

PETROGRAPHY OF LOWER TAL PHOSPHORITES, MUSSOORIE SYNFORM, UTTAR PRADESH, INDIA*

by H. S. PAREEK†, *Geological Survey of India, Lucknow*

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Phosphorites occur as thin to thick bands in the Lower Tal formations of the Mussoorie synform in Dehradun and Tehri districts of Uttar Pradesh, India. The phosphorites appear as bedded-massive, bedded, platy, lenticular, nodular, pelletal or granular, fragmentary, and oolitic varieties, that are named so, on the basis of the predominant mode of occurrence of the phosphates. The phosphate mineral is commonly opaque, as masked by carbonaceous matter, but the outcrop specimens reveal their inherent nature. Many of the phosphate bodies have oxidized rims of anisotropic nature. These varieties are described and illustrated in this paper. The matrix is siliceous, calcareous, or clayey, being weakly to moderately phosphatic. Of all the phosphorites examined, the ultra-fine-grained matrix shows maximum radioactivity. Pyrite is in intimate association with the phosphates as a replacing mineral, and isolation of the pure phosphate from such associations is difficult, unless pyrite can be transformed into pyrrhotite by thermal heat, and separated magnetically.

INTRODUCTION

In India, phosphorites have been recorded and reported only recently from the areas in Dehradun and Tehri districts, Uttar Pradesh (Chaterji 1967; Ghosh 1968), and Jaisalmer and Udaipur districts, Rajasthan (Mukti Nath 1967; Mukti Nath *et al.* 1969; Sri Kantan *et al.* 1970). These deposits hold promise to save considerable foreign exchange of the country by contributing towards the manufacture of ferro-phosphorus, super-phosphate, potash, etc., for the fertilizer industry. Thin bands of phosphorite have also been recorded from the Nigali Dhar and Korgai synclines, district Sirmur, around Darla in district Mahasu (Aggarwal 1970; Pareek 1971; Srikantia *et al.* 1970), and the Rajgarh and Pachmunda synclines, district Simla, Himachal Pradesh (Joshi 1970). Studies on these have also been taken up by the author (Pareek 1973*b*). This paper records first time the petrographic nature of the phosphorites from the areas of Dehradun and Tehri districts, named "Mussoorie Synform", named after the famous nearby hill station Mussoorie in Uttar Pradesh.

GEOLOGICAL SETTING

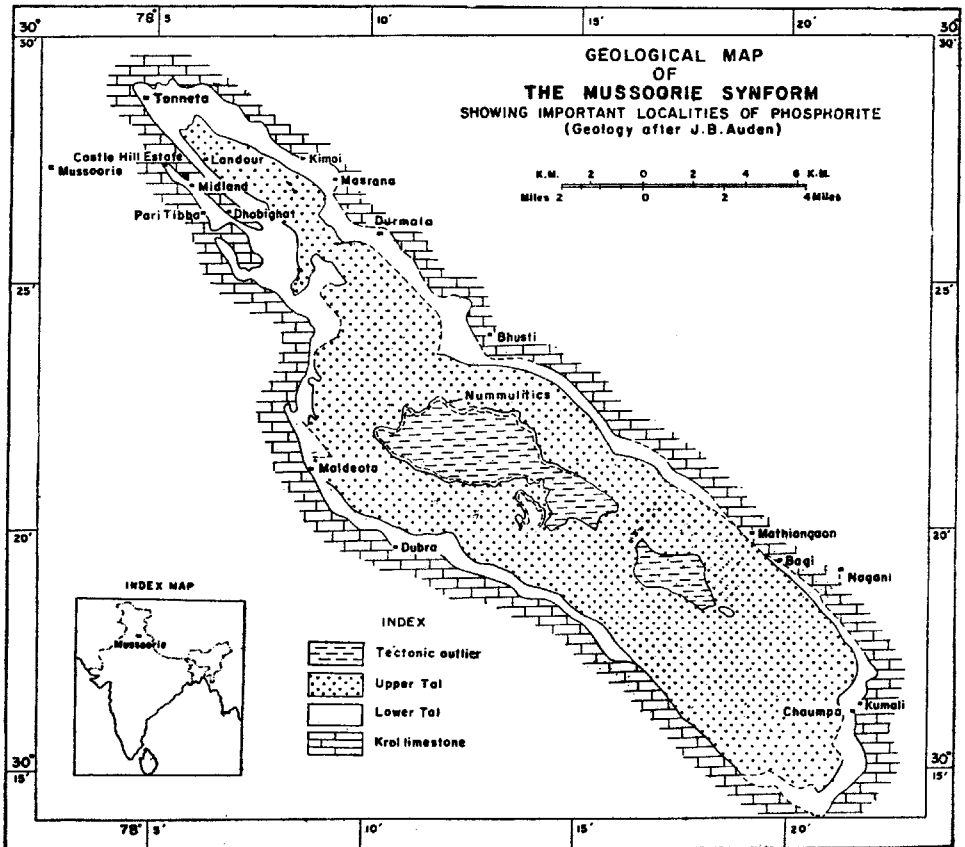
The phosphorites are restricted to the basal Tal formations of *Jurassic* age. The Tals comprise the Upper and Lower Tal formations, which are separated by an unconformity, and have a maximum thickness of 1325 m and 815 m, respectively.

