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By JAMES B. CATHCART *and* DWIGHT L. SCHMIDT

CONTRIBUTIONS TO THE GEOLOGY OF ANTARCTICA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 456-E

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

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MIDDLE PALEOZOIC SEDIMENTARY PHOSPHATE IN THE PENSACOLA MOUNTAINS, ANTARCTICA

By James B. Cathcart and Dwight L. Schmidt

ABSTRACT

Primary sedimentary phosphorite was discovered in middle Paleozoic quartz sandstone about 600 km from the South Pole in the Neptune Range of the Pensacola Mountains, Antarctica. Both volume and grade of phosphate are low, and the possibility for any deposits of significant volume and grade is unfavorable.

Two principal types of carbonate fluorapatite are found: (1) primary sedimentary phosphorite and (2) secondary phosphate as cement. Both occur in the middle part of a 3,000-m section of quartz-rich sandstones that is equivalent to the widespread lower part of the Beacon Supergroup of the Transantarctic Mountains. The primary phosphorite is in several thin silty sandstone beds in the Elbow Formation which in most places consists of thin-bedded red siltstone interbedded alternately with thick-bedded quartzose sandstone. The age of the Elbow Formation is not younger than Early Devonian but may be as old as Ordovician. Black pebbles and cobbles of reworked phosphorite are found in a few places in sandstone beds directly overlying the primary phosphorite beds in the Elbow. Similar black pebbles and cobbles of phosphorite occur 200 m above the Elbow Formation in the basal conglomerate of the Dover Sandstone. In addition, small areas of basal conglomerate of the Dover have been cemented by secondary phosphate. The Dover Sandstone is Middle Devonian age.

During the middle Paleozoic the Pensacola Mountains area was part of a large epicontinental sea in which the shallow-water accumulation of several thousand meters of quartz sandstones kept pace with slow basin subsidence. The Elbow Formation and its primary phosphorite were deposited in marine water that was restricted from open-ocean circulation. The basal conglomerate of the Dover was most likely a transgressive beach deposit where access to acid surface water may have resulted in the solution of some of the detrital phosphate. The P_2O_5 in solution precipitated as phosphate cement with a change in pH below the zone of aeration during early diagenesis.

Present-day offshore phosphorite occurs between lats 44° N. and 52° S., and ancient phosphorites probably were deposited between similar paleolatitudes. The primary phosphorite of the Elbow Formation is at present located at lat 84° S. Reconstruction of Gondwanaland and its paleopole positions for Ordovician(?) to Early Devonian time (the time within which the Elbow was deposited) suggests that the Elbow phosphorite may well have been deposited north of 40° S. paleolatitude in temperate marine waters.

INTRODUCTION

Sedimentary phosphate was first discovered in Antarctica in December 1963 during reconnaissance geologic mapping of the Neptune Range, the middle range of the Pensacola Mountains (fig. 1). The phosphate at this Elliott Ridge locality consists mostly of sparse black pebbles in the basal conglomerate of the Middle Devonian Dover Sandstone. The conspicuous black phosphate pebbles make the light-colored quartz conglomerate an excellent marker horizon. Mapping during the 1963-64 (Schmidt, 1964) and 1965-66 (Huffman and Schmidt, 1966) austral field seasons shows that the phosphate-bearing basal conglomerate is exposed over an area of about 90 by 30 km (2,700 km²). A primary phosphate bed was discovered during the 1965-66 field season at the Mount Feldkotter locality (fig. 1). The bed is in the middle part of the Elbow Formation, about 200 m stratigraphically below the phosphate-bearing conglomerate of the Dover Sandstone.

Phosphate has been reported from only one other area in Antarctica: in the Beardmore Glacier area of the central Transantarctic Mountains, where sparse phosphate pebbles are present in the Fremouw Formation of Triassic age (Barrett, 1969, p. 54).

None of the known occurrences of phosphate in Antarctica are of economic significance, but the occurrence of sedimentary phosphate in Antarctica is, in itself, of special interest because known phosphate deposits characteristically form at low latitudes in temperate marine environments. The Neptune Range deposits, within 600 km of the South Pole, therefore, have important climatic implications that bear on the larger problem of movement of the Antarctic plate. The field study of the phosphate occurrences, because it was only one aspect of the work done in the Neptune Range, was necessarily limited in scope. Most of the data reported here were obtained from the phosphate-bearing sandstones at the Mount Feldkotter and Elliott Ridge localities (fig. 1).
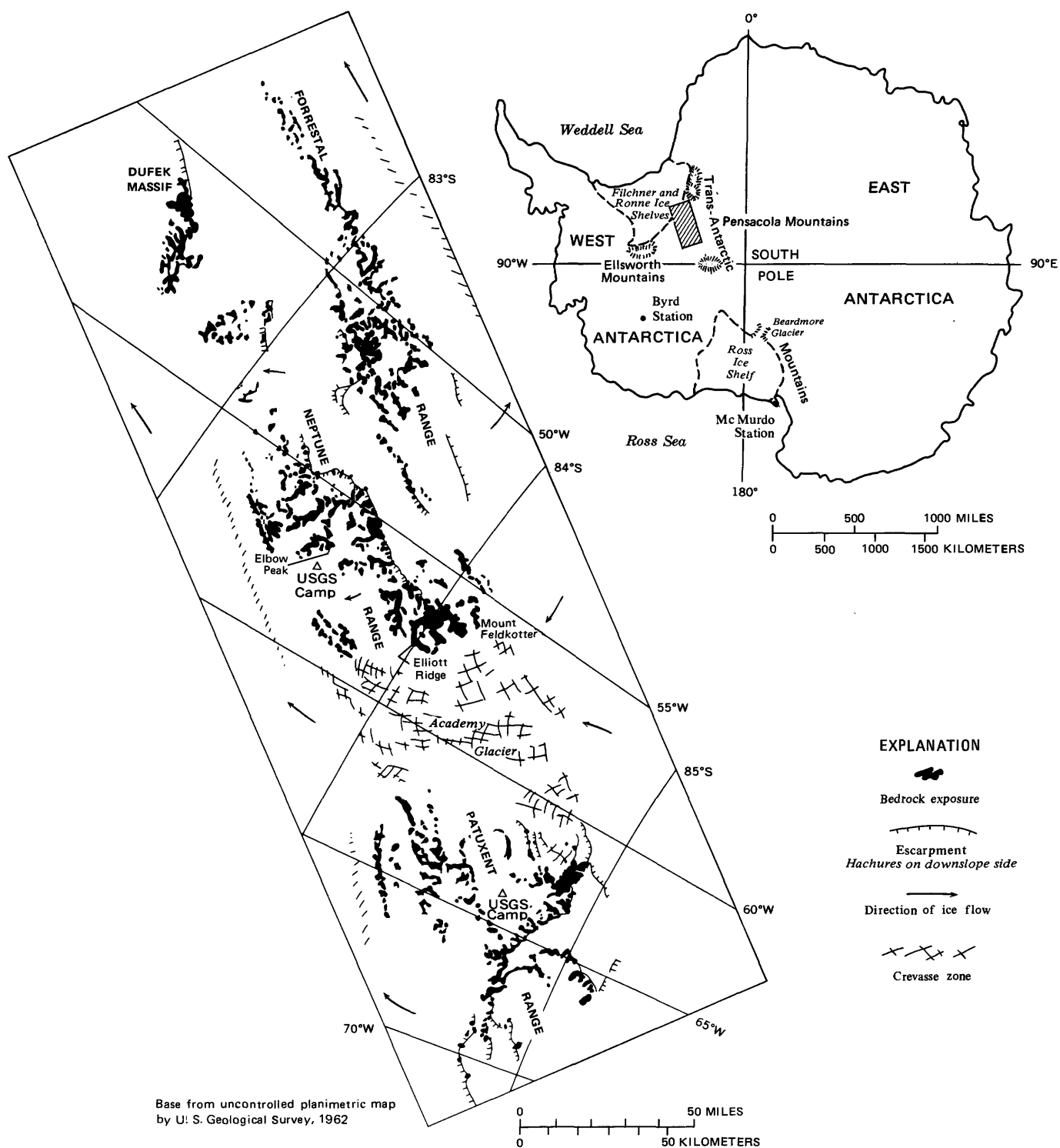
FIGURE 1.—Index map of Antarctica and the Pensacola Mountains showing localities in the Neptune Range. Phosphate localities are Elliott Ridge and Mount Feldkotter. Modified from Schmidt (1964).

The Neptune Range forms the central part of the Pensacola Mountains (fig. 1). It is separated from the Patuxent Range to the south by the Academy Glacier, a major outlet glacier draining ice from the

3,000-m-high interior Polar Plateau to the Weddell Sea via the Filchner and Ronne Ice Shelves. Snowfields and ice of local derivation separate the Neptune Range from the Dufek Massif and Forrestal

Range to the north. Mountain summits generally range in elevation from 1,000 to 2,000 m, and local relief ranges from about 200 to 1,400 m. Rock exposures are generally fresh owing to recent deglaciation and to frost riving. Climate is that of a cold desert: precipitation is slight, and summer temperatures range from about -18° to 4°C. Mean annual temperature, as determined from temperature at 10-m borehole depth, is about -26°C (Boyd, in U.S. Geological Survey 1964, p. A121).

GENERAL GEOLOGIC SETTING

The Neptune Range, along with the rest of the Pensacola Mountains, belongs physiographically and geologically to the province of the Transantarctic Mountains, a major mountain chain which marks the boundary between the Precambrian craton of East Antarctica and the younger mobile region of West Antarctica (fig. 1). Lower(?) Precambrian crystalline rocks, although not exposed in the Pensacola Mountains and only sparsely exposed elsewhere in the Transantarctic Mountains, form a basement beneath strongly deformed geosynclinal rocks of late Precambrian to Cambrian age that, in turn, lie unconformably beneath little-deformed Paleozoic and younger platform deposits (Ford, 1964).

In the Pensacola Mountains, the oldest rocks compose a thick sequence, the first sequence of figure 2, of upper Precambrian eugeosynclinal graywacke and slate belonging to the Patuxent Formation that was strongly deformed and regionally metamorphosed prior to deposition of fossiliferous marine limestone (Nelson Limestone) during the Middle Cambrian (Palmer and Gatehouse, 1972). This limestone, along with overlying felsic volcanic and clastic rocks (Gambacorta and Wiens Formations),

forms the second sequence, which was folded and intruded by granitic plutons during early Paleozoic time.

