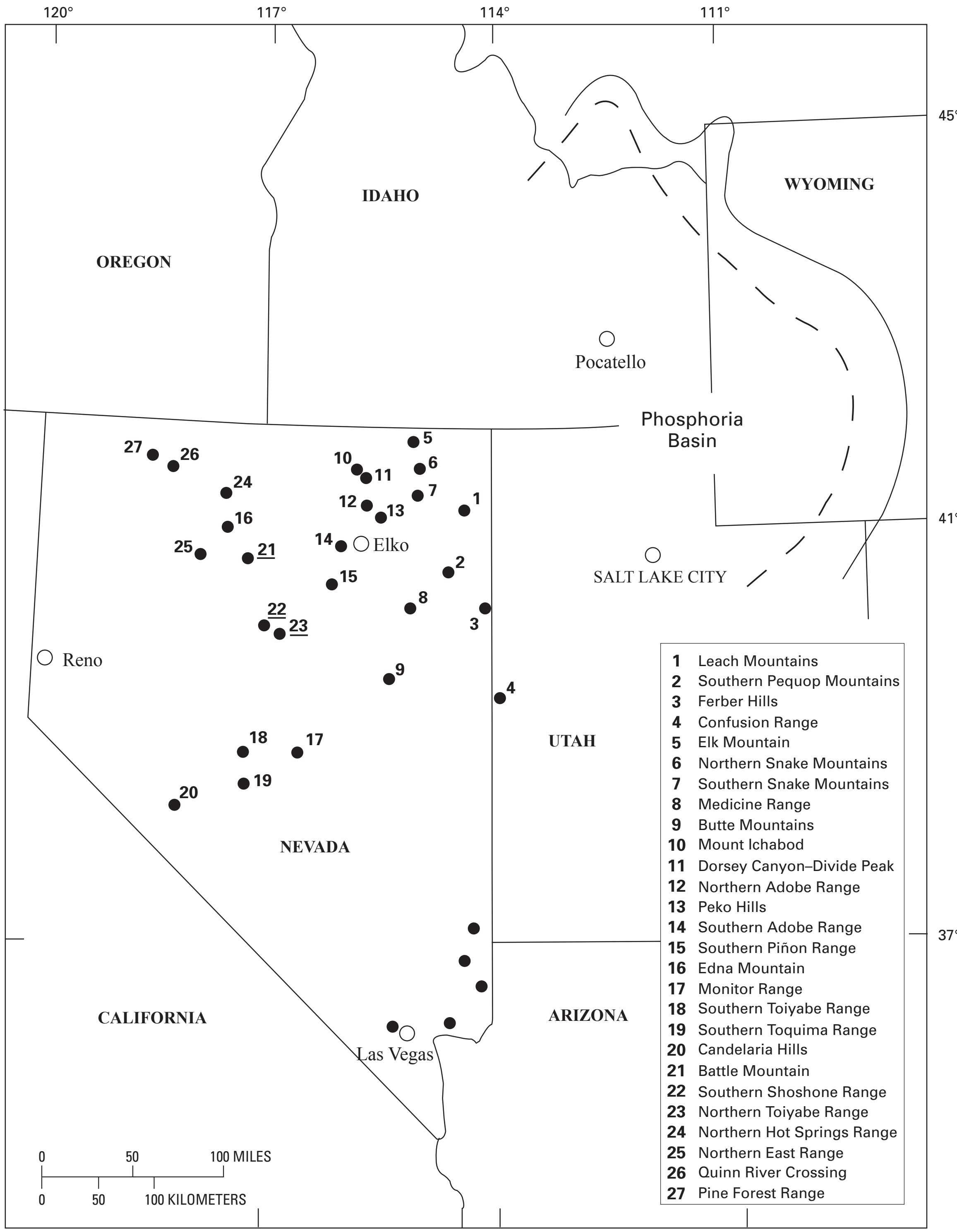

Figure 1. Index map of Nevada, Idaho, and vicinity showing localities to which reference is made, and the outline of the core Phosphoria Formation centered on southeastern Idaho (dashed line is boundary between organic-rich siltstone and carbonate in the mid-Permian according to Piper and Link, 2002; solid line is the outer limit of phosphate according to Sheldon and others, 1967). Both lines project through southern Nevada north of the cluster of Kaibab exposures near Las Vegas. Underlined localities (21, 22, 23) are Havallah sequence transported eastward on thrust faults.

Stratigraphy and Definitions

The stratigraphic divisions of the Permian proposed by McKelvey and others (1959) of Phosphoria, Shedhorn, and Park City, and names used in eastern Nevada such as Kaibab, Plympton, Murdock Mountain, and Gerster are difficult to apply in much of Nevada where local names have long been used, and no attempt is made here to regularize the nomenclature. For brevity, in much of the discussion that follows, those formations are subsumed under the term mid-Permian strata.

Some terms used in this report are defined as follows: *mid-Permian* is late Leonardian and Guadalupian; *Phosphoria Sea* is the mid-Permian sea in which rocks of the type Phosphoria, Shedhorn, and Park City Formations were deposited. *Phosphoria Sea* is also used in this report for its extension westward and southwestward in Nevada where phosphate is a significant component of its sediments. The Phosphoria Sea thus defined was a small part of a much more extensive largely epicontinental sea that extended from Nevada to Kansas and Montana to Texas (McKee, Oriel, and others, 1967, plates 4B and 5B); *phosphate* is essentially the mineral apatite—or more specifically carbonate fluorapatite; *phosphorite* is a rock rich in phosphate; *phosphate bloom* is the bluish-white sheen produced by weathering on the surface of phosphatic rocks; *steinkern* is the phosphatic filling of a small shell; *pellet* is a small ovoid grain of phosphate which may or may not have a nucleus of another mineral; *length-slow chalcedony* is chalcedony with an anomalous optical feature; the slow ray is parallel with the fibers, which was shown to indicate replacement of an evaporite mineral (Folk and Pittman, 1971). Because length-slow chalcedony has been reported in pelagic deposits, however, its presence is not, by itself, evidence for a shallow depositional environment (Keene, 1983).

In this report, the Permian rocks at every locality were correlated with rocks of the type Phosphoria by means of fossils including bivalves and conodonts, backed up by observation of stratigraphic position and the unique Phosphoria hallmarks of pelletal phosphate and spicule chert. They are described in order starting in the northeast and ending in the northwest with an excursion to the far south.

Shallow Marine Deposits of the Phosphoria Sea in Nevada

Northern and Central Nevada

1. Leach Mountains

The stratigraphic sequence in the Leach Mountains includes Permian beds designated, from the base upwards: Kaibab Limestone, Meade Peak Phosphatic Shale Member of the Phosphoria Formation, Murdock Mountain Formation, and Gerster Limestone (Wardlaw and others, 1979). The Meade Peak is primarily composed of phosphatic siltstone, chert, and shale. The Murdock Mountain is composed principally of cherty dolomite and the Gerster is principally cherty bioclastic limestone. According to Martindale (1986), "Deposition of the Meade Peak Phosphatic Shale Tongue in the Leach Mountains is interpreted to have taken place in very shallow water, as based on sedimentary structures and textures, types of fossils and their mode of preservation, and the evident intertidal to supratidal deposition of underlying and overlying rocks." Thickness of the interval between the Kaibab and Gerster is about 1,600 m of which the Meade Peak is about 100 m. Chemical analyses of 15 randomly selected samples of the Meade Peak yielded several in the 1 to 4 percent P_2O_5 range, one of 19 percent, and one of 28 percent (this report). Figures 2 and 3 are samples of phosphatic siltstone from the Meade Peak.

2. Southern Pequop Mountains

The Permian sequence in the southern Pequop Mountains overlies Pennsylvanian beds of the Ely Limestone unconformably. From the base upwards, it includes a thick sequence of silty, sandy limestone assigned to several formations. The overlying mid-Permian strata of the Phosphoria Sea include the Kaibab Limestone, the Plympton Formation, and the Gerster Formation (Fraser and others, 1986). The Kaibab is rich in bioclastic debris and replacement chert nodules. The Plympton is principally massively bedded dolomite and dolomitic limestone containing sparse replacement chert nodules. Noncarbonate beds of the Plympton include sparse sandy beds; phosphatic shale, limy and dolomitic quartz siltstone, phosphorite, and chert composed of sponge spicules, of which the axial canals are filled with phosphate. Analyses of 12 random samples of the Plympton yielded nine in the 1 to 10 percent P_2O_5 range and three of about 30 percent (this report).

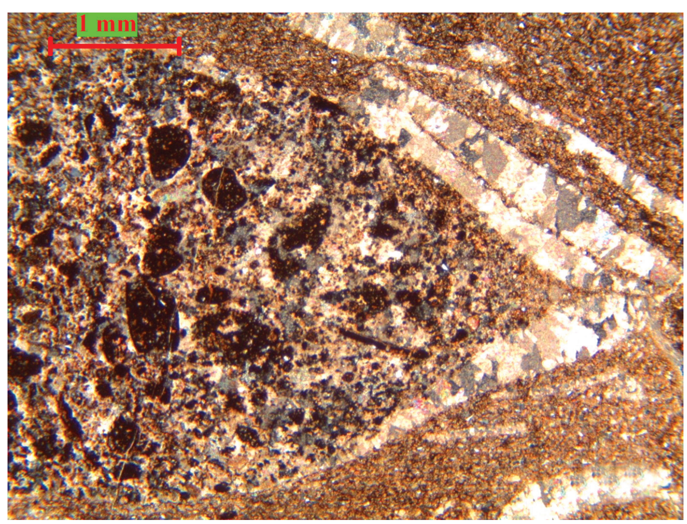

Figure 2. Leach Mountains, Meade Peak Member; steinkern with part of carbonate shell intact. Phosphate pellets and steinkerns are in a phosphatic siltstone matrix.

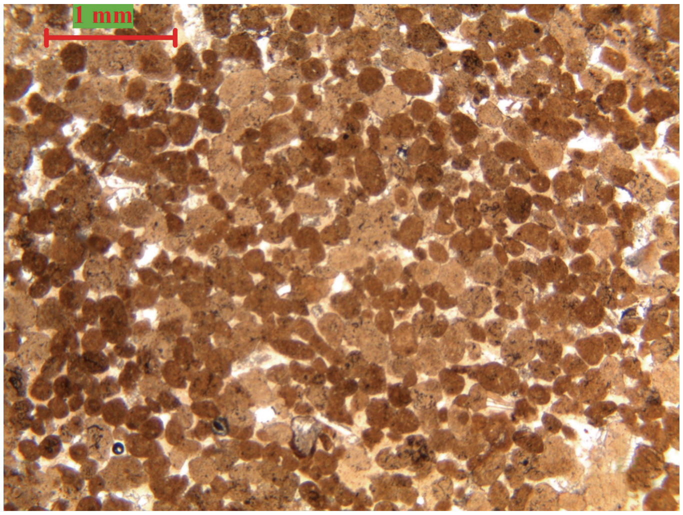

Figure 3. Leach Mountains, Meade Peak Member, closely packed pellets with interstitial quartz silt and carbonate.