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†*Present address* : Geological Survey of India, Rajasthan Circle, Jaipur.

The structural set-up is of a doubly plunging syncline, which covers an area of about 180 sq. km, NW from the famous hill station Mussoorie (30°27'10" : 78°6'), to Nagani (30°19'20" : 78°21'30") in the south-east, with the axis trending NW-SE and 10°-15° plunge towards SE in the NW portion and at shallower angle towards NW in the SE portion. The only detailed account published on the geology of the area is by Auden (1934). During the past few years, field parties of the Geological Survey of India have carried out large scale geological mapping for phosphorite exploration, aided by drilling and selective mining in the phosphorite-bearing areas; the work, when published, will considerably advance the existing knowledge of the geological relationship of the beds and the structural set-up of the syncline.

The geological sequence of the rock formations, as observed by the author during his field work in the different areas (Pareek 1970 a) appears on page 64 in a summarised form.



Text FIG. 1. Geological Map of "The Mussoorie Synform", showing the important localities of phosphorite

The Lower Tals overlie the Krol limestone unconformably at places, and conformably at others. They include thin to thick beds of chert, phosphorite, variegated shale, siltstone, and limestone. The phosphorites are associated with black chert and shale sequence (Pl. VI, Fig. 3), and to the transitions between the different lithologic units of the basal Tals, over most of the areas. The lithology of any rock type may grade laterally or vertically into another type. The laminations, though crude, are distinct (Pl. VII, Fig. 2) in arenaceous rocks.

Stratigraphic Sequence of Rock Formations

Subathus	Shale, marl and limestone	Eocene
	-----Unconformity-----	
Upper Tal	Limestone—light grey to bluish gray with sandy shale Quartzite—medium to coarse-grained whitish-gray (spotted) to pinkish, arkosic, gritty, pebbly, associated with gray shale and slate. Best exposures near Jabarkhet (30°27' : 78°7')	20 m. Cretaceous
	>1000 m. <1300 m.	
	-----Unconformity at places-----	
	Unconformity marked by conglomerate : greyish siltstone pebbles appear in a gritty, quartzitic matrix near Pipelett (30°16'25" : 78°21'30").	
	Limestone—gray to bluish gray, siliceous, and associated with micaceous sandstone and red and gray silty shales.	1-5 m.
Lower Tal	Siltstone—fine-grained, gray, dark gray, blackish and micaceous. Shales—Olive to greyish, cleaved banded, calcareous, highly splintery (Pl. VI, Fig. 3), buff on weathering, and underlain by light greyish to blackish (carbonaceous and sandy shales, often with pyrite). Phosphorites—Phosphatic nodules in cherty matrix, as near Masrana, the bed directly overlies cherts in Maldeota, intercalated with cherts in Castle hill, with argillaceous shales in Kimoi, Masrana, and with chert and shale in Bagi, Nagani areas. Cherts—blackish, bedded with thin greyish shale bands. Not developed in northern and southern limbs, i.e. near Mathiangaon, and east of Bandal river, Phosphorite bed.	300-500 m. Jurassic 150 m. 10 m. <150 m.
	-----Faulted-----	
	(A nodular bed appears at the Krol-Tal contact in the Castle Hill, Midland, Pari-Tibba, and Masrana areas, suggestive of pre-Tal erosion).	
	-----Unconformity-----	
Krol	Limestone—argillaceous, light gray with bands of shale and slate, Thin bands of phosphatic material in Maldeota and Nagani. Thin lenses of cherty material present in Pari-Tibba area.	Triassic