The phosphate beds described in this report occur in the middle part of the third sequence in the Neptune Range. The third sequence correlates approximately with the Paleozoic part of the Beacon Supergroup (Harrington, 1965) that is widely distributed in the Transantarctic Mountains (Barrett, 1970, p. 256) and regionally ranges in age from Ordovician(?) to Jurassic. The Beacon Supergroup is subdivided into a lower and an upper part in the Neptune Range. The lower Beacon consists largely of quartz-rich sandstones that contain sparse fish remains and plant fragments of Devonian age · (Rigby and Schopf, 1969, p. 92). It was deposited in epicontinental basins. The base of the upper Beacon is marked by the upper Paleozoic (Permian) glacial deposits that are known throughout most of the Transantarctic Mountains (Barrett, 1970, p. 256). Carboniferous sedimentary rocks have not been reported, although the glacial rocks may in part be Carboniferous (Rigby and Schopf, 1969, p. 102). The upper Beacon consists of arkosic sandstones and siltstones and coal measures of dominantly continental origin, and it commonly contains abundant Permian and Triassic to Jurassic plant fossils; the Upper Permian coal measures are widespread (Rigby and Schopf, 1969). Only the Permian and older rocks of the Beacon are present in the report area.

Detrital phosphate pebbles are sparsely distributed in a quartzose part of the Triassic Fremouw Formation at three localities ranging over a distance of 125 km in the Beardmore Glacier area of the central Transantarctic Mountains (Barrett, 1969, p. 54). The reported pebbles are dark gray, spheroidal 1-4 cm in diameter, and consist of microcrystalline apatite, quartz, and sericite. The apatite mineral is a carbonate fluorapatite as determined by X-ray diffraction by J. B. Cathcart although it is reported simply as fluorapatite. The source of the phosphate pebbles is not known.

Phosphatic concretionary nodules and lenses occur at two different stratigraphic horizons in Gondwana rocks in South Africa. Although these horizons are widespread, neither has been successfully exploited (DuToit, 1954, p. 536). We do not know of any other phosphate occurrences in Gondwana sequences in Gondwanaland. On this hemispherical scale, the Beacon Supergroup of the Transantarctic Mountains has a gross lithology, lithologic succession, and paleobotany that is similar to that of middle Paleozoic to middle Mesozoic sedimentary
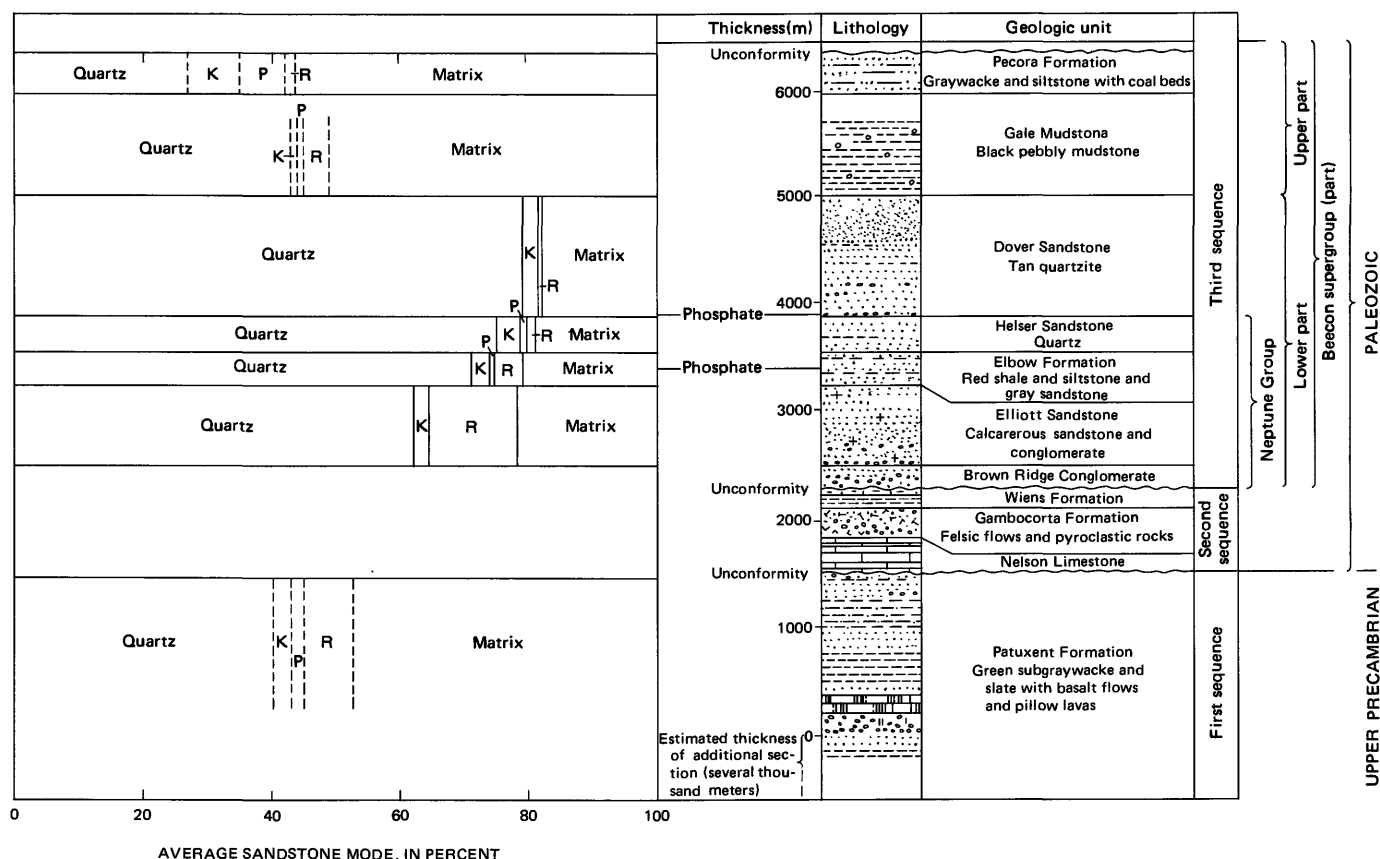
FIGURE 2.—Composite stratigraphic column (modified from Schmidt and others, 1965) and average modal composition of sandstones in the Neptune Range. Average modes are shown only for formations that are dominantly sandstone, and only sandstone modes are used (data from Williams, 1969, p. 1458). For middle Paleozoic quartz sandstone formations that are of interest for phosphatic occurrences, the composition is shown by solid lines; for other formations it is shown by dashed lines. K, potash feldspar; P, plagioclase; R, detrital rock fragments. Where plagioclase is not shown, its modal composition is less than 0.5 percent.

rocks of Gondwanaland on the other southern hemisphere continents and India.

In the Pensacola Mountains the third sequence (fig. 2), equivalent to part of the Beacon Supergroup, consists of more than 4,000 m of clastic rocks, chiefly of Devonian and Permian age (Schmidt and others, 1965; Schmidt and Ford, 1969). The predominantly quartzose sandstones, about 3,000 m thick, are equivalent to the lower Beacon strata and are subdivided into five formations, two of which, the Elbow Formation and the Dover Sandstone, contain phosphate (fig. 2). The Dover Sandstone in the Patuxent Range (fig. 1) contains several thin carbonaceous shaly-silt lenses with plant microfossils, apparently Middle Devonian in age (Schopf, 1968); associated plant megafossils of Haplostigma(?) and Cyclostima-type are also indicative of the Devonian (Rigby and Schopf, 1969, p. 92). The four formations below the Dover contain only trace fossils that are not identifiable and may be as old as Ordovician. Equivalents of the upper Beacon strata in the Pensacola Mountains

are the Gale Mudstone (Gondwanid tillite) and the overlying Pecora Formation. The Pecora is referable to the middle and late Permian as indicated by the presence of the characteristic Gangamopteris-Glossopteris flora and coalbeds. The Gale may be Early Permian (Rigby and Schopf, 1969, p. 103).

All Beacon-equivalent sedimentary rocks of the Pensacola Mountains were moderately deformed and folded during a regional orogeny, the Weddell Orogeny, in the early Mesozoic (Ford, 1972a; Ellsworth Orogeny of Craddock, 1972). Deformation was accompanied by a slight low-grade regional metamorphism during which argillaceous minerals in the matrix of the sedimentary rocks were recrystallized chiefly as sericite and chlorite (Beck and Schmidt, 1971, p. C175).

STRATIGRAPHY AND PETROLOGY

The phosphate-bearing sandstones of the Neptune Range occur in a 3,000-m-thick succession of

sedimentary rocks consisting of the Neptune Group and Dover Sandstone (fig. 2). This succession of rocks represents a gradual change from a high-energy environment (locally derived coarse sediments of the Brown Ridge Conglomerate and Elliott Sandstone) to one of moderate energy (alternating fine sandstone and siltstone red beds of the Elbow Formation) and back to one of moderately high energy (quartz sandstone of the Heiser Sandstone and coarse well-sorted sparse quartz-pebble ortho-quartzite of the Dover Sandstone) (Williams, 1969). The orogenic Brown Ridge Conglomerate consists largely of locally derived volcanic debris, whereas the Elliott Sandstone contains an average of only 8 percent of such volcanic rock fragments; the Elbow and Heiser Formations have much less, and the Dover none (Williams, 1969). The total thickness of about 2,000 m of moderately well to well-sorted quartzose sandstones suggests that deposition was in relatively shallow water in a slowly subsiding basin of an epicontinental sea.

ELBOW FORMATION

The Elbow Formation (Schmidt and others, 1965; Schmidt and Ford, 1969) gradationally overlies the Elliott Sandstone; the contact is placed below a conspicuous change to red clastic rocks. The formation is about 300 m thick at the type section at Elbow Peak (fig. 1) but thins to the east and south and is only about 140 m thick at Mount Feldkotter 65 km south-southeast (fig. 3).

The Elbow Formation throughout most of the Neptune Range consists of well-bedded red argillaceous siltstone and interbedded light-gray fine-grained quartz-rich sandstone. Parts of the section consist of regularly alternating beds of sandstone and siltstone in pairs 0.3–2 m thick. Beds are commonly well laminated, and crossbedding and ripple marks are conspicuous. Irregular curved tubules, 0.5–2 cm in diameter, trend at a variable but commonly high angle to bedding and are mottled light gray in red siltstone beds; these are probably fossil burrows.