Many lithic components of the formation contain length-slow chalcedonic blebs which, according to Folk and Pittman (1971), indicate the former presence of evaporite nodules. The Plympton is about 350 m in thickness. The Gerster Limestone is thick bedded and coarse grained, and contains abundant large brachiopods in a matrix of fossil debris with replacement chert nodules.

A persistent breccia occupies a position low in the Plympton Formation. This breccia is composed of mainly angular fragments of all lithic components of the Plympton. Calcite veins and cavity fillings are very abundant and in places constitute more than half the volume of the breccia. This unit is interpreted to be both a collapse breccia formed by the solution of evaporites and a superposed tectonic breccia formed by a low-angle fault that tended to coincide with the evaporite zone.

The dolomite, the collapse breccia, and the abundant fauna of brachiopods indicate the Permian rocks of the southern Pequop Mountains were deposited in a shallow marine depositional environment.

3. Ferber Hills

The Ferber Hills are in Nevada near the Utah border. Permian strata overlie Pennsylvanian beds of the Ely Limestone. The mid-Permian sequence includes, from the base upwards, the Kaibab Formation, the Meade Peak Member of the Park City Formation, the Plympton Formation, and the Gerster Limestone (Hintze, 1988, Gold Hill section). The upper, exposed part of the underlying Arcturus Formation is composed mainly of sandstone, siltstone, and dolomite, but a minor constituent is gypsum, and collapse features are present, indicating the former presence of soluble salts. The Meade Peak is abundantly phosphatic, and the Plympton is mostly dolomite with minor bedded chert and phosphatic beds. Figure 4 is from the Meade Peak Member.

4. Confusion Range

The Confusion Range is in Utah near the boundary with Nevada. The mid-Permian sequence includes, from the base upwards, the Kaibab Limestone, the Plympton Formation, and the Gerster Limestone (Hose and Repenning, 1959). The underlying Arcturus Formation is mainly interbedded sandstone and limestone or dolomite; gypsum is present at several horizons, and collapse breccias are prominent in some intervals.

The Kaibab is mainly bioclastic detrital limestone with chert nodules. According to Hose and Repenning, the unit contains sparse phosphate pellets throughout. Fossils of the Kaibab include crinoids, echinoids, bryozoans, and a brachiopod fauna typical of the Kaibab Limestone of the Colorado Plateau (E.D. McKee *in* Hose and Repenning, 1959).

The Plympton is approximately equivalent to the Phosphoria Formation and, like the Phosphoria, includes dolomite (fig. 5), phosphatic rocks (fig. 6), and spicule chert (fig. 7). Hose and Repenning divided the Plympton into five zones. These, from base to top, are (1) bedded chert; (2) dolomite; (3) chert and dolomite with phosphate pellets; (4) siliceous dolomite; and (5) a mixed unit of dolomite, chert, carbonate breccia, sandstone, siltstone, and gypsum. The Plympton attains a thickness of about 200 m in the Confusion Range.

The Gerster is a very fossiliferous detrital limestone with abundant chert nodules and abundant brachiopods including the *Punctospirifer pulcher* fauna characteristic of the type Phosphoria and Park City Formations. The faunas of the Kaibab and Gerster, listed above, and the dolomite and gypsum in the Plympton indicate the mid-Permian rocks of the Confusion Range were deposited in a shallow marine environment.

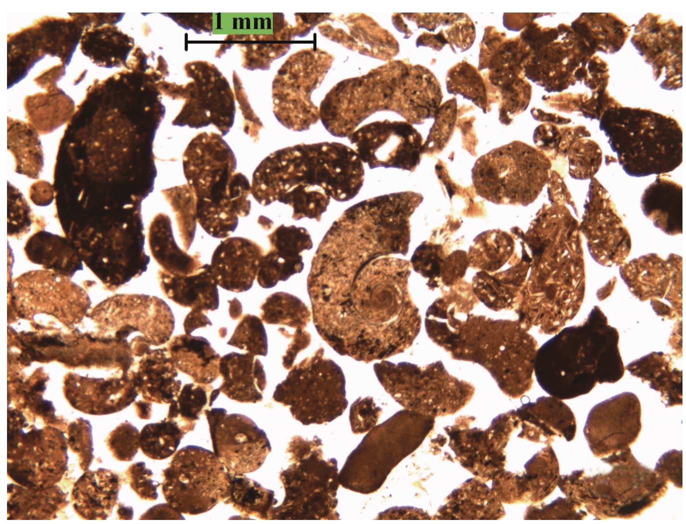

Figure 4. Ferber Hills, Meade Peak Member, steinkerns and pellets are cemented with clear secondary chert.

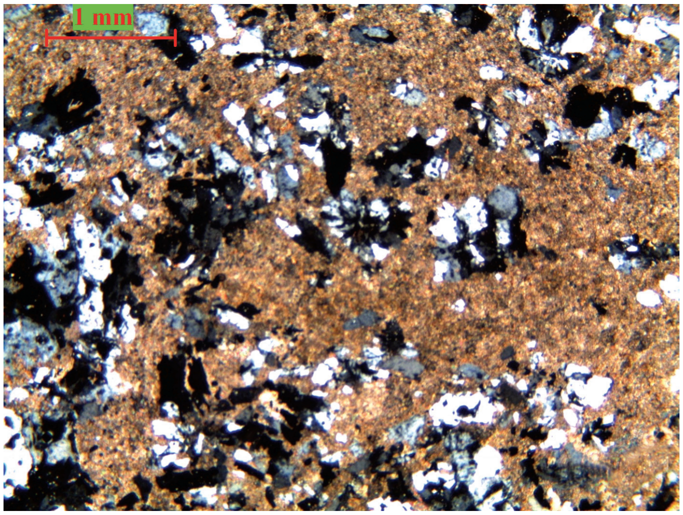

Figure 5. Confusion Range, Plympton Formation, dolomite with dispersed crystals and rosettes of gypsum.

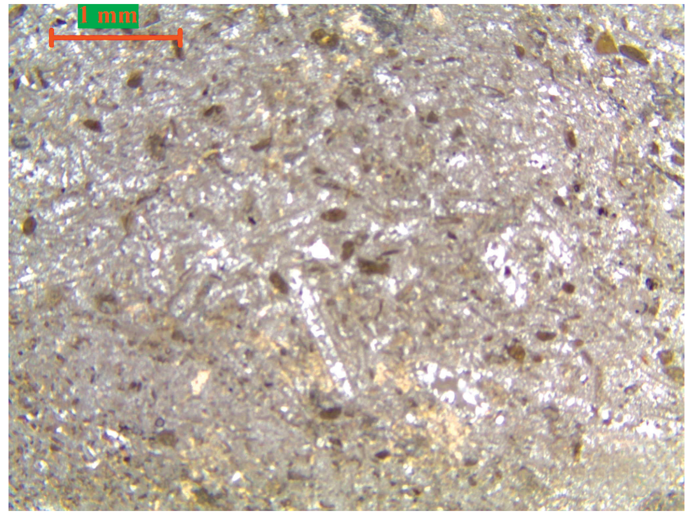

Figure 7. Confusion Range, Plympton Formation, spicule chert with sparse, minute phosphate pellets

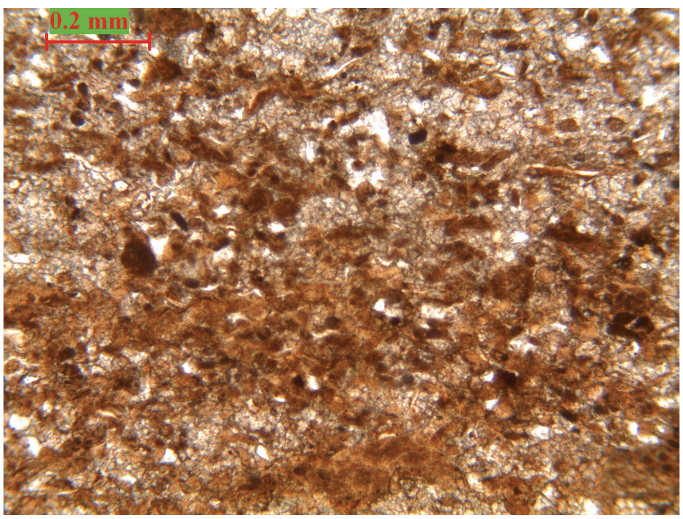

Figure 6. Confusion Range, Plympton Formation, minute pellets and masses of phosphate in fine-grained dolomite.

5. Elk Mountain

Collections of brachiopods from this area were reported by Coats (1986). The report on one of the collections by Mackenzie Gordon, Jr., and B.R. Wardlaw of the U.S. Geological Survey stated: "This fauna is Roadian, uppermost Lower Permian, and typical of the upper part of the Meade Peak Phosphatic Shale Member of the Phosphoria Formation in Idaho and Utah." Two other brachiopod collections from the same area confirm that age determination. Although little stratigraphic and lithic information is available, the brachiopods at this locality indicate a marine environment in the mid-Permian.

6. Northern Snake Mountains

Bezzerides (1967) described the Phosphoria Formation in the O'Neil Pass area of the northern Snake Mountains as overlying the Pennsylvanian Oquirrh Formation and underlying the Triassic Dinwoody Formation. The Phosphoria here is about 250 m thick and consists primarily of interbedded siltstone, limestone, and chert. Chert interbedded with phosphorite is dominant near the top of the formation. The phosphorite is described as occurring in beds as much as 0.6 m thick and consisting of phosphatic ovules 0.2 to 1.2 mm in diameter. A few consist of coated quartz grains, and a few are concentrically laminated. Some of the cement consists of phosphate and some is carbonate. A fauna of brachiopods and gastropods indicates a mid-Permian age.