Occurrence of Phosphorite bands—The phosphorite areas are confined to hilly and valley areas. Pl. VI, Fig. 1 shows the panoramic view of the Bandal

valley where the well-known Maldeota deposits are located. The lower right corner of the Fig. 1 (Pl. VI) shows a portion of the area where phosphorite is being mined.

The maximum thickness of phosphorite in the northern limb is in the Kimoi and Masrana areas, and in the southern limb of the syncline, in the Pari-Tibba and Maldeota areas, examined by the author. Text Fig. 1 shows the prominent localities of the phosphorite deposits in the geological map of the Mussoorie synform after Auden. The general thickness of the phosphorite bands in the different areas examined appear below :

Castle Hill (30° 27' 10" : 78° 5' 15")	: 0.6–2.1 m.
Midland (30° 27' : 78° 06')	: 1.8 m.
Pari-Tibba-Dhobighat (30° 20' 10" : 78° 06' 10", 30° 27' : 78° 06' 15")	: upto 7.2 m.
Masrana (30° 27' : 78° 9')	: 1–7 m.
Kimoi (30° 28' : 78° 8' 30")	: 0.5–3.0 m.
Durmala (30° 25' 55" : 78° 14' 5")	: upto 11 m.
Maldeota (30° 28' 40" : 78° 8' 20")	: 5 m.
Dubra (30° 19' 30" : 78° 10')	: 1 m.
Bagi (30° 19' 30" : 78° 19' 30")	: 1–2 m.
Nagani (30° 19' 20" : 78° 21' 30")	: 1–6 m.
Chaumpa-Kumali (30° 16' 45" : 78° 21' 30", 30° 17' 15" : 78° 21' 40")	: Thinned.

P_2O_5 content—The P_2O_5 contents determined in these phosphorites by the Rapid Field Method of Shapiro (1952) show the range from 15 to 35 per cent.

Chaterji (1967) has mentioned that the phosphorite deposit of the area is of medium grade, ranging up to 20 per cent of P_2O_5 at the most, and that no workable deposit of phosphate suitable (i.e. P_2O_5 content 30 per cent–34 per cent) for the manufacture of super-phosphate could be located.

Certain specimens of the rocks from different areas under report were tested for P_2O_5 content. A phosphorite exhibits 15 per cent to 40 per cent P_2O_5 , but since the associated beds are also phosphatic, though very feebly, they can be named as phosphatic chert, phosphatic shale, phosphatic limestone, etc. The nodules separated from the nodular phosphorite of Midland area gave 30 per cent, while the carbonate matrix yielded 16 per cent of P_2O_5 contents. These results show the potentiality of the area, but, unfortunately, this band is of a localised nature, and forms the only occurrence of nodular phosphorite in the synform. The powdery phosphorite from the N.M.D.C. Incline, Pari-Tibba area, showed 31.47 per cent P_2O_5 . The associated carbonaceous shale is phosphatic. The specimens of Masrana area show that the association of phosphatic minerals with chert does not yield encouraging results and also that the associated rocks are only feebly phosphatic, probably because leaching of strata was not actively possible.

The variation in the percentage of P_2O_5 in different specimens of phosphorite from Maldeota area seems to be related to the proportion by volume of the phosphatic minerals occurring as layers or as granular bodies. The higher percentage of P_2O_5 in the specimens from Nagani area is governed by the fact that the phosphates occur as bedded layers.