At Mount Feldkotter the Elbow Formation is thinner, slightly coarser grained, and more feldspathic than elsewhere in the Neptune Range, suggesting that this is a more shoreward facies. It is mostly nonred (fig. 3). The formation consists of thick crossbedded pale-greenish-buff quartz sandstone interbedded with thin medium-drab-green silty sandstone. In contrast to the red siltstone interbeds of the Elbow elsewhere, only the upper part of the silty sandstone beds is deep red brown. The basal part of many of the thick sandstone interbeds consists of gritstone or conglomeratic sandstone con-taining intraformational clasts of sandstone and siltstone. Sandstone and silty sandstone alternations are well developed. A middle 20- to 30-m-thick part of the Elbow section contains several thin silty phosphatic sandstone beds (fig. 3).

The average modal composition of eight samples of Elbow Formation from widely spaced localities within the Neptune Range is given in table 1 and is shown graphically in figure 2. Quartz sandstone from the Elbow Formation at Mount Feldkotter (samples a and d, table 1) contains more quartz and potash feldspar than the average mode, while the silty phosphatic sandstone (sample b, table 1) contains less quartz and more potash feldspar than the average. Whole-rock X-ray diffractometer patterns of two additional sandstone samples indicate compositions that are in close agreement with those counted microscopically. The X-ray patterns indicate about 70 percent quartz (compared with the X-ray pattern of a quartz standard), 20 percent chlorite, and 10 percent muscovite (based on relative peak heights), and a trace of pyrophyllite. The pyrophyllite was identified only by its major peak at about 3 nanometers, and the identification must be regarded as tentative. Apatite lines were not detected even though the samples are from the phosphate-bearing middle part of the Elbow Formation. Sericite, chlorite, and pyrophyllite, at least in part, are products of low-grade metamorphism.

HEISER SANDSTONE

The nonphosphatic Heiser Sandstone gradationally overlies the Elbow Formation; the contact is placed below the first trace-fossil bed which is located at approximately the top of the conspicuous red clastic rocks of the Elbow. The formation is about 300 m thick throughout most of the Neptune Range (fig. 2), but it thins to 125 m at Mount Feldkotter. The stratigraphic section shown on figure 3, although thinner, is representative of the Heiser throughout the Neptune Range.

The Heiser Sandstone consists of thick-bedded (0.3–1 m) and crossbedded buff to medium-brown medium-grained quartz sandstone irregularly and cyclically interbedded with thin beds (0.03–0.6 m) of dark-drab-green to dark-brown silty sandstone. The Heiser is characterized by abundant narrow tubules, 2–5-mm diameter, in many of the thick sandstone beds; the tubules, probably fossil burrows, are perpendicular to bedding.

The average modal composition of five typical sandstones of the Heiser from well-distributed localities in the Neptune Range is shown graphically on figure 2. Two samples from the top of the section at

DOVER SANDSTONE
Unit C—Thick-bedded buff medium- to coarse-grained quartz sandstone and quartzite beds 2-3 m thick containing sparse round quartz pebbles
Unit B—Dark-red-brown sandstone about 20 m thick
Unit A—Well-bedded crossbedded medium-red-brown quartz-pebble conglomerate 3-4 m thick containing sparse black phosphatic pebbles and blocks

HEISER SANDSTONE
Cyclically interbedded thick-bedded crossbedded buff medium-grained quartz sandstone beds 0.3-1 m thick and thin dark-drab-green silty sandstone beds 0.03-0.6 m thick. Cycles of sandstone and silty sandstone average 1 m thick. Tubules (t) are characteristic of formation and are abundant and common in thick sandstone beds where they trend vertical to bedding; tubules are 2-5 mm in diameter
Unit B—Dark brown owing to interbedding of dark-red-brown sandstone with the silty sandstone
Unit A—Light-tan faintly crossbedded medium- to coarse-grained sandstone

ELBOW FORMATION
Interbedded thick-bedded crossbedded buff medium-grained sandstone beds 0.3-2 m thick and thin-bedded green and red-brown silty sandstone beds 0.1-0.6 m thick. Bases of sandstone beds are commonly gritstone and conglomeratic. Alternations of sandstone and silty sandstone are common, especially in upper half. Phosphatic silty sendstone occurs sparsely in a 10- to 20-m interval in middle part of formation. Total thickness of formation is 140 m

ELLIOTT SANDSTONE
Thick-bedded crossbedded light-green medium-grained sandstone and interbedded medium-green silty sandstone

UNIT

METERS

PHOSPHATE-BEARING BASAL CONGLOMERATE

Sandstone, thick-bedded, red-brown
Gritstone and sandstone, buff
Conglomerate, quartz-pebble, sandy, buff; rare black round phosphatic pebbles
Sandstone, crossbedded, buff
Conglomerate, quartz-pebble; rare black round phosphate pebbles
Sandstone, crossbedded, dark-brown
Sandstone, conglomeratic, quartz-pebble, buff; scattered round black phosphate pebbles and cobbles and irregularly shaped lenses of phosphate-cemented sandstone
Sandstone, thick-bedded, yellow to medium-brown

Modal analyses, Ta

PHOSPHATIC ZONE

Sandstone, buff
Gritstone, sandy, buff
Sandstone, silty, dark-drab-green
Sandstone; weathers pale red brown. Intraformational conglomeretic sandstone at base; scattered dark-gray phosphatic cobbles, maximum 8-cm diameter
Sandstone, silty, 30-cm-thick. Upper two-thirds is dark-gray phosphatic sandstone that grades down to lower one-third, which is medium-gray silty sandstone
Sandstone, light-greenish-buff

Samples d c b a

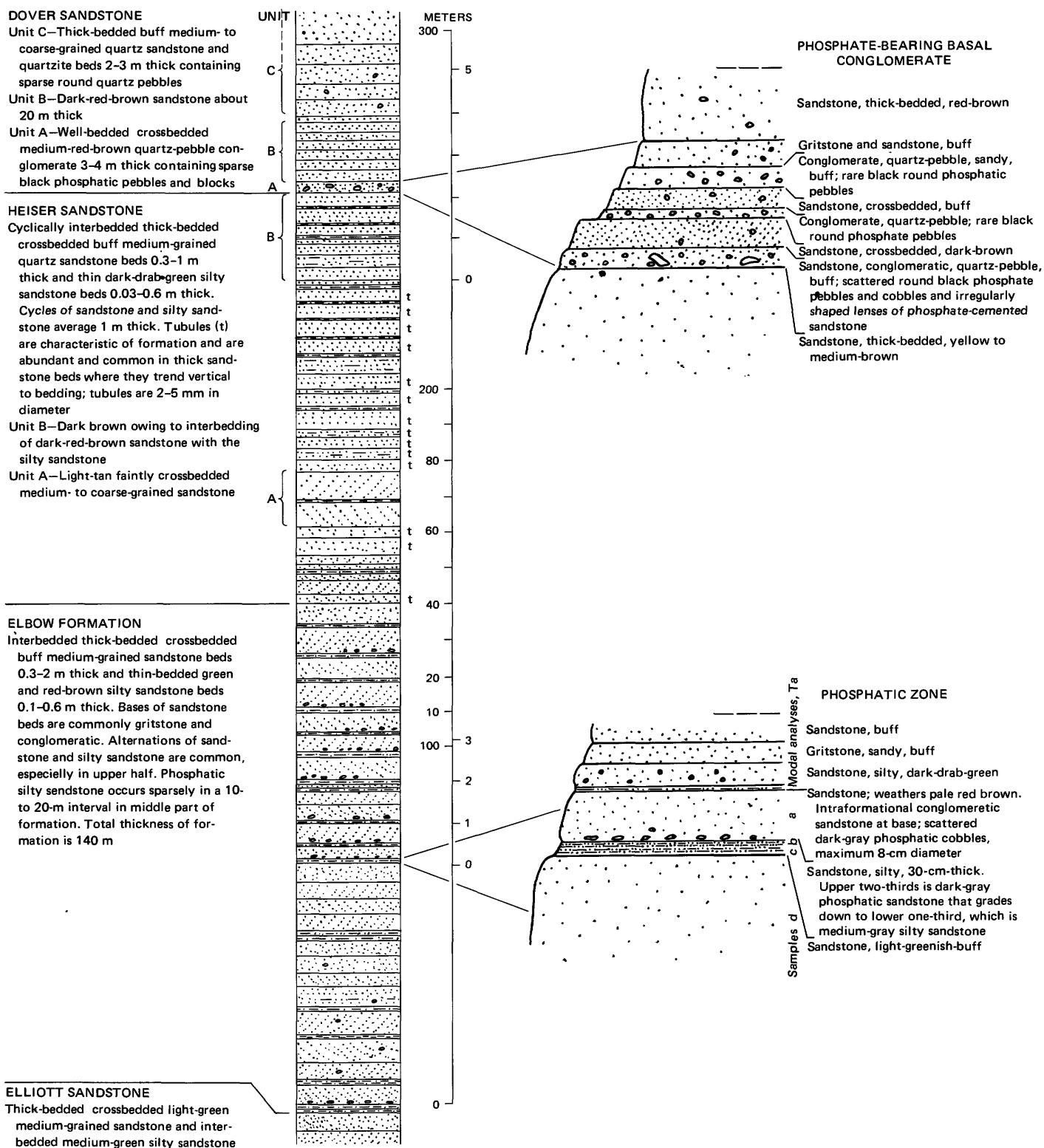FIGURE 3.—Measured stratigraphic section of phosphate-bearing middle Paleozoic sandstones at Mount Feldkotter in the southernmost Neptune Range.

Elliott Ridge (fig. 1) give X-ray diffractometer patterns indicating that quartz is the principal mineral phase (60-75 percent) and that chlorite, sericite, and potash feldspar are also present. Mica recrystallization in the matrix is suggestive of low-grade metamorphism.