Gardner (1968) described similar rocks overlying a thick sequence of siltstone 10 km to the southwest. The lower part of the Phosphoria here is interbedded phosphatic shale, siltstone, and limestone. The upper part is bedded chert and lesser amounts of phosphatic shale, siltstone, and limestone. Dolomite rhombs are scattered throughout. The Phosphoria Formation was estimated to reach a maximum thickness of 335 m. According to Mackenzie Gordon, the fauna in the Phosphoria at this locality indicates a late Early Permian age (Coats, 1968). Chemical analyses of 16 randomly selected rocks of the Phosphoria Formation indicate a wide variation with 12 of them under 2 percent P_2O_5 and 4 in the 13 to 34 percent range (this report).

7. Southern Snake Mountains

According to Smith and others (1990) the Permian sequence that overlies lower Paleozoic rocks unconformably consists of quartz- and chert-grain sandstone and conglomerate composed mainly of chert clasts, overlain by siltstone and sandstone containing brachiopods and meandering trails. Brachiopods from the upper part of the unit indicate a late Early Permian age (B.R. Wardlaw *in* Coats, 1968). The thickness below the erosional top of the unit is 305 m.

8. Medicine Range

The Permian sequence in the Medicine Range includes a thick sequence of siltstone and limestone termed the Arcturus Group by Collinson (1968). The overlying mid-Permian sequence consists of the Kaibab, Plympton, and Gerster Formations. The Plympton Formation, about 150 m thick, was described by Collinson as follows: “In the Medicine Range the formation can be divided into four lithologic units. The lowest, which rests conformably on the Kaibab Formation, is 22 m of silty chert.… The second unit comprises about 35 m of light-gray calcareous dolomite which resembles Kaibab dolomite but is finer grained. This unit is capped by a bed of chert-granule conglomerate. The third unit, 57 m thick, is predominantly chert, with thin interbeds of fine-grained phosphatic dolomite. The uppermost 38 m consists of interbedded dolomite and chert.”

The environmental data are scanty, but dolomite and conglomerate indicate a shallow-water depositional environment for part of the mid-Permian. The chert-granule conglomerate is typical of other mid-Permian sequences in northern Nevada.

9. Butte Mountains

The mid-Permian sequence in the Butte Mountains as described by Sides (1966) is underlain by about 1,100 m of interbedded sandstone and limestone of Early Permian age. The mid-Permian rocks were divided into three units: The Kaibab Limestone, the Plympton Formation, and the Gerster Limestone. The Kaibab consists of about 75 m of dolomite and chert and is described as consisting of dolomite of which the lower beds “…are locally highly brecciated suggesting collapse on solution of underlying evaporites.” Fossils are scarce and the age of the Kaibab at this location is uncertain. The Plympton consists of about 60 m of dolomite, dolomitic limestone, limestone, and chert. Again, fossils are scarce and the age of this unit is uncertain from the local evidence. The Gerster consists of abundantly fossiliferous limestone, and its age, based on a large brachiopod fauna, was determined by Sides to be Guadalupian, early Late Permian. The unit is about 500 m thick in the Butte Mountains. The brecciated dolomite interpreted as collapse breccia due to solution of evaporites indicates a shallow marine environment of deposition for the Plympton, and the abundant brachiopod fauna of the Gerster is compatible.

10. Mount Ichabod

An Upper Pennsylvanian and Permian sequence at Mount Ichabod lies with a depositional contact on quartzite of the mostly Ordovician Valmy Formation (Ketner and others, 1996). It consists from the base upwards of conglomerate, limestone, siltstone-sandstone, and phosphatic bedded chert. Fusulinids from the limestone are of Late Pennsylvanian age. The overlying beds are undated locally, but they resemble middle Permian beds at other locations.

Another, mainly clastic, unit is interpreted to be in low-angle fault contact above the Upper Pennsylvanian to Permian sequence described in the previous paragraph. This unit is composed of conglomerate with clasts ranging from sand size to large boulder size. Many of the clasts are composed of phosphatic rocks ranging from slightly phosphatic spicule chert (fig. 8) to phosphatic sandstone (fig. 9). The large size and angularity of these clasts indicate a nearby source. One collection of radiolarians from a clast and another from chert, thought to be a sedimentary bed rather than a clast, were determined to be of Wordian age (early Late Permian, Ketner and others, 1996). Conceivably, both are from clasts, in which case the conglomeratic unit could be of Triassic age but composed of mostly Permian clasts. Whether the unit is of Permian or Triassic age, it records the former presence of richly phosphatic rock and spiculitic chert typical of mid-Permian rocks of the region.

11. Dorsey Canyon–Divide Peak

In the Dorsey Canyon–Divide Peak area, the Ordovician Valmy Formation and related Silurian beds are overlain unconformably by a Permian sequence that consists, from base

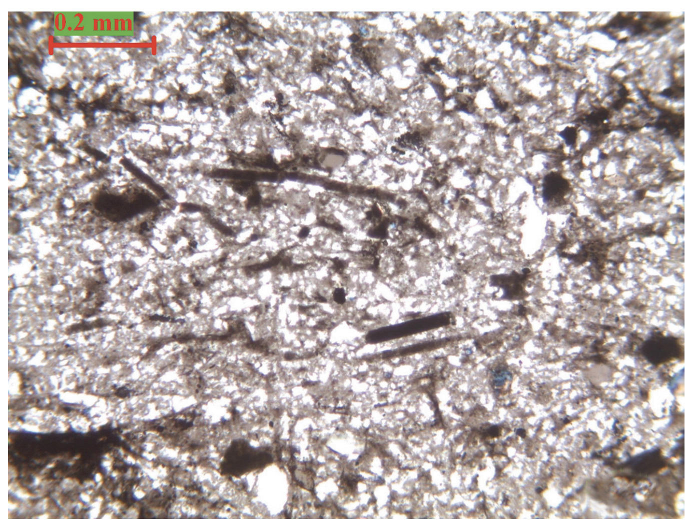

Figure 8. Mount Ichabod, slightly phosphatic spicule chert in which most of the phosphate is in the axial canals of the spicules.

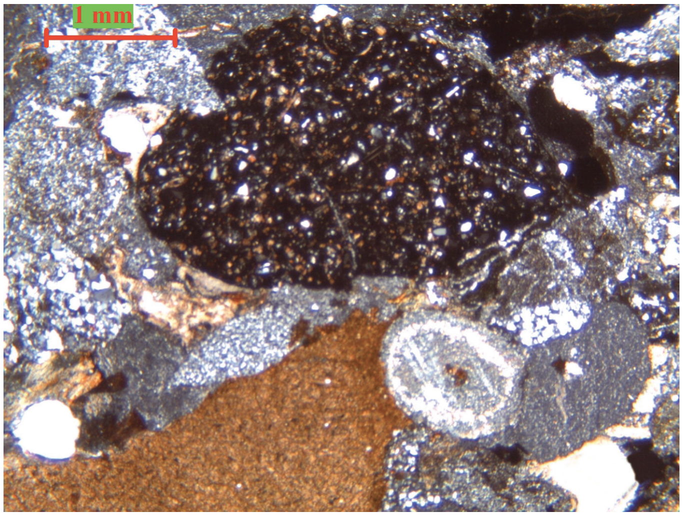

Figure 9. Mount Ichabod, phosphatic sandstone. Dark clast is a phosphatic steinkern; the brown clast is phosphate containing spicules; the circular clast is a crinoid columnal; other clasts are mainly chert (gray) and quartz (white).

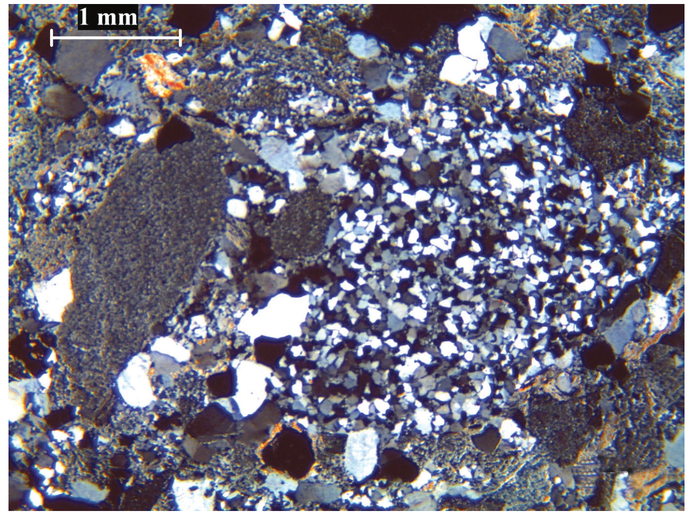

Figure 10. Dorsey Canyon, sandstone from unit 2. The clasts consist of quartz, chert, shale, and (sparse) phosphate. An angular quartzite clast occupies most of the right-hand side of the picture. The large ovoid grain on the left side is shale. Smaller grains are mostly quartz (white) and chert (gray).

to top, of (1) conglomerate composed of large clasts identical in composition to quartzite and chert of the underlying Ordovician and Silurian units, (2) sandstone and siltstone composed mainly of quartz and chert grains (fig. 10), and (3) a unit of mainly interbedded sandstone and chert. The depositional contacts at the base of each of the three units are well exposed (Ketner and others, 1993).

The depositional contact between units 2 and 3 is important because it solves a longstanding structural problem. Coats and Gordon (1972) discussed two Permian stratigraphic units in the area that they believed were structurally juxtaposed: a siltstone and sandstone unit termed the Edna Mountain Formation, and a chert-bearing unit termed the Phosphoria Formation (the type Edna Mountain Formation is 150 km to the southwest). Actually, these two units constitute the upper two stratigraphic units at Dorsey Canyon, and they are in stratigraphic continuity.

Coats and Gordon (1972) tabulated 14 fossil collections from the Dorsey Canyon–Divide Peak area, a very informative contribution to the nature and age span of the Phosphoria Sea in northern Nevada. All 14 of the collections contain the brachiopod *Spiriferella* assemblage characteristic of the type Edna Mountain Formation. Four of the collections, in addition to the *Spiriferella* assemblage, contain the brachiopod *Cyrtorostra* assemblage characteristic of the Phosphoria Formation. As interpreted in the present report, the 10 collections containing only the Edna Mountain assemblage are from unit 2 described previously. The four collections with both the *Spiriferella* and *Cyrtorostra* assemblages are from the stratigraphically highest beds, unit 3 described previously. The ample paleontological data from units 2 and 3 presented by Coats and Gordon (1972) show beyond doubt that the Permian rocks in the Dorsey Canyon area are contemporaneous with both the Edna Mountain Formation of northwestern Nevada and the Phosphoria Formation in its core area.