Weathering Effects—The borehole cores and mine workings show that the phosphorites are carbonaceous at depth, ranging from blackish to greyish-black in colour. The outcrop samples are, however, brownish to brownish-gray at places. This is due to the removal of carbonaceous matter at outcrop by weathering agencies. This would increase the P_2O_5 content of the phosphorite. Similarly, the outcrop samples show reduction of calcareous matter due to weathering and its leaching away, resulting in the increase in proportion of the phosphatic minerals; there is thus an increase in the P_2O_5 content by residual effect in the outcrop samples.

Phosphorites—Of the different rocks of the earth's crust, phosphorite is the most unfamiliar rock to a wider section of the geologists; its detection and confirmation cannot be said with certainty even by specialists in the field, unless aided by the commonly adopted field method of Shapiro (1952) for the determination of its P_2O_5 content. The phosphorites also contain Uranium that can help in tracing the phosphorite bands or horizons by Geiger Counters. These are some of the rapid field methods usefully employed in confirming the occurrence of these rocks. They also suggest that the phosphorites have developed certain basic characteristics, which need be ascertained in the succeeding pages.

Phosphorites are of sedimentary origin directly or indirectly. The deposits are always stratified with fine to ultra-fine-grained rocks as shale, limestone, carbonaceous shale, etc. The phosphatic content varies very widely in the bed and in the associated rocks, and may range upto 40 per cent or slightly more. The rocks containing less than 15 per cent P_2O_5 are designated as phosphatic shale, phosphatic limestone, etc., as the case may be, while those containing above 15 per cent P_2O_5 are the phosphorites. The phosphatic minerals constituting the rock are mainly colophane, dahllite and francolite. McConnel (1950) has listed 38 phosphatic minerals in rock phosphates, but to distinguish them with a petrological microscope is a remote possibility, owing to their rare occurrence, very often only as traces, and due to the absence of categorisation of well-marked features.

The isotropic form of phosphorites is kollophan, collophane, or collophanite, a carbonate fluor-apatite. Even the term collophanite, used for that mineral, is preferred by the author to bring all phosphatic minerals within the usage ending in *-ite*. The type of secondary phosphate deposited from reworked phosphorite is considered to be francolite—a carbonate fluor-apatite, that exists as fibrous concentric rings in oolites, and disseminated throughout collophanite as small grains.

Nature of world occurrences—Phosphorites have been recorded and described from different parts of the world (Pareek 1970). The deposits of the North-western Wyoming, Idaho, Florida, Tennessee, North Carolina, Rocky Mountain region, etc., in the U.S.A., and of Morocco, Tunisia, Senegal, Israel, Egypt, Algeria, Jordan, Syria and U.S.S.R. are worth-mentioning. A brief review of the available literature on the nature of some of these rock phosphates is included here to bring out a uniform terminology of nomenclature for the mode of occurrence and distribution of phosphatic bodies that could be applicable to the phosphorites under study.

The phosphorite deposits on the sea floor off southern California range from thin flat slabs to nodular masses, having the same general characters in individual areas (Dietz *et al.* 1942). Collophane is the principal mineral, francolite being sometimes associated with it. The nodules are mostly irregularly-shaped; many are conglomeratic and nearly all the phosphorite is somewhat oolitic. Detrital matter is enclosed in phosphate bodies, the organic matter being replaced by francolite. The Phosphoria formation of Permian age in the Deer Creek-Wells Canyon area, Idaho, contains phosphatic shale having spherical, elliptical and irregular phosphatic ovules as much as 60 mm. in long diameter (Lowell 1952).

The phosphorite near Marble Falls in Texas is composed mostly of well-rounded grains of 0.1 to 0.6 mm. in diameter; the grains are mostly oolitic, a few appearing to be structureless pellets, while others being parts of organisms (Barnes 1954).

The phosphorite of the Kara baba Dag area in Turkey is a white to dark brownish-gray pelletal rock, both poorly-sorted and well-sorted, containing fossils of fish, teeth, bones, and scales (Sheldon 1964 *a*).

In the Bone valley formation of Central Florida, megascopic spherulitic aggregates of wavellite are found (Bergendahl 1955). Wavellite is of secondary origin, being a replacement of apatite. The deposit comprises pellets and nodules, composed largely of carbonate fluor-apatite ranging in diameter from less than 0.1 mm. to about 60 cm. (Cathcart *et al.* 1953).