TABLE 1.—*Petrography of sandstone samples from across the phosphatic middle part of the Elbow Formation at Mount Feldkotter compared with average petrography of eight sandstone samples of the Elbow Formation from localities throughout the Neptune Range* (Williams, 1969, p. 1458)

[Modes by P. L. Williams; 500 points counted on thin sections,
potash feldspar verified on stained rock slices]

Sample No.	Rock name	Mode (percent)					Grain size (average)	Sorting	Clast roundness[1]
		Quartz	Potash feldspar	Plagioclase	Matrix	Rock fragments			
		Mount Feldkotter (phosphatic middle part of Elbow Formation)							
a-----	Quartz sandstone.	76	7.6	Trace	14	2.6	Medium---	Fair----	SA
b-----	Silty phosphatic sandstone.	62	9.0	.4	[2]23	4.8	------do-------	Good---	SA
c----	Silty sandstone.	63	4.2	Trace	[3]29	4.2	------do-------	---do----	SA
d-----	Quartz sandstone.	69	9.9	.2	17	4.0	------do-------	Fair----	SR
		Neptune Range (average of eight samples from Elbow Formation at widespread localities)							
e-----	Sandstone---	71	2.8	0.5	21	4.5	Medium---	Good---	SR

[1] SA, subangular; SR, subrounded.
[2] Includes about 12 percent modal microcrystalline apatite.
[3] Includes probably less than 1 percent apatite.

DOVER SANDSTONE

The Dover Sandstone overlies the Heiser Sandstone with apparent conformity (fig. 2), but a thin basal conglomerate may represent a considerable break in sedimentation. The formation is about 1,200 m thick and is disconformably overlain by the Gale Mudstone. The lower 50 m of the Dover section at Mount Feldkotter is shown on figures 3 and 4. This section at Mount Feldkotter is representative of the lower Dover elsewhere in the Neptune Range.

The Dover Sandstone is a buff medium- to coarse-grained quartz sandstone and orthoquartzite, containing sparse round pebbles of quartz. The rock is thick bedded (beds 0.6-1 m thick) and is coarsely crossbedded in many places. The quartz grains are rounded and well sorted.

The base of the Dover is an irregularly bedded crossbedded buff to pale-red-brown conglomeratic sandstone, 3-7 m thick, that contains round quartz pebbles and a few round pebbles of black phosphate and black chert.

The average modal composition of seven samples of the Dover Sandstone (fig. 2) from well-distributed localities in the Neptune Range indicates a sandstone of high quartz content, about 80 percent. Two samples of quartz sandstone from the lower part of the Dover on Elliott Ridge give X-ray diffractometer patterns indicating major amounts of quartz

and minor amounts of muscovite (sericite) and potash feldspar; light-green shalelike pellets in the sandstone contain only quartz and muscovite (sericite). Minor pyrophyllite was tentatively identified by X-ray in another sandstone sample. In thin

FIGURE 4.—Outcrop of lower part of Dover Sandstone overlying the Heiser Sandstone (H) at Mount Feldkotter. Above the contact is 3.3 m of basal conglomerate (A) that contains sparse phosphate. Units A, B, and C are shown on stratigraphic section (fig. 3).

section, recrystallized sericite and pyrophyllite(?) in the matrix suggest low-grade metamorphism.

PHOSPHATE OCCURRENCES

Phosphatic beds are found in the middle part of the third sequence (fig. 2). Phosphate, as carbonate fluorapatite, has been found in the middle of the Elbow Formation only at Mount Feldkotter (figs. 5, 6). No phosphate thus far discovered is economic.

ELBOW FORMATION

The phosphate in the Elbow Formation at Mount Feldkotter is a matrix mineral in a silty sandstone bed and also in silty sandstone pebbles and cobbles. The silty sandstone bed, about 30 cm thick (fig. 3), pinches down to a thin parting plane in a distance of 50 m along strike. The phosphate in the bed at the place of maximum thickness is confined to the upper 20 cm and is greatest in amount near the top of the bed. Other similar thin silty sandstone beds in the Elbow Formation possibly contain some phosphate but have not been studied. A sample (b, fig. 3; table 1) from the phosphate sandstone bed contains about 20 percent apatite, 60 percent quartz, and about equal amounts of muscovite (sericite), chlorite, and potash feldspar, as determined by X-ray diffraction. About 12 percent modal apatite was estimated in a thin section of the same sample (table 1).

In thin section, the silty phosphatic sandstone consists of medium-grained quartz and potash feldspar set in a matrix of brown microcrystalline apatite, quartz, sericite, and chlorite (fig. 7).

Most of the apatite appears to be primary. However, some apatite is recrystallized; patches of matrix containing abundant phosphate in places have clear or light-brown apatite centers (possibly the remnants of original apatite pellets) and thin rinds of apatite replacing quartz. The recrystallization is probably diagenic.

The thin basal conglomerate of the thick sandstone bed that overlies the silty phosphatic sandstone at Mount Feldkotter (fig. 3) contains locally derived intraformational pebbles, cobbles, and subangular blocks of dark-gray phosphatic sandstone (fig. 8) that are similar in composition to the underlying silty phosphatic sandstone. Other thick sandstone beds, which are located 2–30 m above the one described here, have conglomeratic parts that contain similar subangular black phosphatic sandstone clasts.

DOVER SANDSTONE

Two types of phosphate occur in the basal conglomerate of the Dover Sandstone, which is 3–7 m

FIGURE 5.—Outcrop of basal conglomerate of the Dover Sandstone on Elliott Ridge showing typical occurrence of phosphate pebbles and cobbles (P) and phosphate-cemented conglomeratic sandstone (C) in well-crossbedded moderately channeled flat-lying quartz-pebble sandstone. Geologic hammer shows scale.

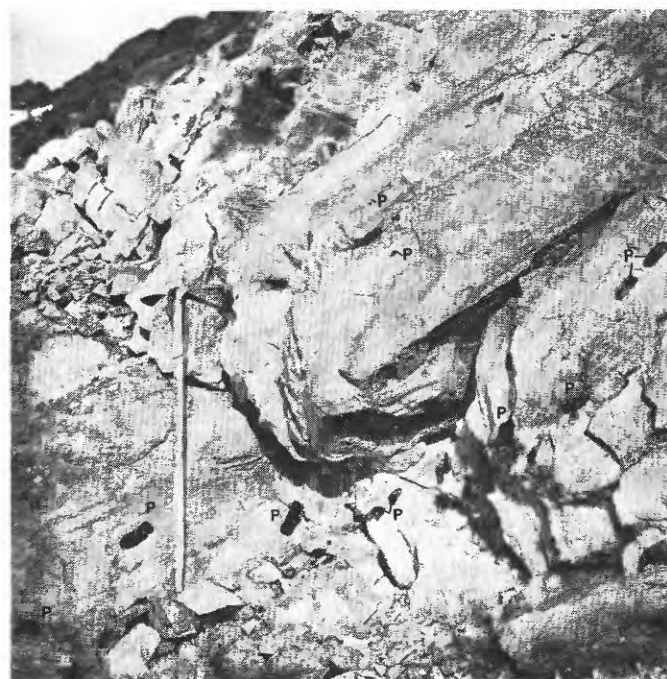FIGURE 6.—Outcrop of basal conglomerate of Dover Sandstone on Elliott Ridge showing phosphate cobbles and pebbles (P) in quartz-pebble sandstone that dips 50° to left. Ice axe shows scale.

thick throughout the Neptune Range (figs. 3, 4). In one type the phosphate consists of black phosphate pebbles and cobbles (fig. 6); in the other it is a black phosphate cement in quartz sandstone. The phos-

1 mm

1 mm

FIGURE 7.—Photomicrograph of silty phosphatic quartz sand-
stone in middle part of Elbow Formation at Mount Feld-
kotter (sample b, fig. 3). Matrix (ps) is about half micro-
crystalline apatite and half microcrystalline quartz, sericite,
and chlorite. Q, detrital quartz; kf, potash feldspar; R, argill-
aceous rock clast. Plane-polarized light.

FIGURE 8.—Photomicrograph of edge of silty phosphatic sand-
stone pebble (left) and adjacent conglomeratic sandstone
(right). Sample is from base of thick sandstone bed (a, fig. 3)
and above the silty phosphatic sandstone bed (b, fig. 3) in
middle part of Elbow Formation at Mount Feldkotter. Q, detri-
tal quartz; S, sericitic matrix in conglomeratic sandstone;
ps, microcrystalline apatite-sericite-chlorite matrix in pebble.
Plane-polarized light.

phate-cemented sandstone occurs either as pods and
lenses or as large blocklike clasts (fig. 5).

The phosphate pebbles and cobbles are sub-
angular to rounded and as much as 15 cm across;
most are only 1–2 cm in diameter. Many are flattened
and oriented parallel to bedding (figs 5, 6, 9). Where
abundant, the phosphate clasts are concentrated at
the base of conglomeratic layers (fig. 9). The pebbles
and cobbles are composed largely of microcrystalline
apatite, but they also contain abundant silt-sized
quartz and sericite. The sericite generally has a
distinct preferred orientation that may have paral-
leled original bedding (fig. 10). The black phosphate
pebbles and cobbles are transported clasts of un-
known source. The only known phosphatic beds are
those of the underlying Elbow Formation.

A few of the phosphate pebbles have a narrow
rind of phosphate-cemented sandstone that is part of
the sandstone enclosing the pebbles. This rind is
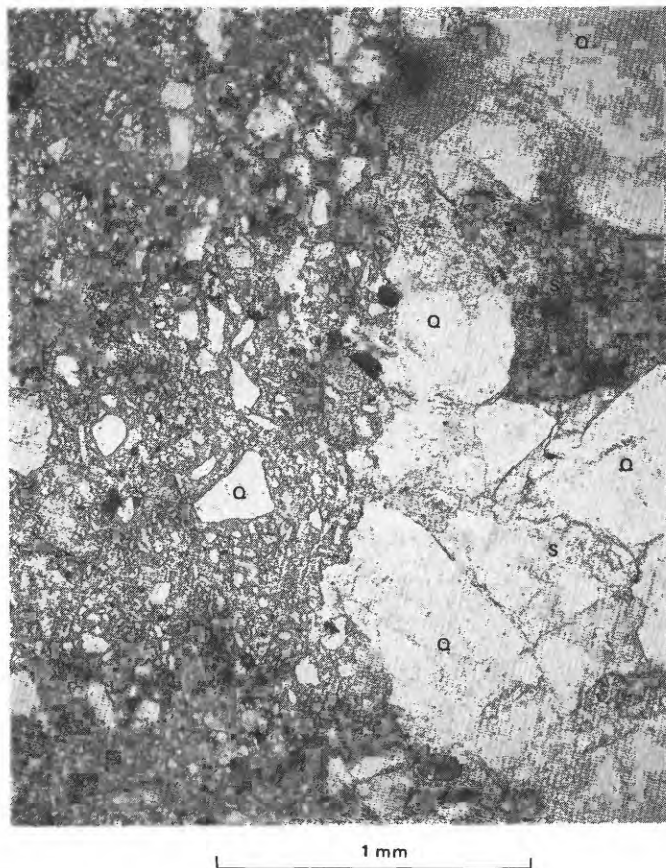about 3 mm thick on the pebble shown in figure 11.