12. Northern Adobe Range

In its chief exposure in the south limb of the Adobe Range syncline, the Permian sequence exposed above a low-angle fault consists of three members (Ketner and Ross, 1990). The lowest member is extremely varied in lithology and thickness and reflects sedimentation in a very shallow environment. It differs from the overlying units in its coarse grain size and lateral variability. Principal lithologies are pebble conglomerate and sandstone. Individual clasts in these detrital beds are composed of chert, shale, quartzite, quartz, and phosphorite. With the exception of phosphorite, these are the constituents of the Silurian and Ordovician strata in the underlying rocks. Detrital beds commonly show effects of strong currents such as abundance of scours and crossbedding. Beds of bioclastic limestone are fairly common in the sequence. These are generally quartz-silty, quartz-sandy, and phosphatic, and locally they are partially replaced by secondary silica. They contain abundant brachiopods, mollusks, bryozoa, and scarce specimens of the mollusk *Atomodesma* (fig. 11), the latter as determined by Bruce Runnegar (written commun. (1969). Some beds contain abundant length-slow chalcedony blebs and nodules that suggest the former presence of evaporite minerals. The brachiopod fauna indicates the lowest member is of mid-Permian age. The lowest member ranges from 0 to at least 100 m thick.

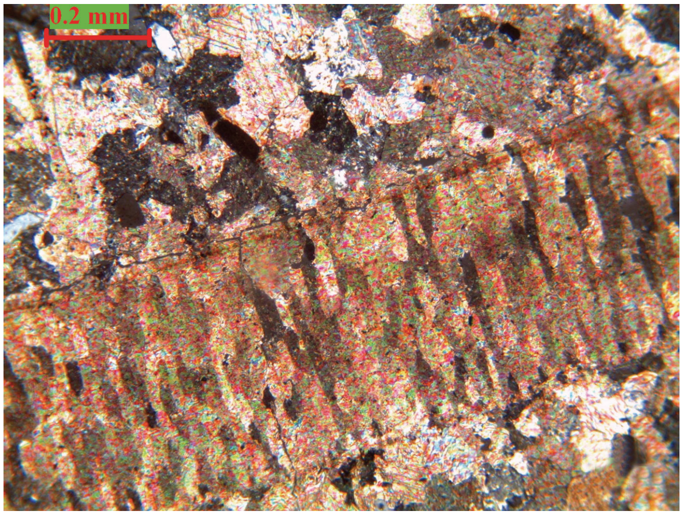

Figure 11. Northern Adobe Range, lower member, prismatic shell of *Atomodesma* in phosphatic limestone laced with length-slow chalcedony.

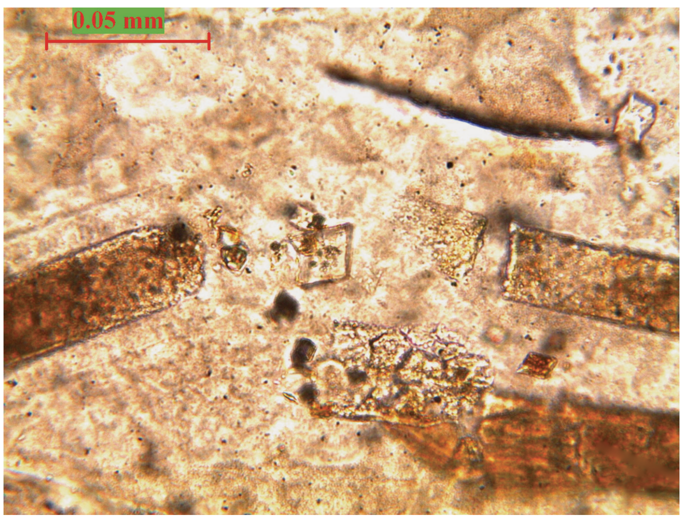

Figure 12. Northern Adobe Range, middle member, spicule chert showing dolomite rhombs and phosphate (dark brown) in axial canals of spicules.

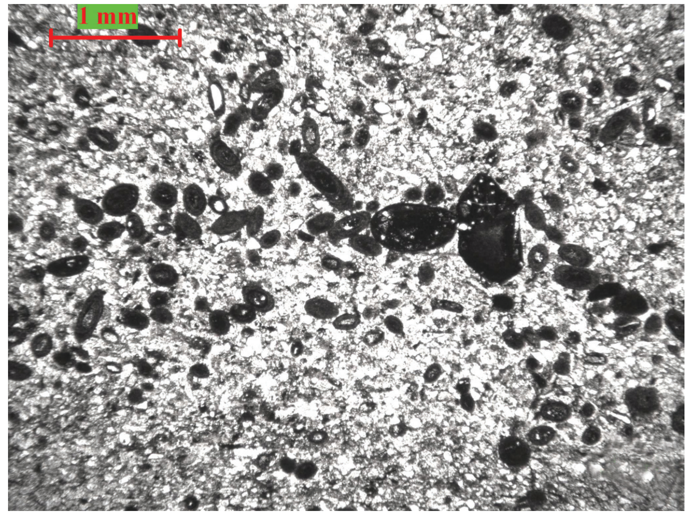

Figure 13. Northern Adobe Range, top member, phosphatic pellets in siltstone matrix of dolomite rhombs, quartz, and spicules. Some of the pellets are obscurely concentrically laminated; some have quartz grain cores.

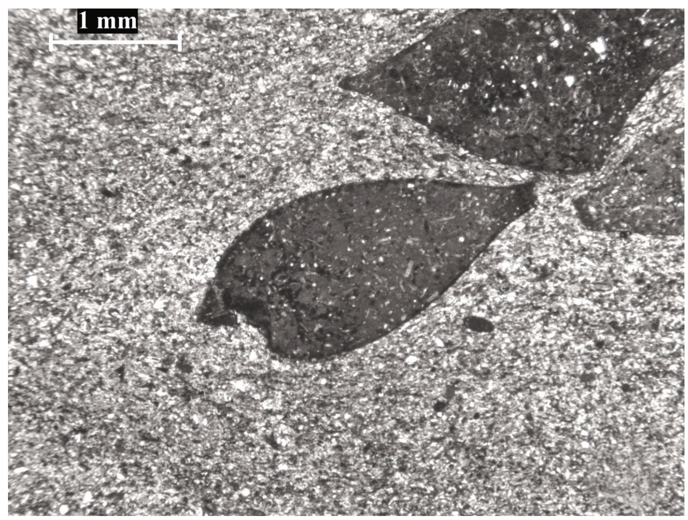

Figure 14. Northern Adobe Range, top member, phosphatic steinkerns in slightly phosphatic siltstone.

The middle member although relatively thin and inconspicuous can be traced continuously for several kilometers. This member is composed of brown, richly phosphatic, pelletal, crossbedded quartz siltstone or mudstone and chert (fig. 12). It contains sparse shells of *Atomodesma.* The middle member is about 20 m thick.

The upper member consists almost entirely of dark-brown phosphatic quartz siltstone (fig. 13), mudstone, and shale. Less common constituents are lenses of sandstone and small-pebble conglomerate composed of chert clasts and phosphate rock clasts, crossbedded phosphatic siltstone with small phosphatic steinkerns (fig. 14) resembling that of the middle unit, and thin phosphorite beds. The upper member is at least 180 m thick.

The upper and lower members were dated by collections of brachiopods and pelecypods as mid-Permian by B.R. Wardlaw and Mackenzie Gordon (Ketner and Ross,1990).

An isolated map unit, not subdivided into members, consists of sandstone, conglomerate, limestone, dolomite, phosphatic siltstone, phosphatic mudstone, and phosphatic spicule chert. This unit, probably equivalent to the three units described previously, was dated by a fossil collection of which Mackenzie Gordon wrote: “This collection, from a limestone bed, is... equivalent to part of the Park City Formation.” The

Park City is a carbonate facies of the Phosphoria Formation (McKelvey and others, 1959).

Although the percentage of phosphate is low on average (table 1), the substantial thickness of the mid-Permian sequence indicates a large amount of phosphate.

The principal forms of phosphate in the northern Adobe Range are as follows:

1. Round or ovoid pellets of pure phosphate between 0.05 and 0.5 mm in diameter. Some of these are built up around nuclei of detrital quartz grains or carbonate grains.

2. Small irregularly shaped grains. These are common in siltstone where they conform to the spaces available among detrital quartz grains.

3. Large irregular nodules composed of homogeneous phosphate or aggregates of phosphatic pellets and other sedimentary debris. These grains, which can be at least 4 cm in the longest dimension, seem to be fragments of preexisting beds of phosphorite that have been broken up and moved short distances.

4. Internal casts of small pelecypods about 0.5 to 1 cm in length.

5. Rodlike fillings of the axial canals of spicules. These range from 0.2 mm to 0.3 mm in diameter, and although they can be a few millimeters long they are usually broken into short segments.

Table 1. Percent P_2O_5 of samples chosen at arbitrary equal intervals across mid-Permian stratigraphic units, northern and southern Adobe Range.[1]

Northern Adobe Range (loc. 12) Lower member ±100 m thick ±7-meter intervals	Northern Adobe Range (loc. 12) Middle member ±20 m thick ±7-meter intervals	Northern Adobe Range (loc. 12) Upper member ±180 m thick ±8-meter intervals	Southern Adobe Range (loc. 14) Upper half ±300 m thick ±10-meter intervals
0.66 (top)	1.34 (top)	1.33 (top[2])	12.9 (top[3])
0.50	1.64	3.52	10.1
0.24	1.45 (base)	1.54	1.88
3.57	1.5 (average)	4.14	9.31
2.82		1.54	1.23
1.66		1.36	1.60
1.30		1.05	0.94
1.76		2.89	0.69
2.02		3.10	0.62
2.97		0.56	1.54
4.26		1.54	0.34
1.66		2.38	0.63
1.02		1.59	0.18
3.20		1.66	0.41
0.94		1.66	0.35
2.35 (base[2])		1.48	0.43
1.9 (average)		1.13	0.54
		1.62	3.88
		1.08	1.08
		1.01	2.82
		0.66	2.35
		1.35	2.07
		0.35	1.84
		0.58 (base)	1.00
		1.6 (average)	2.18
			7.57
			0.52
			0.99
			1.02
			0.89
			0.83
			1.10 (base)
			2.3 (average)

[1] Analyst: G.D. Shipley, U.S. Geological Survey.