The phosphorites of the Phosphoria formation, Western Wyoming, show the following mode of occurrence of phosphatic minerals (Sheldon 1957) :

- (i) Pelletal phosphorite—structureless collophane and francolite of spherical to ellipsoidal or even irregular shape with less than 2 mm. dia.
- (ii) Nodular phosphorite—structureless grains of collophane and francolite of size larger than 2 mm. in dia.
- (iii) Oolitic phosphorite—Grains of diameter less than 2 mm. and exhibiting concentric or layered structure. Their shape, size and roundness is similar to those of pellets and nodules.
- (iv) Pisolitic phosphorite—Grains larger than 2 mm. diameter showing oolitic structure, the rings ranging from 2 to 10 in number.
- (v) Organic phosphorite—composed dominantly of fossil fragments.

The following limits are given by Mabie and Hess (1964) for various pellet-size classes of Western Phosphate ores.

Median of maximum thin-section pellet diameters, mm	Class designation
0.50 and more	Very coarse grained
0.30—0.50	Coarse grained
0.20—0.30	Medium grained
0.10—0.20	Fine grained
Less than 0.10	Very fine grained

The definitions given by these authors for phosphate bodies are as follows :

Nodule : A syngenetic spherical, oval, ellipsoidal, discoidal or plate-like body with a maximum diameter greater than 16 mm. Pellets have less than 16 mm. diameter.

The phosphorite pellets in the phosphorites of the Meade Peak member have been classified by Emigh (1958, 1967) into the following types :

- (i) Fossil pellet—phosphatized rounded fossils or fossil fragments.
- (ii) Encased pellets—ovoid pellets with a centre of phosphatized fossil in an outer phosphate shell.
- (iii) Nodule pellet—structureless pellets in which the original structure has been obliterated by phosphatization.
- (iv) Oolite pellet—concentric phosphatic shell with or without a nucleus of quartz or fossil.
- (v) Multiple pellet—two or more of any of the above pellets encased in an outer shell of phosphate.
- (vi) Coprolite—animal secretion.

Three principal types of phosphorite are described in California—pelletal, nodular and argillaceous laminar (Gower and Madsen 1964). Each one is composed dominantly of one type, but may contain minor amounts of others. The argillaceous laminar phosphorites are composed of finely-divided phosphatic mineral and abundant silt-sized non-phosphatic clastic material in light gray laminae, often cemented with phosphate.

The bedded deposits of phosphorite have been classified by Youssef (1965) into (i) dark coloured, fine-grained type consisting of elongated and angular grains embedded in a groundmass of finely-divided phosphorite, clay material, and micro-crystalline calcite, with pyrite and bituminous material, and (ii) light-coloured, coarse-grained type generally formed of round pellets and nodules, at least partly oxidized, containing detrital quartz, little pyrite, and organic material.

The phosphatic beds in Syria are commonly dense, detrital, granular or nodular and even conglomeratic (Omara 1965). The phosphate concretions vary from 0.05 mm. to 5 mm. in silicified, carbonatic occasionally, and rarely partly siliceous, and partly carbonatic matrix in folded deposits, and rounded, oval, or irregular phosphatic grains varying from 0.2 to 3.0 mm. in diameter, cemented in a chalcedonic matrix in the unfolded deposits.

In the northern Saudi Arabia, calcareous, siliceous, and unconsolidated types of phosphorite are recorded; they comprise well-sorted fine sand-sized pellets of carbonate fluor-apatite (francolite), cemented by calcite, quartz or minor clay (Cathcart 1968 a). The phosphorites of the Atlantic and Gulf Coastal Plains of the U.S.A. are an unconsolidated mixture of phosphate pellets, quartz grains, clay, limestone and dolomite. The primary phosphate mineral is a carbonate fluorapatite, the phosphate from North Carolina contains the most carbonate and that from Florida the least. The clays include montmorillonite, illite, attapulgite (Cathcart 1968 b).

The sedimentary phosphate minerals in rock phosphate from Jordan have been divided by Reeves and Saadi (1971), into (i) fossil teeth and bone, and

(ii) sub-rounded, ovulate, or cylindrical pellets, and the rock classified as loose friable, and cemented phosphate.