The phosphate cement contains few fine-grained
inclusions relative to the abundant argillaceous
material in the phosphate pebbles. Most of the
phosphate within the rind has extensively replaced
coarse-grained quartz of the enclosing conglomer-
atic quartz sandstone.

Similar phosphate cement is locally much more
extensive in the basal conglomerate. Elongate pods
and lenses, as long as 60 cm and mostly concord-
ant with bedding, consist of black phosphate-
cemented quartz gritstone and conglomeratic quartz
sandstone (fig. 12). The phosphate has cemented
pore space but more extensively has replaced quartz
and argillaceous matrix (fig. 13).

Some large angular to subrounded blocks of
black phosphate-cemented sandstone similar to the
in situ pods and lenses have internal bedding that is
discordant to the outcrop bedding. These blocks have
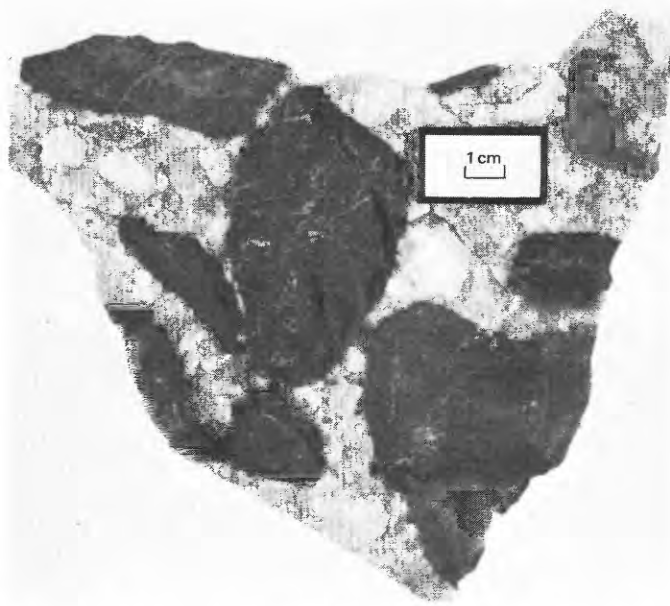been rotated and slightly transported penecontemp-

FIGURE 9.—Phosphate cobbles in sandy quartz-pebble conglomerate of the basal conglomerate of the Dover Sandstone on Elliott Ridge. View is perpendicular to bedding.

oraneously during deposition of the basal conglomerate. Some of the blocks are more than 15 by 30 cm in size and are elongate parallel to their internal bedding. The phosphate cement is relatively pure (fig. 13) and free of the argillaceous inclusions that characterize the phosphate pebbles.

In summary, the two types of phosphate in the basal conglomerate of the Dover are readily distinguished at both outcrop scale and microscopic scale. Phosphate clasts less than pebble size are not found in the basal conglomerate. One possible explanation is that the smaller than pebble-size phosphate clasts were penecontemporaneously dissolved and were the source for the secondary phosphate that locally precipitated as cement in the in situ pods and lenses and as rinds on some phosphate pebbles. Clearly the secondary phosphate replacement and cementation followed deposition of the phosphate pebbles and the enclosing quartz sandstone. The evidence provided by the locally transported blocks of phosphate-cemented sandstone indicates that this secondary phosphate was precipitated between intervals of sedimentation of successive conglomeratic sandstone beds. Therefore, the secondary phosphate is early diagenic. Thin section study indicates that phosphate was not mobilized during the early Mesozoic metamorphism; at most, the phosphate was locally recrystallized along microscopic planes of strain (fig. 13).
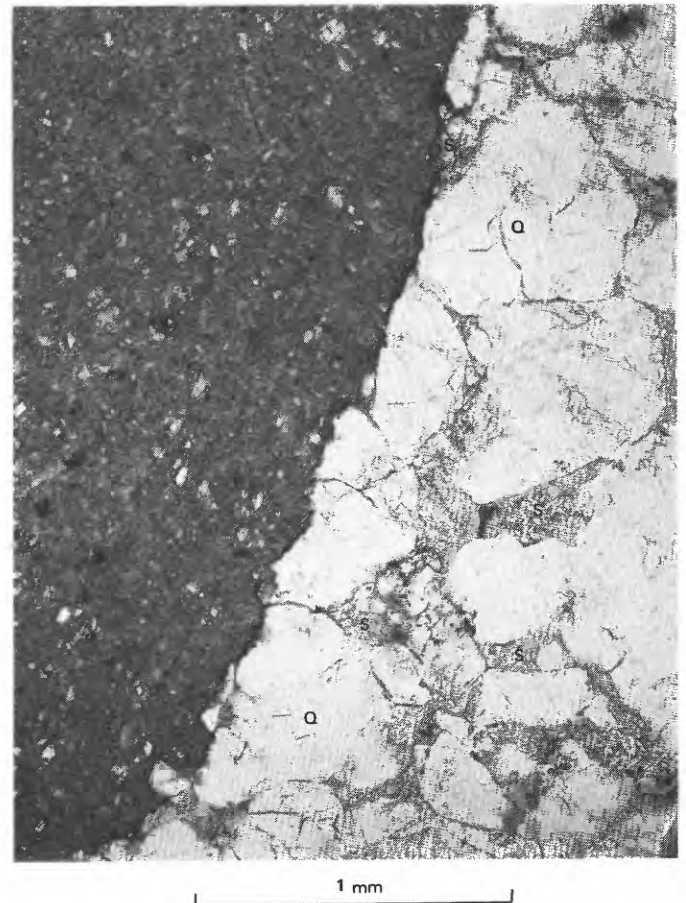
FIGURE 10.—Photomicrograph of edge of phosphate pebble (left) and adjacent quartz sandstone (right). Pebble consists of microcrystalline apatite and abundant semioriented silt-sized sericite and quartz. Sample is from the basal conglomerate of the Dover Sandstone on Elliott Ridge. Q, detrital quartz; S, sericite and chloritic matrix. Crossed nicols.

MINERALOGY

The apatite mineral of marine phosphorites is a carbonate fluorapatite. Altschuler, Clarke, and Young (1958, p. 48) pointed out that carbonate fluorapatite "is generally characterized relative to fluorapatite by a deficit in P_2O_5 content of 3-6 percent, an excess of F, OH (or both) of 0.5 to 1.0 percent, and by the presence of 2-3 percent of carbonate."

Recent work by Lehr and his colleagues (Lehr and others, 1968; Smith and Lehr, 1966; McClellan and Lehr, 1969) established a relation between the carbonate substitution and the mineral's cell dimensions. Gulbrandsen (1970), using data from McClellan and Lehr (1969), showed that there is a direct correlation between the carbonate content and the a-cell dimension. Because the calculation of the a-cell

FIGURE 12.—Sample containing two generations of phosphate in basal conglomerate of the Dover Sandstone on Elliott Ridge: (1) detrital phosphate cobble 9 cm lon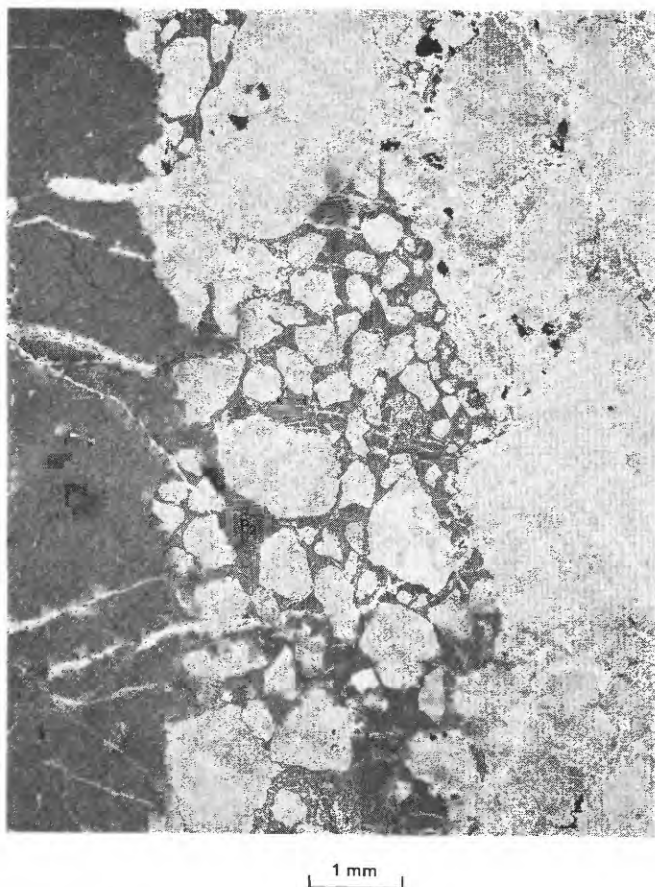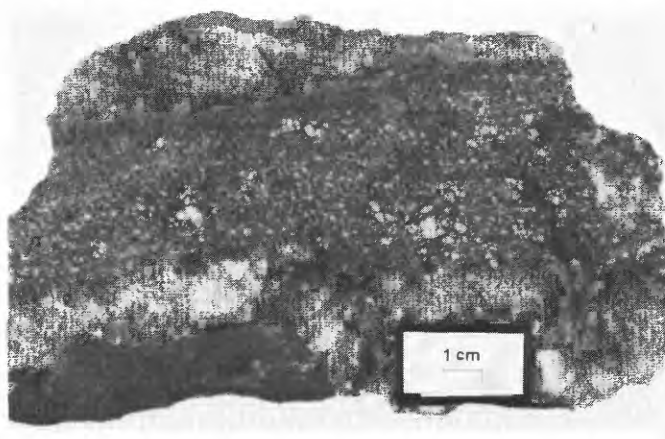g (left of scale) and (2) phosphate-cemented quartz-pebble sandstone (large dark zone, center of sample) containing partially replaced quartz grains and quartz pebbles floating in phosphate. This secondary phosphate tends to follow bedding but in places cuts irregularly across bedding.