[2] The top and base of the Permian sequence in the northern Adobe Range are faulted.

[3] The stratigraphic top of the Permian sequence in the southern Adobe Range is concealed.

6. Concentrically laminated phosphate oolites or the nuclear portion of carbonate oolites.
7. Colloform cavity fillings. These may be secondary deposits formed after consolidation of the sediments.

13. Peko Hills

An intact sequence of upper Paleozoic rocks in the Peko Hills has been divided into basal, middle, and upper units (Ketner and Evans, 1988). The basal unit is composed mainly of dolomite. Lower beds of this unit consist of quartzite-pebble and chert-pebble conglomerate, cherty dolomite, and limestone. Most of the upper beds of the basal unit are variably phosphatic, and dolomite beds contain length-slow chalcedonic blebs that probably represent original evaporite nodules. The maximum exposed thickness of the basal unit is about 610 m. The unit contains an Upper Pennsylvanian (Virgilian) fusulinid fauna and a Lower Permian conodont fauna. The basal unit therefore correlates with the Upper Pennsylvanian and Lower Permian Strathearn Formation of the Carlin Canyon area, 65 km to the southwest, in its age range and to some extent in its lithic composition (Smith and Ketner, 1975). However, the Strathearn is mostly limestone rather than dolomite.

The middle unit is extremely heterogeneous. It consists of crossbedded, phosphatic quartz siltstone (figs. 15, 16, 17), phosphorite, chert-grain and quartz-grain sandstone, chert-pebble conglomerate, quartz-sandy and chert-pebbly dolomite, and chert beds composed of spicules with phosphate-filled axial canals. Chemical analyses of phosphorite samples indicate P_2O_5 levels of as much as 30 percent. The middle unit contains abundant evidence of shallow water origin such as crossbedding in coarse-grained sandstone, scoured surfaces, and gypsum (fig. 18). Phosphatic red beds with chalcedonic blebs are present in one exposure. The middle unit, which is about 245 m thick, contains an abundant fauna of silicified brachiopods and Lower Permian conodonts. Based on lithic composition and stratigraphic position, the middle unit is considered equivalent to the Plympton and Phosphoria Formations.

The upper unit is identified as the Gerster Formation. At this location it is composed mostly of thick-bedded limestone with sporadic chert nodules and lenses. In some exposures, upper beds are composed of thick-bedded dolomite containing blebs of length-slow chalcedony, disseminated grains and distinct beds of quartz sand, chert sand, chert conglomerate,

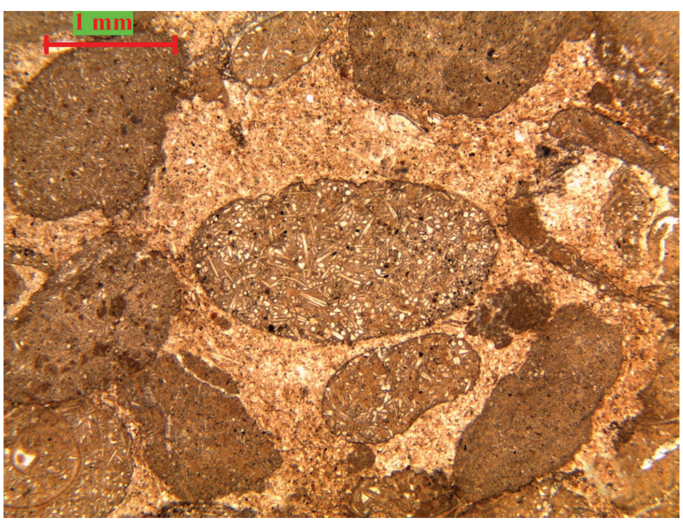

Figure 15. Peko Hills, middle unit, central pellet composed largely of spicules with interstitial phosphate. Darker pellets in this view have higher concentrations of phosphate; lighter pellets have higher concentrations of spicules. The pellets are in a matrix of dolomitic, spiculitic, phosphatic silt.

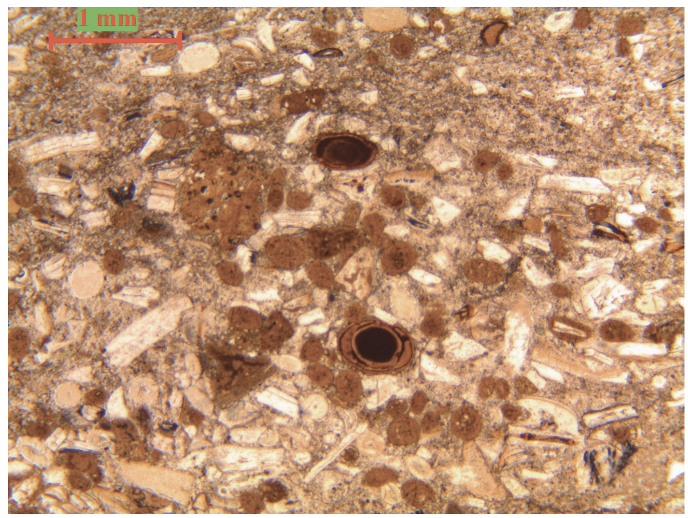

Figure 16. Peko Hills, middle unit, small pellets and ooides in matrix of broken spicules and fragments of phosphatic shells.

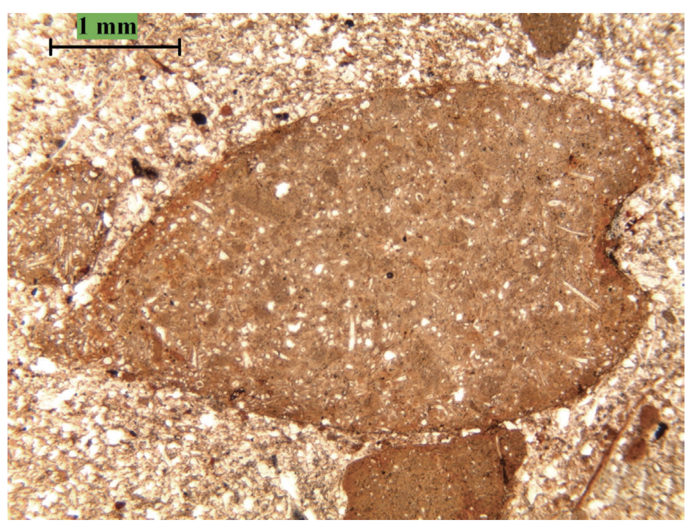

Figure 17. Peko Hills, middle unit, steinkern with phosphate and spicules in a matrix of silt-size quartz, spicules, and phosphate.

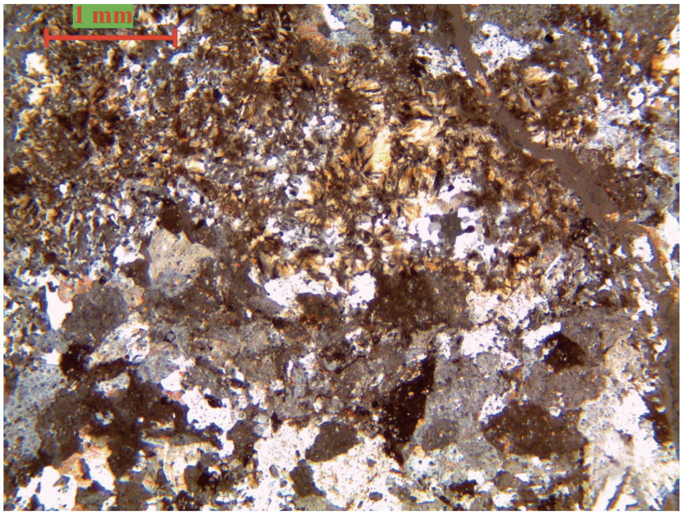

Figure 18. Peko Hills, middle unit, bed of mainly gypsum (gray) and length-slow chalcedony (light brown) among clasts of phosphatic chert and siltstone.

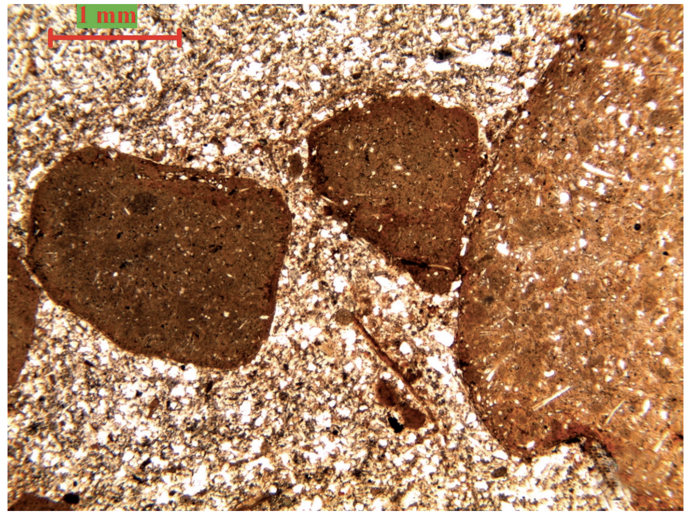

Figure 19. Southern Adobe Range, irregular phosphate pellets and a steinkern in a matrix of angular quartz clasts, spicules, and minute phosphate pellets. The steinkern, on the right, contains numerous spicules and quartz grains.

and spicule chert. This unit, which is about 200 m thick, contains an abundant fauna of productid brachiopods and large silicified pelecypods. The Gerster, in its type section in western Utah, is correlative with the Park City and Phosphoria Formations (Nolan, 1935) and is presumed to be of that age in the Peko Hills. Altogether, the lithic features of all three units indicate very shallow-water conditions.

14. Southern Adobe Range

The exposed Permian sequence of the southern Adobe Range consists of the upper, Permian part of the Strathearn Formation, and a thick, unnamed unit (Ketner, 1973; Smith and Ketner, 1975). The topmost Permian beds and Triassic beds are not exposed in the southern part of the range as they are in the northern part described previously. The unnamed unit consists mostly of siltstone, sandstone, limestone, dolomite, and chert. The approximate upper half of the Permian sequence is somewhat phosphatic, and the uppermost beds include phosphatic chert and phosphatic, siltstone (table 1; fig. 19). Of six samples with hand-lens-visible phosphate not shown in table 1, two were below 1 percent and four ranged from 2 to 8 percent P_2O_5. The measured section is about 600 m thick, but the topmost beds, commonly the most phosphatic, are covered and of unknown thickness.