In the continental shelf off north-west Africa, apatite has been recorded in the phosphorites and conglomerates in which phosphorite pebbles are cemented by a non-phosphatic matrix (Tooms and Summerhayes 1968).

It will thus appear that a unified terminology based on the nature and mode of occurrence of phosphates in the different parts of the world, could be adopted and applied in describing the Mussoorie phosphorites (*see* Table I).

TABLE I
Nomenclature of the Phosphorites

Nome of the rock	Nomenclature of the phosphatic bodies	Shape of the phosphatic bodies	Size of the phosphatic bodies
Fragmental phosphorite	Fragmentary	Irregular	Less than 1 mm
Pelletal phosphorite	Pellet	Spherical, ellipsoidal, or irregularly-shaped.	Less than 2 mm.
Nodular phosphorite	Nodule	Spherical, rounded, or ellipsoidal.	More than 2 mm. across.
Oolitic phosphorite	Oolite	Concentrically-arranged layers	Less than 2 mm.
Pisolitic phosphorite	Pisolite	Concentrically-arranged layers	More than 2 mm.
Lenticular phosphorite	Lenticle/ lenticular	Lenticular or lensoid body characterised by tapering edges.	Much more than 2 mm. in length
Platy phosphorite	Plate/platy	Long thin continuous layers with or without any regular edges.	More than 1 cm. in length.
Bedded-Massive phosphorite	Massive	Bedded layers	Persistent layers

PETROGRAPHIC STUDY

The phosphorites are deep brownish, brownish-black, greyish, blackish to jet-black in colour, depending on the amount of organic or carbonaceous matter present. Usually the borehole and mine samples are real blackish in colour. Those from the outcrop appear brownish to brownish-gray, which is due to the removal of the carbonaceous matter by the weathering agencies at the surface. In hand specimens, phosphorites are friable, soft, or medium hard, appearing as fine-grained compacted mass with phosphate mineral embedded in different modes of occurrence and concentration. Besides these, phosphatic nodules also occur in associated beds, varying in size from a few mm. to as much as 60 cm. in diameter.

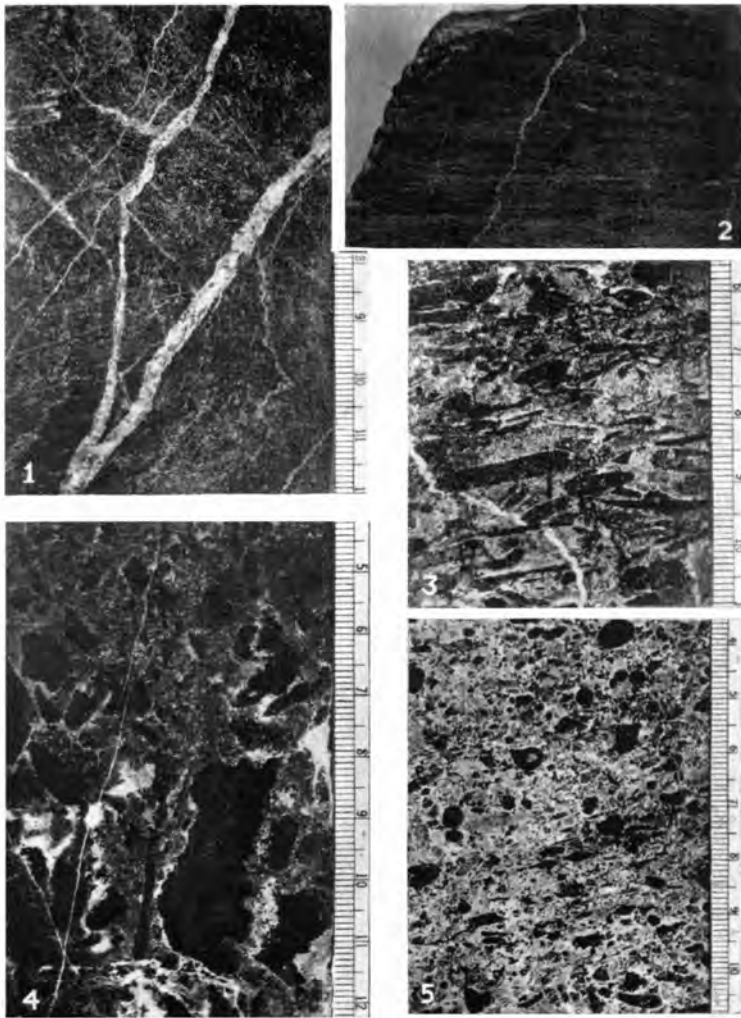
The phosphate mineral occurs in a wide variety of structureless bodies of size varying from that of a pin point to that of pellets (less than 2 mm. long), plates,