FIGURE 11.—Photomicrograph of edge of phosphate pebble (P_1) with rind of phosphate-cemented sandstone (P_2) that is part of the conglomeratic quartz sandstone enclosing the pebble. The phosphate cement (P_2) contains few inclusions relative to the more abundant argillaceous material in the phosphate pebble (fig. 10). The phosphate within the rind has replaced quartz after the deposition of the pebble. Small quartz veinlets transect the rock. Sample is from the basal conglomerate of the Dover Sandstone on Elliott Ridge. Plane-polarized light.

dimension is time consuming, Gulbrandsen used a peak-pair method that requires only the measurement of the angular difference between two X-ray diffraction peaks to show the same correlation. Silverman, Fuyat, and Weiser (1952) also used a peak-pair method to show the difference between the carbonate fluorapatite and other apatites. Gulbrandsen (1970, p. B10) used the (410) and (004) peaks, which occur near 51.6° and 53.1° 2θ, and his data (shown on fig. 2 of his paper) are reproduced here on figure 14. Data from carbonate fluorapatite samples from the Pliocene Bone Valley Formation of Florida and data from samples from the phosphate of the Dover Sandstone from Elliott Ridge are also plotted on the diagram.

The solid line on the diagram (fig. 14) is the least-squares line calculated by Gulbrandsen using data from McClellan and Lehr. The plots of samples from the Permian Phosphoria Formation from Idaho and Wyoming fall on this line and indicate that the correlation is good. The plots of samples from the Bone Valley Formation of Florida do not plot on this line but seem to have a positive correlation. The samples from the Dover Sandstone fall on the line with the Phosphoria samples and, therefore, seem to be more closely allied with the samples from the Phosphoria Formation than they do with the samples from the Bone Valley Formation. The plots of the phosphate from the Dover Sandstone fall well within the area on the diagram that is characteristic of carbonate fluorapatite.

CHEMICAL ANALYSES

Chemical analyses (table 2) were made in the Denver laboratories of the U.S. Geological Survey under the direction of Claude Huffman, Jr. P_2O_5 was determined volumetrically by G. D. Shipley. Acid insoluble and loss on ignition were determined gravimetrically by G. D. Shipley. Al_2O_3 was determined, by Alizarin Red-S with cupferron separation, by H. H. Lipp. Total Fe, CaO, MgO, Na_2O, K_2O, Mn, Sr, and Zn were determined, by atomic absorption, by Johnnie Gardner. SiO_2 was determined colorimetrically by H. H. Lipp. TiO_2 was determined, by tiron spectrophotometric method, by Elsie Rowe. Fluorine (F) was determined volumetrically by Johnnie Gardner. Arsenic (As) was determined, by modi-
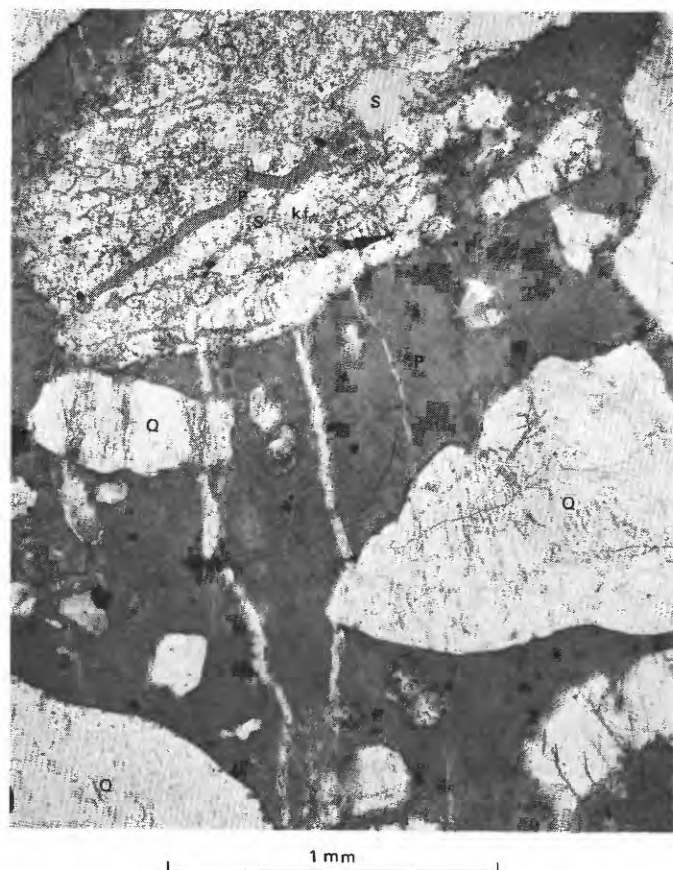
FIGURE 13.—Photomicrograph of phosphate-cemented sandstone from the basal conglomerate of the Dover Sandstone on Elliott Ridge. Thin section is from phosphate-cemented zone of rock shown in figure 12. Light-brown microcrystalline apatite (P) cements quartz and potash feldspar chiefly through the replacement of preexisting sericitic matrix and fine-grained detrital clasts; in many places most clasts less than 0.5 mm across have been replaced. The phosphate is nearly free of argillaceous inclusions; black specks are iron oxide. Q, quartz clast; kf, potash feldspar; S, sericitic alteration product in feldspar. Recrystallized apatite fills white veinlets that parallel strain structures in quartz clasts—both features are related to early Mesozoic orogeny. Plane-polarized light.

fied Gutzeit method, by E. J. Fennelly. Total carbon was determined by induction furnace, mineral carbon was determined gasometrically, organic carbon was determined by difference, and total sulfur (S) was determined by induction furnace compared to Land Rock Phosphate Standard, all by I. C. Frost. eU was determined, by beta gamma scaler, by Johnnie Gardner.

The content of the major elements reflects the mineralogic composition of the analyzed samples; that is, major apatite, minor quartz and sericite, and a trace of potassium feldspar. The contents of P_2O_5, CaO, and F and the ratios of CaO to P_2O_5 and F to

$\Delta 2\theta_{(004)-(410)}$, IN DEGREES
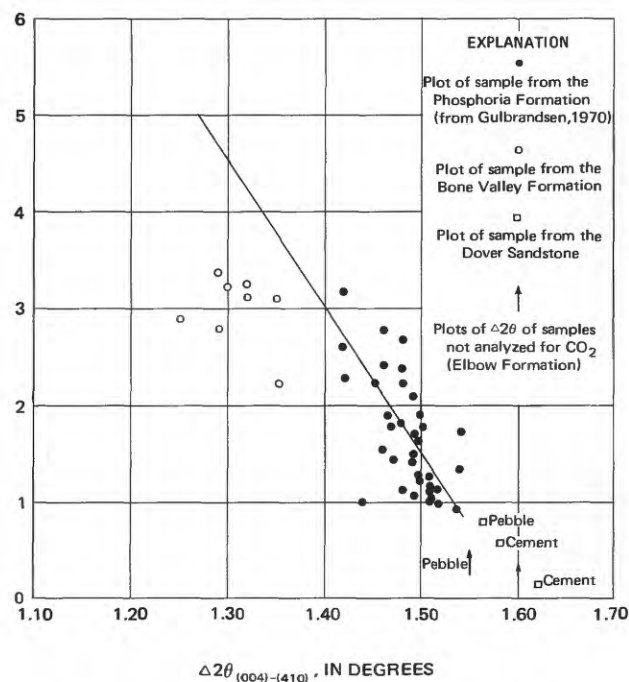
FIGURE 14.—Plot of CO_2 and $\Delta 2\theta_{(004)-(410)}$ showing relation of samples of Antarctic phosphate rock to samples of the Phosphoria Formation from the Western United States and the Bone Valley Formation from Florida.

TABLE 2.—*Chemical analyses of phosphate samples from the Dover Sandstone, Elliott Ridge, Neptune Range*

[Values are in percent except as noted]

Sample No Laboratory No Sample type	A D137451 Apatite cement[1]	B D137452 Apatite cement[1]	C D137453 Apatite pebble[2]
P_2O_5	27.2	26.1	27.4
CaO	39.8	38.2	40.5
F	2.54	2.46	2.48
SiO_2	22.4	18.8	16.8
Acid insoluble	22.8	20.3	18.8
Al_2O_3	2.76	4.68	4.91
Fe_2O_3[3]	1.42	2.06	1.05
MgO	.14	.18	.22
Na_2O	.05	.04	.04
K_2O	1.19	1.66	1.76
TiO_2	.3	.1	.3
Mn	.05	.17	.04
Sr	.04	.06	.04
Zn	.003	.005	.003
S	.30	.19	.08
eU	.037	.020	.021
C(total)	.31	.58	.34
(mineral)	.15	.03	.21
(organic)	.2	.6	.1
CO_2[4]	.55	.11	.77
As (ppm)	125	35	85
Loss on ignition	1.3	2.1	1.6

[1]Separated from matrix in bromoform (sp. gr. = 2.86).
[2]Handpicked coarse black dense phosphate pebbles.
[3]Total iron as Fe_2O_3.
[4]CO_2=mineral carbon times 3.67.

P_2O_5 are within the range for the apatite mineral, and all these can be assigned to the apatite mineral. The CO_2 content can be assigned to the apatite mineral because no other carbonate-bearing mineral has been detected in the samples.

The silica contents of the samples are high, reflecting the abundance of fine-grained quartz and silicate minerals, and the generally high content of Al_2O_3 (considerably higher than phosphorite from the Bone Valley Formation or the Phosphoria Formation) reflects the high content of the aluminum silicate minerals sericite and feldspar.

The samples are low in Na_2O content—much lower than the Phosphoria Formation of the Western United States and Bone Valley Formation of Florida, both of which average about 0.6 percent Na_2O but are high in K_2O content. Sodium is much higher than potassium in the Bone Valley phosphate, and the contents of these alkalies are about the same in the Phosphoria phosphates, in strong contrast to the Antarctic phosphates, where K_2O is much more abundant than Na_2O.

Sodium probably substitutes for calcium in the apatite mineral, whereas the potassium is present in one of the diluting minerals—sericite or feldspar. The reason for the low sodium content is not known; all that can be said is that the Antarctic apatite samples are deficient in sodium, as compared with other apatite samples.

The content of TiO_2 is low but is within the range shown by samples of marine apatites from the Bone Valley Formation and from the Phosphoria Formation. Titanium is probably present in one of the titanium-bearing minerals, but the mineral is in such small amounts that it cannot be detected by the X-ray. The titanium may be present in the mineral leucoxene, tentatively identified from thin section study.

The amount of MgO in the samples of the Dover Sandstone is low and is at the lower end of the range of MgO content of samples of phosphate rock from the Phosphoria and Bone Valley Formations. The minor amounts of MgO in the samples from Antarctica may be in the mica chloritic or in the apatite minerals.