15. Southern Piñon Range

Permian rocks in the southern Pinon Range consist of limestone, sandy and silty limestone, limy siltstone, and conglomerate (Smith and Ketner, 1975). They overlie Mississippian conglomeratic rocks disconformably, and the top is erosional. The extensive fauna clearly indicates a late Permian age (Mackenzie Gordon, Jr., *in* Smith and Ketner, 1975) and a shallow-water environment. Among the forms found at this locality are numerous genera of brachiopods, bryozoans, and crinoids.

16. Edna Mountain

This area was described by Ferguson and others (1952), and Erickson and Marsh (1974). It is the westernmost exposure of the relatively shallow-water sediments of the Phosphoria Sea at the latitude of the core area of the Phosphoria Formation. Permian rocks of Edna Mountain include the upper part of the Antler Peak Limestone and the unconformably overlying Edna Mountain Formation. Phosphatic strata that would normally be present between these two units have been incorporated into the Edna Mountain Formation in the form of sandstone and conglomerate composed, in part, of phosphatic clasts. The Antler Peak Limestone is chiefly bioclastic limestone and is stratigraphically equivalent to the Strathearn Formation and the Kaibab Limestone of more easterly parts of Nevada. The overlying Edna Mountain Formation as described by Erickson and Marsh is composed of "Chiefly brown, blocky-weathering, fine- to medium-grained, dark-gray, calcareous quartzite; locally conglomeratic. Black chert grains and black coprolites of fluorapatite composition are common. Brachiopod faunas of Late Permian age (Mackenzie Gordon, Jr., written commun., 1970) are locally abundant, particularly in upper part." The mid-Permian age of the unit and the incorporation within it of phosphatic and spiculitic clasts, and the Permian age of some of the underlying rocks indicate the unconformity is of mid-Permian age.

Microscopic examination for the present report indicates the formation is composed largely if not mostly of angular radiolarian chert grains or chert grains without either spicules or radiolarians. Minor clastic components include dolomite rhombs, spiculitic chert, irregular, apparently abraded, phosphorite clasts (fig. 20), and in some beds, abundant angular clasts of length-slow chalcedony (fig. 21).

The lithic composition of the Edna Mountain in general matches that in parts of the mid-Permian sequences of north-central Nevada, as was stressed by Coats and Gordon (1972).

The angularity and poor sorting of clasts, the presence of spiculitic chert clasts, and the presence of phosphate pellets suggest derivation from nearby primary shallow-water sedimentary rocks typical of the Phosphoria Sea.

The age of the Edna Mountain and its content of phosphatic, spicule, and chalcedonic clasts testify to uplift, erosion, and a return to deposition in the time interval of the Phosphoria Formation. The area was therefore, briefly, an ephemeral island in the Phosphoria Sea.

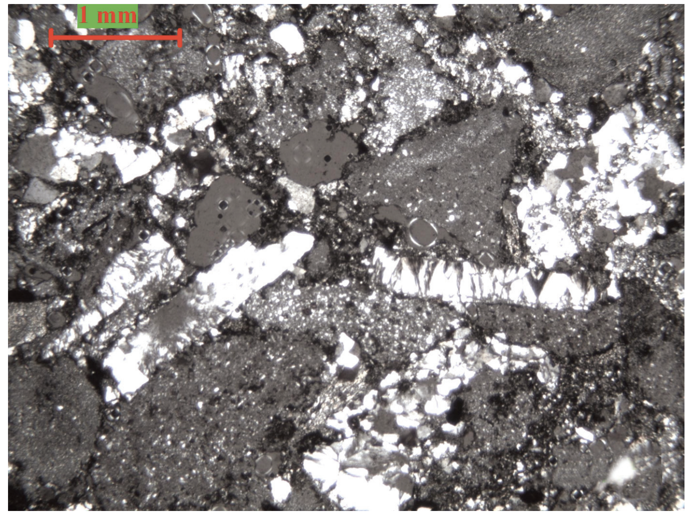

Figure 21. Edna Mountain Formation, length-slow chalcedony clasts (light-colored bars) in sandstone, here composed mainly of angular chert grains.

17. Monitor Range

At Danville Canyon in the central Monitor Range, a thick sequence of chert, siltstone, sandstone and limestone includes phosphatic beds (Rogers and others, 1970). The sequence was dated as Permian by its stratigraphic position, its resemblance to known mid-Permian strata of the Phosphoria Sea, and the presence of the conodont *Gondolella* in phosphatic beds.

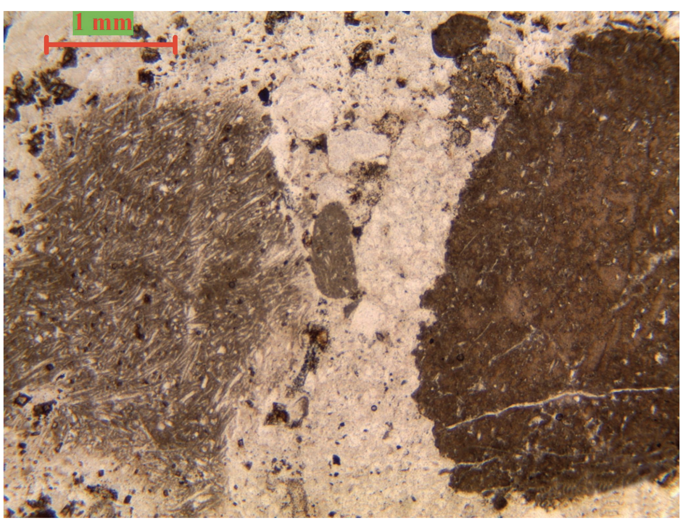

Figure 20. Edna Mountain, Edna Mountain Formation, two large clasts of phosphate in a matrix of quartz, spiculitic chert, and small phosphate clasts. The large phosphate clasts differ from most Permian pellets in having irregular or ragged surfaces apparently from their history of erosion from the primary phosphatic sediment and redeposition as sandstone and conglomerate. The primary sediment evidently was, in part, spiculitic chert, phosphate, and length-slow chalcedony.

18. Southern Toiyabe Range

The mid-Permian Diablo Formation of the southern Toiyabe Range was described by Speed and others (1977) as "... dominantly fine-to coarse-grained calcarenite and pebbly calcarenite; interbeds of limy quartz-chert sandstone and microbreccia and skeletal hash.…" A predominantly brachiopod fauna indicates a mid-Permian age approximately equivalent with the Phosphoria Formation and lower Gerster Limestone according to Ferguson and Cathcart (1954) and written communications to Speed by Mackenzie Gordon, Jr. (1967), and Bruce R. Wardlaw (1977).

19. Southern Toquima Range

The Diablo Formation in the southern Toquima Range at Willow Springs is described as "... limy siltstone and fine-grained sandstone, subordinate brown and gray silty and sandy limestone, and sparse conglomeratic layers at the base." (Poole and Wardlaw, 1978). Marine fossils indicate a mid-Permian (late Leonardian) age.

20. Candelaria Hills

The middle Permian Diablo Formation in the type area as redefined by Speed and others (1977) is a thin (<25 m), slightly metamorphosed unit composed of conglomerate, sandstone, siltstone, silty chert, and dolomite. The Diablo is underlain by the Palmetto Formation of Ordovician age and is overlain by Triassic rocks. As in correlative sandy strata in northern Nevada, clasts of the Diablo are mainly chert and quartz. Phosphate, which is somewhat recrystallized, occurs as irregular masses of pelletal phosphorite (fig. 22) and as isolated pellets and steinkerns in sandstone (fig. 23). An

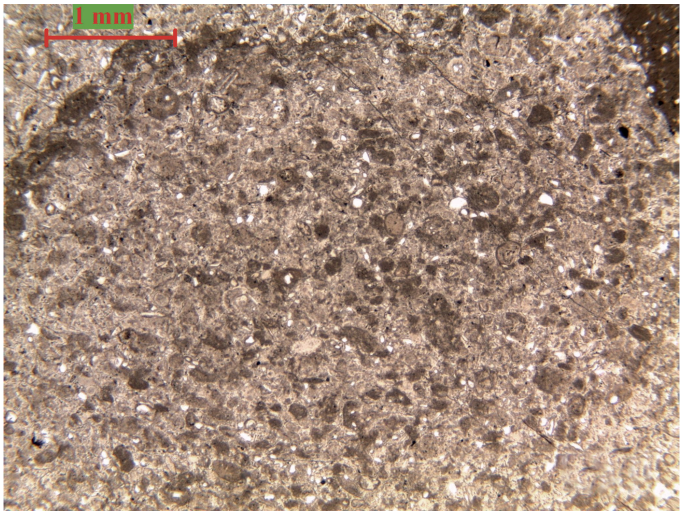

Figure 22. Candelaria Hills, Diablo Formation, phosphorite mass composed of phosphate pellets in a matrix of quartz-silty phosphorite. Some pellets ar nucleated; some show faint concentric structure.

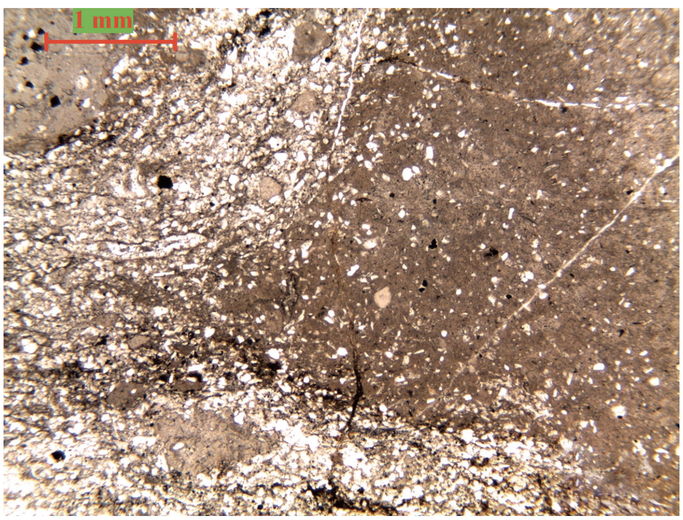

Figure 23. Candelaria Hills, Diablo Formation. A large phosphatic steinkern, on the right, is in a matrix of phosphate pellets and silt-size chert and quartz clasts. The tip of the steinkern has been drawn out toward the left and its outlines blurred by the metamorphic process.

unusually conspicuous phosphate bloom coats some of the weathered surfaces.

As noted by Speed and others (1977) a shallow depositional environment is indicated by onlap of the Diablo onto the source beds of clasts composing the Diablo. The shelly, mainly brachiopod, fauna is similar to that of the Phosphoria Formation (Ferguson and others, 1954).

Southern Nevada

Permian strata in extreme southern Nevada consist of a thick sequence of limestone, red beds, and cherty, gypsiferous limestone of Early Permian age, overlain by the Kaibab Limestone (Tschantz and Pampeyan, 1970). The Kaibab in southern Nevada is composed mainly of limestone with chert nodules and lenses, and minor dolomite (Tschantz and Pompeyan, 1970; Longwell and others, 1965). Phosphate pellets are very sparsely present in some exposures. Similar deposits are present at the base of phosphatic deposits in northern Nevada and some of them have been termed Kaibab; but if richly phosphatic beds had ever been present above the Kaibab in southern Nevada they were eliminated by Late Permian or Early Triassic erosion. The existence of such an erosional interval in middle to southern Nevada where phosphatic sediments appear to be missing has been observed at many localities (Longwell and others, 1965; Tschanz and Pampeyan, 1970; Hose and Blake, 1976).

Conodonts extracted from each of the Kaibab localities of southern Nevada shown in figure 1, and others in the vicinity, are of mid-Permian age according to A.G. Harris (Harris, unpub. data; Harris and others, 2005; Harris and Crafford, 2007), which makes the formation approximately correlative with the phosphatic rocks of northern Nevada.

The Kaibab has been reported just over the southern Nevada border in southeastern California (Hewett, 1956), but the significance of Phosphoria-age strata in other parts of California (for example, Merriam and Hall, 1957) is uncertain owing to recent radical revisions in stratigraphy and tectonics (for example, Stone and Stevens, 1988; Stevens and others, 2005).

The Allochthonous Havallah Sequence

The Havallah sequence is a relatively deep water deposit of Late Devonian to mid-Permian age exposed widely in more westerly parts of Nevada. The sequence is sliced by low-angle faults and is almost universally considered to be entirely allochthonous. In the interval between 1972 and 1992, a large number of published reports established the concept that the Havallah had been thrust to its present location from a distant oceanic or back-arc basin. However, evidence cited by Murchey (1990) and Ketner (2008) suggest a more local site of deposition. Ketner (2008) presented evidence that the Havallah was deposited, not directly on oceanic crust, but on a thick sequence of Cambrian to Silurian terrigenous strata of the miogeocline. Lithic and paleontological data from the following three localities indicate that the uppermost part of the Havallah is of mid-Permian age and closely related to strata of the Phosphoria Sea.

21. Battle Mountain

The Pumpernickel Formation of Roberts (1964), a subunit of the Havallah sequence, is a relatively deep water deposit. According to Roberts, it consists largely of chert and argillite but includes some limestone, sandstone, conglomerate and intercalated greenstone.

Roberts' pioneer work was supplemented by a very informative study by B.L. Murchey (1990) of the lithic composition and fauna of the entire Havallah sequence including the "Pumpernickel" at Battle Mountain. Although Roberts tentatively assigned the "Pumpernickel" at this location to the Pennsylvanian, Murchey's data clearly indicate the unit contains a mid-Permian fauna and the mid-Permian part is genetically related to the Phosphoria Formation. The Phosphoria connection was expressed by Murchey as follows, p. 145 and 147: "The faunas in the sponge turbidites are indistinguishable from faunas in the lower Guadalupian Rex chert member of the Phosphoria Formation...." and "Sponge spicule turbidites of Leonardian or Guadalupian age were redeposited into the … slope setting from a shelf environment similar to, and possibly coeval with, that in which the Rex Chert Member of the Phosphoria Formation was deposited."

Not only is the fauna of part of the "Pumpernickel" similar to that of the Phosphoria, some aspects of the lithic composition also are similar. Axial canals of spicules in the spicule chert turbidites of the "Pumpernickel" are commonly filled with phosphate as they are in the Phosphoria Formation, and phosphate pellets typical of the Phosphoria are present in some (figs. 24, 25).

Phosphate is moderately concentrated in some beds of the mid-Permian parts of the Havallah. Chemical analyses of five samples of spicule chert with hand-lens-visible phosphate indicate P_2O_5 contents ranging from 2.7 to 4.0 percent, and of a sample of phosphatic sandstone, 5.4 percent P_2O_5 (fig. 26). The thickness of the mid-Permian part of the sequence at Battle Mountain is uncertain owing to faults and folds.

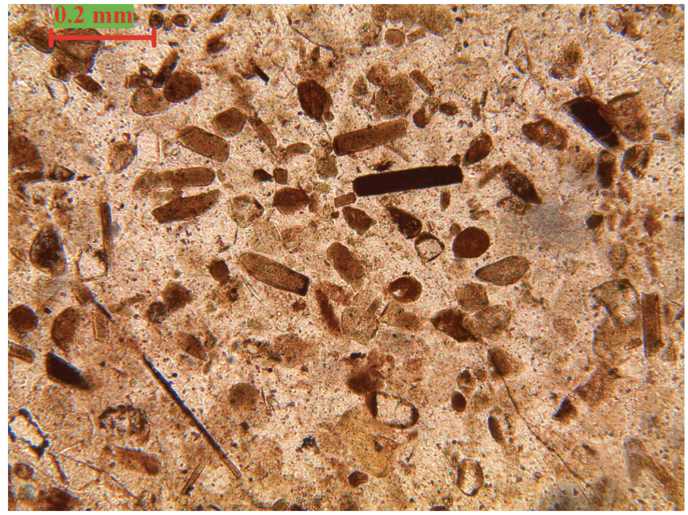

Figure 24. Battle Mountain, mid-Permian part of Havallah sequence, "Pumpernickel" of Roberts (1964). Small phosphate rods and pellets are in chert-cemented quartz silstone. The rods are likely fillings of axial canals of spicules, although that is not apparent in this specimen owing to recrystallization of silica.

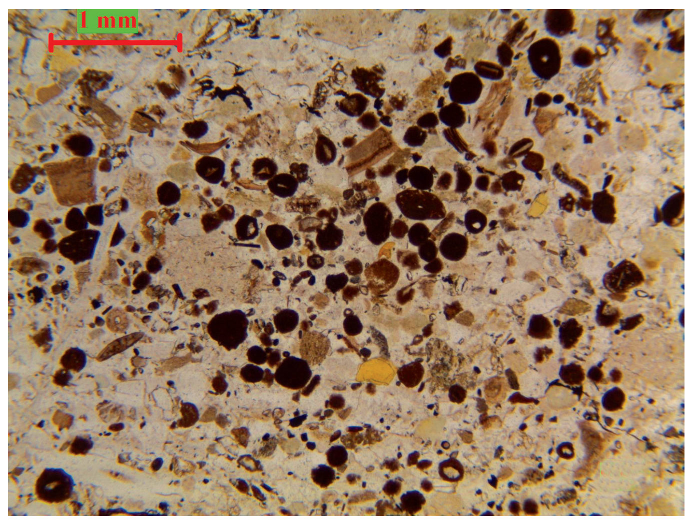

Figure 25. Battle Mountain, mid-Permian part of Havallah sequence, "Pumpernickel" of Roberts (1964). Phosphate pellets are in a matrix mainly of spicules and silt-size quartz and chert grains. Minor components are shell fragments, schist, and feldspar.

22. Southern Shoshone Range

In the southern Shoshone Range, the upper part of the allochthonous Havallah sequence includes sandy limestone, bedded chert, spicule chert, and phosphatic sandstone (Tomlinson, 1990). Benita Murchey examined sponge spicules from this area (termed Reese River area by Tomlinson) and concluded that they were identical to those in the upper Havallah of Battle Mountain. The mid-Permian age was determined by means of radiolarians and conodonts.

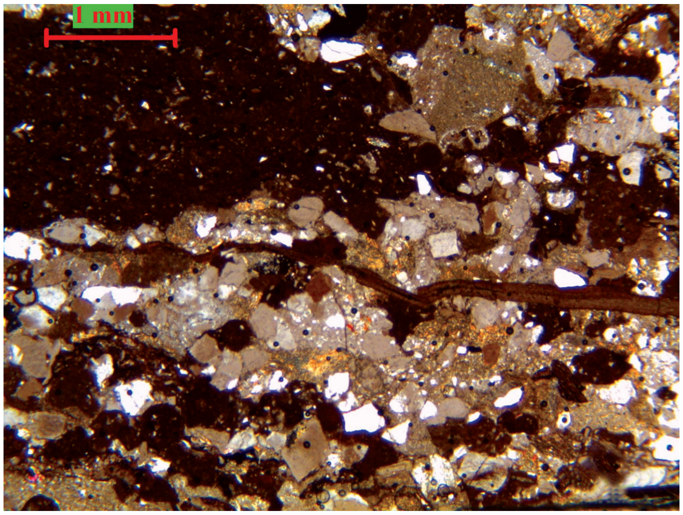

Figure 26. Battle Mountain, mid-Permian part of Havallah sequence, "Pumpernickel" of Roberts (1964), phosphatic sandstone. Large dark clast in upper left corner and numerous small dark clasts are phosphate, white clasts are quartz, and clasts of various shades of gray are mostly quartz and chert. Schist, siltstone, and feldspar are minor components. This specimen contains 5.4 percent P_2O_5. It resembles the Edna Mountain Formation in its variety and angularity of chert and quartz clasts and in the ragged outlines of the phosphate clasts.

Tomlinson describes the phosphatic grains in the phosphatic sandstones as follows: "Collophane pellets, intraclasts, ooliths, and bioclasts. Bioclasts include conodonts, vertebrate debris, and small phosphoratized gastropods, bivalves, and ostracods." This assemblage suggests derivation of clasts from the more shallow Phosphoria Sea.

23. Northern Toiyabe Range

In the northern Toiyabe Range, the upper part of the allochthonous Havallah sequence includes unmeasured thicknesses of mudstone, argillite, phosphatic sandstone, and radiolarian chert (Tomlinson, 1990). Sedimentary structures indicate these strata, like correlative strata at Battle Mountain, are turbidites. In the Toiyabe Range, the cherts are radiolarian rather than spiculitic, indicating a relatively deep-water depositional environment (Murchey, 1990). A mid-Permian age was determined by means of the radiolarians.

Tomlinson describes the phosphate clasts in the phosphatic sandstones as follows: "Collophane pellets, intraclasts, and ooliths...." These commonly have inclusions of sponge spicules. The description suggests derivation of clasts from the Phosphoria Sea.