Sulfur, present in the Antarctic samples in minor amounts, probably is in the form of SO_4 as a substitute for PO_4 in the apatite mineral.

The content of organic matter in these samples generally is low, although the phosphate pebbles and cement are black in hand specimen. The content of organic carbon is less than 1 percent, much lower than that of the samples of the Phosphoria

Formation, and close to the content of the samples from the Bone Valley Formation.

The X-ray data (fig. 14) and the chemical analyses (table 2) clearly show that the apatite mineral is a carbonate fluorapatite. The apatite of the phosphate pebble contains more CO_2 than does the phosphate cement. Mobilization of the phosphate and its precipitation as cement may have driven off a part of the CO_2. The cement is more similar to fluorapatite than is the phosphate pebble.

SPECTROGRAPHIC ANALYSES

Six-step semiquantitative spectrographic analyses were run on two samples of phosphate cement separated from the rest of the rock by bromoform, on one sample of phosphate pebble, and on one sample of phosphate cement handpicked under the microscope. The results (table 3) are to be identified with geometric brackets whose boundaries are 1.2, 0.83, 0.56, 0.26, 0.18, 0.12, etc. but are reported arbitrarily as midpoints of these brackets, 1.0, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, etc. The precision of a reported value is approximately plus or minus one bracket at 68-percent confidence or two brackets at 95-percent confidence. Elements looked for but not detected (those elements whose concentration is below the limit of detection), with their limits of detection shown in parentheses, include: As (200), Au (10), B (10), Bi (10), Cd (20), Pd (2), Pt (50), Sb (100), Te (2,000), U (500), W (50), Zn (200), Ge (10), Hf (100), In (10), Li (100), Re (50), Ta (200), Th (200), Tl (50), Eu (100), Tb (300), Er (50), Tm (20), Lu (30).

The minor element content (table 3) is about the same for the phosphate pebble (sample 3) and the phosphate cement (samples 1, 2, 4). The data do not preclude the possibility that the source of the phosphate cement may have been the phosphate pebbles. Evidence from thin section indicates the possibility that phosphate from the pebbles has been mobilized and moved outward from the pebble to cement the sandstone adjacent to the pebble (fig. 11).

The minor element content in the samples from the Dover Sandstone is compared with the content of trace elements in phosphorite from the Phosphoria Formation of the Western United States and from the Bone Valley Formation of Florida (table 4). In addition, the minor element content is compared with the crustal abundance of these elements relative to which an enrichment factor is recorded. The trace metals, Ag, Cr, Cu, Mo, Ni, V, Zn, and probably Co, are much more abundant in the Phosphoria Formation than in the samples of the Dover Sandstone but are present in samples of the Bone Valley

TABLE 3.—*Semiquantitative six-step spectrographic analysis of sample of phosphate rock from Dover Sandstone, Elliott Ridge, Neptune Range*

[Analysts: Samples 1, 2, 3, Harriet Neiman, U.S. Geological Survey, Denver; sample 4, W. R. Crandell, U.S. Geological Survey, Washington. G, greater than 10 percent; N, not detected; L, detected, but below limit of determination]

Sample No	1	2	3	4
Lab. No	D137451	D136452	D137453	4128
In percent				
Fe	1	1	0.7	0.7
Mg	.05	.1	.15	.5
Ca	G	G	G	G
Ti	.2	.05	.1	.015
Si	10	10	5	5
Al	2	2	2	2
Na	.07	.05	.07	.02
K	1	1.5	2	N
P	7	10	10	G
In parts per million				
Mn	500	1,500	500	500
Ag	N	N	N	5
Ba	300	500	300	500
Be	7	10	7	10
Co	5	5	3	7
Cr	200	150	150	200
Cu	10	15	7	7
La	70	150	70	150
Mo	7	7	N	N
Nb	L	N	N	N
Ni	100	50	7	30
Pb	70	100	100	100
Sc	30	15	15	10
Sn	L	10	10	N
Sr	700	700	500	700
V	70	15	100	70
Y	200	200	200	200
Zr	300	100	70	15
Ce	150	500	200	150
Ga	N	5	10	N
Yb	15	15	10	2
Nd	100	200	100	N
Sm	N	100	N	N
Gd	N	50	N	N
Dy	N	50	L	N
Ho	N	L	L	N

Sample:
  1 and 2—Heavy mineral separate (bromoform sink) of phosphate cement.
  3—Handpicked black pebble.
  4—Handpicked black cementing material.

Formation in about the same amounts as in the Dover. In fact, these elements are enriched in the Phosphoria Formation and are, in general, depleted in the Dover and the Bone Valley. Krauskopf (1955) pointed out that Ag, As, Cr, Mo, Ni, V, and Zn probably are concentrated by organic matter associated with phosphates rather than by the phosphate mineral, and Gulbrandsen (1966) concluded that these elements plus Cd, Cu, Sb, and Se also are concentrated by organic material. These conclusions are supported by the data on phosphate rock from Antarctica, because those elements that are thought to be concentrated by organic material are in much lesser amounts in the relatively organic poor Florida and Antarctic phosphates than in the relatively organic rich Phosphoria Formation. Arsenic is a notable exception, being considerably enriched in

the Antarctic material, and it possibly is present in the apatite mineral. Young, Myers, Munson, and Conklin (1969) pointed out that arsenic is enriched in an igneous fluorapatite and that it probably replaces the phosphorus ion, and Krauskopf (1955) also noted that a part of the arsenic probably substituted for P in the apatite structure.

Lead, tin, and beryllium all seem to be present in the phosphate of Antarctica in larger amounts than in either the Bone Valley or Phosphoria phosphate. Krauskopf (1955) indicated that lead and beryllium may be concentrated by the apatite mineral, lead substituting for calcium, and that the mode of occurrence of beryllium is not known. The mode of occurrence of tin is not known, but probably it follows the other metals and is concentrated in the organic fraction.

Zirconium is present in larger amounts in the few samples of Antarctic phosphate rock than in either the Bone Valley or Phosphoria phosphate, but it is probably present in the mineral zircon.

Strontium, present in about the same amounts as in the other marine phosphate rocks, probably substitutes for calcium in the apatite mineral. Gallium, present in somewhat larger amounts in these rocks than in the phosphorites from the Bone Valley or the Phosphoria, probably is present as a substitute for aluminum in the aluminum-bearing minerals.

The presence of uranium in marine phosphorite is well known, and uranium substitutes for calcium in the apatite mineral (Altschuler and others, 1958). The uranium content of these rocks is somewhat larger than the average for the Bone Valley or the Phosphoria, but the uranium content of many individual samples from the Bone Valley Formation of Florida is as large as or larger than that of Antarctic samples. Manganese and barium are higher in these rocks than in the averages for the Phosphoria and Bone Valley, but the manganese contents are closer to those for Bone Valley than for the Phosphoria. Gulbrandsen (1966) pointed out that manganese is not likely to precipitate under the strongly reducing conditions typical of the Phosphoria environment, but according to Krauskopf (1957) manganese does precipitate in the sea under strongly oxidizing conditions. The manganese in these rocks is probably present as a manganese mineral, perhaps as a barium-manganese oxide such as psilomelane, but the mineral is present in amounts that are too small to be indicated by the X-ray.

The rare earth elements are concentrated in the apatite mineral. They are more abundant in the Western Interior phosphate than in either the Florida or the Antarctic material. It is thought that the rare earth elements substitute for calcium in the

TABLE 4.—*Minor metal contents of phosphatic materials of this paper compared with crustal abundances of these metals and with amounts in marine phosphorites*

[Abundance values in parts per million. Numbers in parentheses after values for elements are approximate enrichment factors for elements; numbers greater than 1.0 indicate enrichment, numbers less than 1.0 indicate depletion. N=not detected; P=present in some samples but not detected in most (element probably just below limit of detection)]

Element	Crustal abundance (Green. 1953)	This report[1]	Marine phosphorite Phosphoria Formation of Western United States (Gulbrandsen, 1966)	Marine phosphorite Bone Valley Formation of Florida (J. B. Cathcart, unpub. data)
Ag	0.1	N	3(30.0)	0.5 (5.0)
As	5	[2]80 (16.0)	[2]40 (8.0)	[2]20 (4.0)
Ba	250	300 (1.2)	100 (0.4)	70 (0.3)
Be	2	7 (3.5)	N	1 (0.5)
Cr	200	150 (0.8)	1,000 (5.0)	100 (0.5)
Co	23	5 (0.2)	[3]N	3 (0.1)
Cu	70	10 (0.1)	100 (1.4)	10 (0.1)
Ga	15	5 (0.3)	N	P (0.3?)
Mn	1,000	500 (0.5)	30 (0.03)	200 (0.2)
Mo	1	5 (5.0)	30(30.0)	10 (10.0)
Ni	80	50 (0.6)	100 (1.3)	15 (0.2)
Pb	16	100 (6.3)	N	10 (0.6)
Sn	40	10 (0.3)	N	N
Sr	450	700 (1.6)	1,000 (2.2)	1,000 (2.2)
V	150	70 (0.5)	300 (2.0)	150 (1.0)
U	2	[2]260(130.0)	[2]90(45.0)	140 (70.0)
Zr	200	100 (0.5)	30 (0.2)	50 (0.3)
Zn	130	30 (0.2)	300 (2.3)	100 (0.8)
Rare earth elements:				
La	20	100 (5.0)	300(15.0)	100 (5.0)
Ce	40	200 (5.0)	[3]N	200 (5.0)
Nd	20	100 (5.0)	300(15.0)	150 (7.5)
Sm	5	P	N	P
Gd	5	P	N	P
Dy	5	P	N	P
Ho	1	P	N	P
Yb	3	15 (5.0)	10 (3.3)	10 (3.3)
Y	40	200 (5.0)	300 (7.5)	200 (5.0)
Sc	5	15 (3.0)	10 (2.0)	7 (1.5)

[1] Modes (most frequent number reported) from all samples on table 3.
[2] Arithmetic average of chemical determinations.
[3] Limit of detection of Co was 10 ppm and of Ce 1,000 ppm when this group of analyses was made.

phosphate mineral, and the enrichment factors for all of the rare earth elements are about the same for each occurrence.

Scandium is put with the rare earth elements, but it is not clear whether scandium tends to follow the rare earths. In any case, its enrichment factor is less, and it is present in minor amounts.

In summary, the data on table 4 indicate clearly that the content of trace elements of the phosphate rock from Antarctica is much closer to the content of phosphate rock from the Bone Valley Formation of Florida than it is to phosphate rock from the Phosphoria Formation.

ORIGIN AND DEPOSITIONAL ENVIRONMENTS OF SEDIMENTARY PHOSPHATE IN ANTARCTICA

The largest and richest of the marine phosphorite deposits are formed in warm waters mostly between the 40th parallels (Sheldon, 1964) in areas of upwelling (McKelvey, 1967) and where clastic sedimentation is at a minimum; that is, in a miogeosynclinal environment. Deposits are characterized by a suite of rocks that consists of black shale, phosphorite, dolomite, limestone, and chert. Phosphate deposits formed in the adjacent stable shelf are associated with chert, sandstone, and shale, which generally are light colored in contrast to the black of the geosynclinal rocks. Large phosphorite deposits had to be deposited in areas that were in contact with oceanic circulation so that phosphate was continuously replenished as it was precipitated. A summary of the origin of phosphate deposits and of economic deposits of the world is given by Cathcart and Gulbrandsen (1973).

Sediments deposited during the middle Paleozoic in what is now the Neptune Range consist of

several thousand meters of quartzose sandy material which is relatively uniform in composition and texture and which probably accumulated in shallow water in a slowly subsiding basin. The areal extent and uniformity indicate that deposition may have been in a large epicontinental sea with the craton to the east. The Elbow Formation is characterized by abundant animal burrows and, except at Mount Feldkotter, by red sedimentary rocks. The beds, initially green, were oxidized possibly by periodic exposure. These features indicate deposition in shallow water. A restricted marine environment is suggested by regional paleogeography and by C^{13} and O^{18} isotopic ratios made from carbonate cement (Schmidt and Friedman, 1974). Phosphate has not been found in the characteristic red facies but is confined to a nearshore non-red-bed facies of the Elbow Formation at Mount Feldkotter.

Phosphate in the Elbow Formation at Mount Feldkotter is the only primary sedimentary phosphorite exposed in the Neptune Range. The shallow water in which the sediments were deposited is thought to have been within the zone of photosynthesis, where phosphate goes into the organic cycle. The phosphate, therefore, probably precipitated below the sediment-water interface during a low-energy interval. The change to higher energy deposition for the overlying sandstone beds resulted in the erosion and mechanical reworking of part of the underlying phosphatic material and the incorporation of subangular phosphatic sandstone clasts into the base of the overlying sediment.

The shoreward facies of the Elbow Formation at Mount Feldkotter that contains the primary phosphorite probably extends more widely beneath the extensive ice and snow cover east and north of Mount Feldkotter. However, the paleogeography of the area and the physical character of the phosphorite make it unlikely that this is a large-tonnage phosphorite deposit.

The Heiser Sandstone was deposited in the same shallow-water environment as the Elbow but under conditions of slightly higher energy. The Heiser contains much less silt and shale than the Elbow. Abundant fossil burrows throughout the Heiser suggest shallow-water deposition. No red beds and no phosphorite beds are known in the Heiser.

The environment of deposition of the Dover Sandstone was a moderately high energy broad shallow-water epicontinental basin. Sparse land-plant fossils as detrital grains in association with carbonaceous silt lenses, the lack of marine fossils, the extensive crossbedding, and the basal conglomerate indicate that most of the formation was de-posited in a continental environment. The basal conglomerate most likely was deposited as a transgressive beach deposit.

The occurrence of 1,200 m of clean quartz sandstone above the basal conglomerate of the Dover indicates deposition in the broad shallow-water slowly subsiding epicontinental basin. The waters of the basin during Dover time may have been fresh, as indicated by solution and redeposition of phosphate in the basal conglomerate, by the sparse occurrence of fossil plant remains, and by the isotopic study of C^{13} and O^{18} in the rocks above the Dover. The thick overlying Gale Mudstone (Gonwanid tillite) is entirely freshwater (Schmidt and Friedman, 1974). The source of the phosphate pebbles in the basal conglomerate of the Dover probably was the Elbow Formation, inasmuch as primary phosphate is known only in this formation.

The apatite mineral in all the occurrences in the Neptune Range is a carbonate fluorapatite that contains only small amounts of CO_2 substituting for PO_4. The phosphate in the Elbow Formation is thought to be primary—deposited in a restricted marine environment. Mechanically rounded and transported pebbles in the Dover probably were derived from the Elbow as are the subangular clasts within the Elbow itself. The secondary phosphate cement in the Dover was derived from solution of the detrital phosphate clasts and reprecipitation of P_2O_5, probably in freshwater in a subaerial environment. The fact that the reprecipitated cement contains less CO_2 than the original material may be due to a progressive loss of CO_2 during the long history of erosion, reworking, solution, and reprecipitation.

Slight regional metamorphism (Beck and Schmidt, 1971) of the Paleozoic rocks in the Neptune Range during the early Mesozoic orogeny (Ford, 1972a) caused the recrystallization of argillaceous material to sericite and chlorite and the slight alteration of the primary and secondary phosphate mineral through additional loss of CO_2.

The primary phosphate of the Elbow Formation likely was deposited at a lower and warmer latitude than its present-day position at 84° S. Evidence from the extensive literature pertaining to plate tectonics and the existence of Gondwanaland precludes the possibility of expanding the southern warm climatic zone to lat 84° S. as proposed by Meyerhoff (1970, p. 17, 25). Sheldon (1964) suggested that when ancient phosphorite deposits are relocated relative to their paleolatitudes as determined from paleomagnetic data, their deposition occurred between the 40th parallels, where most deposits of upper Tertiary and

EXPLANATION
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Polar-wandering curve

Paleopole cluster
ePz, early Peleozoic
eC, early Carboniferous

O

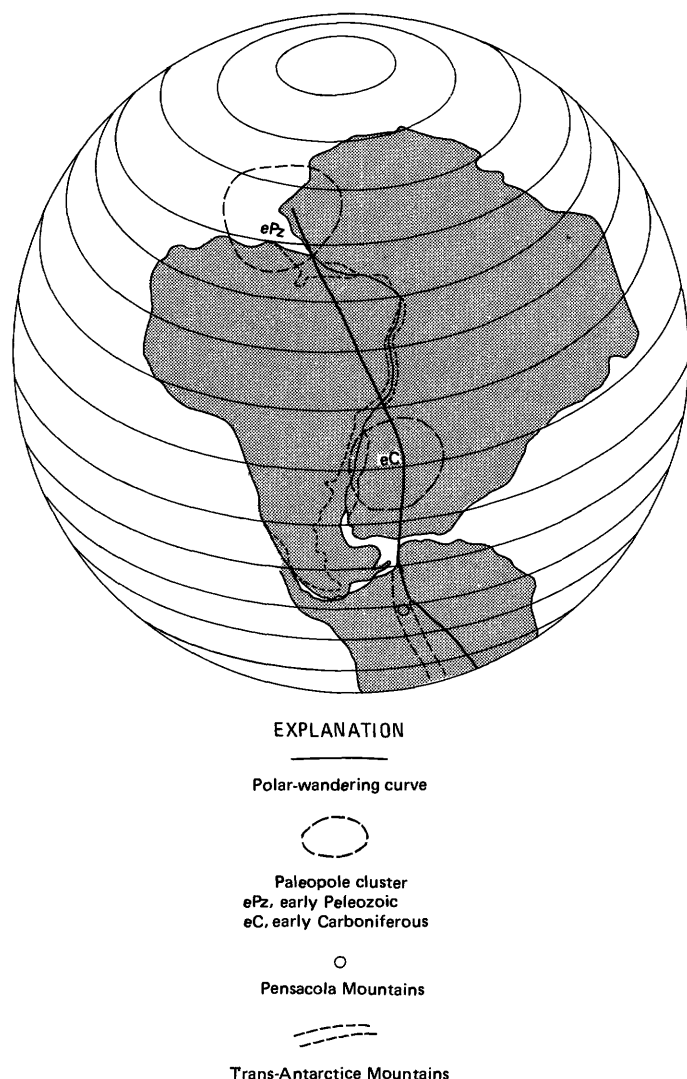Pensacola Mountains

Trans-Antarctice Mountains

FIGURE 15.—Reconstruction of Gondwanaland (position random
in figure) showing position of Pensacola Mountains relative
to the polar-wandering curve for the Paleozoic of Gondwana-
land. Clusters of paleopoles for early Paleozoic and Early
Carboniferous time independently agree roughly with the
central areas of the African glaciation of northern Africa
and the early Gondwana glaciation of southern Africa. The
Elbow Formation of the Pensacola Mountains was deposited
some time between Ordovician(?) and Early Devonian time
when the paleopole lay between the early Paleozoic and Early
Carboniferous positions. Phosphorite in the Elbow Formation
would have been deposited, therefore, when the paleopole
was at lat 50°-20° S. Africa and South America fit from
Bullard, Everett, and Smith (1965); Antarctic fit from Ford
(1972b, p. 116); early Paleozoic and Early Carboniferous
paleopoles and polar-wandering curve from Creer (1970, p. 63).

Quaternary phosphorite are found. More precisely,
present-day offshore phosphorite occurs between
lats 44° N. and 52° S. (McKelvey and Wang, 1969, pl.
4).

The polar wandering curve for Gondwanaland

for the Paleozoic extends southward along the prerift
suture line of western Africa and eastern South
America as determined by paleomagnetic data for
Africa, South America, and Antarctica (Creer, 1970,
p. 63). The polar wandering curve likely represents
movement of the Gondwanaland rigid plate across a
fixed rotational pole. The pole positions are approx-
imately and independently substantiated by the
estimated centers of continental glaciation for the
African glaciation in North Africa during the late
Ordovician (Fairbridge, 1969) and the Gondwana
glaciation in southern Africa during the Early Car-
boniferous, and in Antarctica during Late Carbon-
iferous and Early Permian (Crowell and Frakes,
1970).

The time of deposition of the Elbow Formation is
bracketed between Middle Cambrian (Palmer and
Gatehouse, 1972) and Middle Devonian (Schopf,
1968). During the Ordovician and Silurian the paleo-
south pole can be reasonably considered to be be-
tween northern Africa and southern Africa. Most
reconstructions of Gondwanaland (for various
choices see Ford, 1972b, p. 118) place Antarctica
against Africa and South America such that the
Pensacola Mountains are 30-70 degrees of latitude
from any reasonable pole position during the Ordov-
ician and Silurian (fig. 15). Elbow phosphorite was
deposited in temperate marine waters.

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