Western Correlatives of the Havallah Sequence

The Mississippian to Permian rocks of the Hot Springs Range (fig. 1, no. 24) and the East Range (fig. 1, no. 25) are correlative with the Havallah sequence and are considered to have been deposited in the same marginal sea on the same Cambrian to Silurian strata of the miogeocline (Ketner, 2008).

24. Northern Hot Springs Range

Rocks correlative with those of the Phosphoria Sea are present in the northern Hot Springs Range, but they are of different lithic composition and represent a different environment of deposition from those of the Phosphoria Sea.

Two of the tectonostratigraphic units mapped by A.E. Jones (1997) are correlative with the Phosphoria. Jones described one of the two units, the Golconda mélange, as follows. "Although the melange is a disrupted, heterogeneous unit, it does have mappable lithologic horizons. Large blocks in the sheared basaltic tuff and argillite matrix include pillow basalt, red ribbon chert, interbedded chert and sandstone, calcareous siltstone, and massive limestone and volcanic breccia." No phosphatic beds or spicule chert were mentioned by Jones.

Concerning the age of the Golconda mélange, Jones stated that "Black chert beds in an olive basaltic matrix at the southern boundary of the melange contain middle to late Leonardian conodonts...." Because conodonts can, and frequently are, reworked, the data indicate a middle Leonardian or younger age.

Another tectonostratigraphic unit, termed the Poverty Peak mélange, is described as follows. The Poverty Peak mélange "…has a fabric similar to the Golconda melange but its block composition is somewhat different. It is composed of large blocks of altered serpentine gabbro, basalt breccia, and red radiolarian chert in a tuffaceous basalt matrix." No phosphatic beds or spicule cherts were mentioned by Jones.

Regarding the age of the Poverty Peak mélange, Jones stated that "All of the radiolarian ages from chert blocks in the Poverty Peak mélange are Early Permian." Because the radiolarians are from blocks (clasts), the age of the mélange must be Early Permian or younger. It is highly unlikely that either the Golconda or Poverty Peak could be of Triassic age because the Triassic sequence in the region is well studied and includes no such strata. If the two mélanges are essentially the same stratigraphic unit as interpreted by Ketner (2008), the age of the combined unit must fall within the middle Early Permian to Late Permian interval and be, at least in part, contemporaneous with the Phosphoria Formation. The mid-Permian rocks in the Hot Springs Range were deposited in the same sea as was the Havallah sequence and constitute a western facies of the Havallah (Ketner, 2008).

25. Northern East Range

A principal formation of the East Range is the Inskip Formation, a heterogeneous Upper Devonian to Permian sequence (Whitebread, 1994; Ketner and others, 2000, 2005; Ketner, 2008). The Inskip is thought to be a facies of the more widespread Havallah sequence of the same age range. Fossils are very scarce in the Inskip owing partly to dynamic metamorphism; but at Rock Hill Canyon, in the northern part of the Inskip exposure and close to the contact with Triassic rocks, conodont collections range from Mississippian to Permian and a fusulinid collection is of Early Permian age. Two of the conodont collections indicate a Wordian, Late Permian, age for some of the strata. The upper part of the Inskip at this location includes such lithic types as basalt, felsite, large-slab conglomerate, arkosic sandstone, bedded chert, and limestone. Neither spicule chert nor phosphatic beds were identified but a thorough search was not made.

Like the mid-Permian strata of the Hot Springs Range, those of the East Range are thought to have been deposited in the same sea as the Havallah sequence and to constitute a facies of the Havallah (Ketner, 2008).

Correlatives of the Phosphoria Formation in Terranes Thought to be Accretionary

The Permian rocks at Quinn River Crossing, and the Pine Forest Range are isolated exposures in an area where Permian rocks are widely regarded as having been accreted from an unknown original location (Crafford, 2008; Silberling, 1991; Silberling and others, 1987, 1992). Without much more data their relation to the Phosphoria Sea remains enigmatic.

26. Quinn River Crossing

The Quinn River Crossing area includes an exposure of quartzite composed mainly of quartz grains and angular chert grains but that also contains sporadic clasts of phosphate (Ketner and Wardlaw, 1981). The unit, which appears to be in fault contact with other Paleozoic rocks, resembles the Edna Mountain Formation in the variety of clasts, in their angularity, and in the presence of phosphate. However, according to Jones (1990) the abundant Permian fauna of another structural block, the Black Rock terrane, is closely related to correlatives in northern California. A linkage between the Quinn River rocks with the Phosphoria Sea therefore is problematical.

27. Pine Forest Range

Permian rocks in the Pine Forest Range include a unit composed of three members (Wyld, 1990). Wyld describes these as follows: “The lower member consists of gray limestone with thin interbeds of calcareous shale, and often contains unbroken rugose and/or tabulate corals. Gradationally overlying this member is a clastic member that consists of sandstone, conglomerate, shale, and minor limestone. Sandstone and conglomerate contain abundant sedimentary and volcanic clasts, less common feldspar, minor quartz, and rare plutonic clasts. Interbedded limestones are thin and sometimes contain up to 90 percent fossils, including abundant crinoid stems. The upper member is a limestone that consists of up to 90 percent unbroken fossils (mostly brachiopods) in a muddy carbonate matrix.” Brachiopods in the upper member are of Guadalupian age according to B.R. Wardlaw as quoted by Wyld. This sequence seems to resemble the Kaibab-Plympton-Gerster triplet of more easterly parts of Nevada. However, Wyld sees faunal links with northern California. As at Quinn River Crossing, the data appear to be ambiguous and a close linkage with the Phosphoria Sea cannot be justified at present.

Conclusions

The Phosphoria Sea and Its Sediments in Nevada

The mid-Permian Phosphoria Sea extended continuously more than 500 km westward and more than 700 km southwestward from the core area in southeastern Idaho (the net result of Mesozoic contraction and Tertiary extension is considered to be zero). The Phosphoria Sea therefore extended across formerly postulated emergent areas such as those depicted in publications as “Humboldt highland belt” (Ketner, 1977), “Antler orogenic belt” (Snyder and others, 1991), and “emergent Antler highland” (Piper and Link, 2002). Throughout its extent in Nevada the Phosphoria Sea was shallow, deepening only at its western extremity in western Nevada.

Typical strata of the Phosphoria Sea in Nevada are conglomerate, quartz- and chert-sandstone, siltstone, limestone, dolomite, gypsiferous beds, spicule chert and phosphorite. Testifying to shallow conditions are conglomerate, crossbedding in sandstone, scours, ooids, dolomite, and gypsum. Across its entire extent, it had a fauna similar to that of the type Phosphoria Formation. Phosphate particles, such as pellets, nucleated pellets, concentrically laminated pellets, compound pellets, and phosphatic fossil fragments, are generally similar to those of the type Phosphoria based on this study and on comparison with the descriptions and illustrations of Cook (1969), Lowell (1952), Mabie and Hess (1964), and Trappe (2001).

Steinkerns appear to be more abundant in the Nevada deposits than in the Phosphoria of the type area; fish scales, and phosphatic bioclasts less common. In general, quartz and chert clasts in Nevada are relatively large compared with those in the type area of the Phosphoria, and organic-rich mudstone is less common.

Pennsylvanian and Permian Strata Underlying Sediments of the Phosphoria Sea in Nevada

Commonly the mid-Permian rocks of northern Nevada are underlain conformably by a thick sequence of Middle Pennsylvanian to Early Permian age as indicated in several of the foregoing descriptions. The strata, composed of silty, sandy, commonly gypsiferous rocks, and impure limestone, are hundreds of meters thick in many places, and they lie disconformably or unconformably on rocks ranging from lower Paleozoic to Pennsylvanian in age. Although they are designated by many local stratigraphic names, they are essentially equivalent to, and probably genetically related to, the Oquirrh Formation of Utah and Wood River Formation of Idaho as proposed by Geslin (1998).

The Phosphate Content of Phosphoria-age Sediments in Nevada

Phosphate deposition was a characteristic of the Phosphoria Sea throughout its wide extent in Nevada, but the phosphate was much diluted by clastics and carbonate. From the small amount of quantitative data available based on sampling in the Adobe Range, it seems likely that the amount of apatite in mid-Permian sequences in some parts of Nevada may not differ greatly from that in the core area of southeastern Idaho. However, an exact comparison is not possible because of uncertainty as to the precise stratigraphic equivalence between the two areas and differences in methods of sampling.

The Western Margin of the Phosphoria Sea

The Phosphoria Sea merged westward into a body of relatively deep water in which the mid-Permian part of the Havallah sequence was deposited. The Havallah, an Upper Devonian to Permian sequence, is sliced by thrust faults and is commonly considered allochthonous wherever it is exposed. Arguably, the Havallah has not moved far from its point of origin (Ketner, 2008). This opinion, based on stratigraphic evidence, is supported by paleontological and lithic evidence cited by Murchey (1990) and quoted elsewhere in this report, linking the mid-Permian part of the Havallah sequence at Battle Mountain to the Phosphoria Formation. In any event, the distance traveled by the allochthonous Havallah is a matter of opinion, and the exact location of the transition between the Phosphoria Sea and deeper Havallah Sea therefore remains uncertain.

In the Late Devonian and Mississippian, the sea in which the lower part of the Havallah was deposited was of restricted width, bounded on the west by a landmass (Ketner and others, 2005); but whether that condition persisted through the Permian is unknown. The presence of fusulinid-bearing limestone of Permian age at its westernmost exposure, the East Range, suggests the sea at that point was not very deep. Many geologists believe Paleozoic terranes to the west of the Hot Springs and East Ranges (24 and 25 on fig. 1) were accreted from unknown locations (Silberling, 1991; Silberling and others, 1987, 1992). In the absence of concrete evidence, the question of what lay west of the Hot Springs and East Ranges in mid-Permian time remains unanswered.

Phosphoria Formation and the Oceanic Upwelling Model

Modern phosphorites form along the western margins of continents where nutrient-rich oceanic waters well up against the continental margin. Many believe that ancient giant deposits such as the Phosphoria Formation were deposited in the same situation as indicated by Glenn and others (1994) and quoted in the introduction to this report. However, a close genetic relation between oceanic upwelling at the continental margin and the Phosphoria Formation in its core area of greatest phosphate concentration is hard to justify because of the great expanse of shallow water that lay to the west of the core area. The area in and near southeastern Idaho where the concentration of phosphate is greatest apparently was a euxinic, starved basin deep within a very extensive, shallow sea.

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