and as bedded persistent layers. Some of the phosphate lenticles and plates are composed of phosphate grains, grading from and into nodules, and into smaller layers. The most commonly occurring phosphorite variety is the granular type, in which blackish phosphate grains appear profusely embedded in a calcareous or siliceous matrix, the former being by far more prevalent. Pl. VII, Fig. 1 shows the



FIGS. 1-3 : 1, The Bandal Valley where the well-known Maldeota deposits of phosphorite are located. The right bottom corner shows the location where mining is in progress; 2, Highly cleaved and splintery shales exposed near Maldeota adit in the Bandal Valley; 3, Phosphorite zone showing black chert and shale association in the Huein Valley.

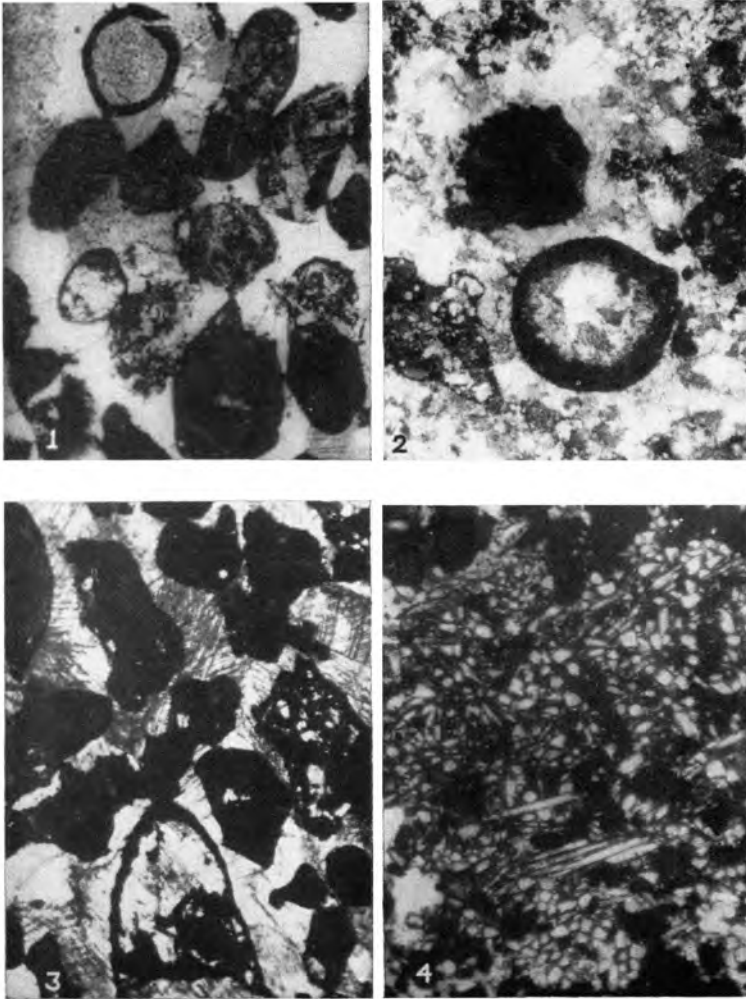
nature of granular phosphorite with calcareous matrix in polished surface with calcite veins traversing it. Still another common variety is the platy and lenticular phosphorite. Polished specimen of the former is illustrated in Pl. VII, Figs. 3, 4, across and along the bedding planes. Pl. VII, Fig. 5 shows the nodular phosphorite of Midland area, in its polished surface, across the bedding plane. The nomenclature of



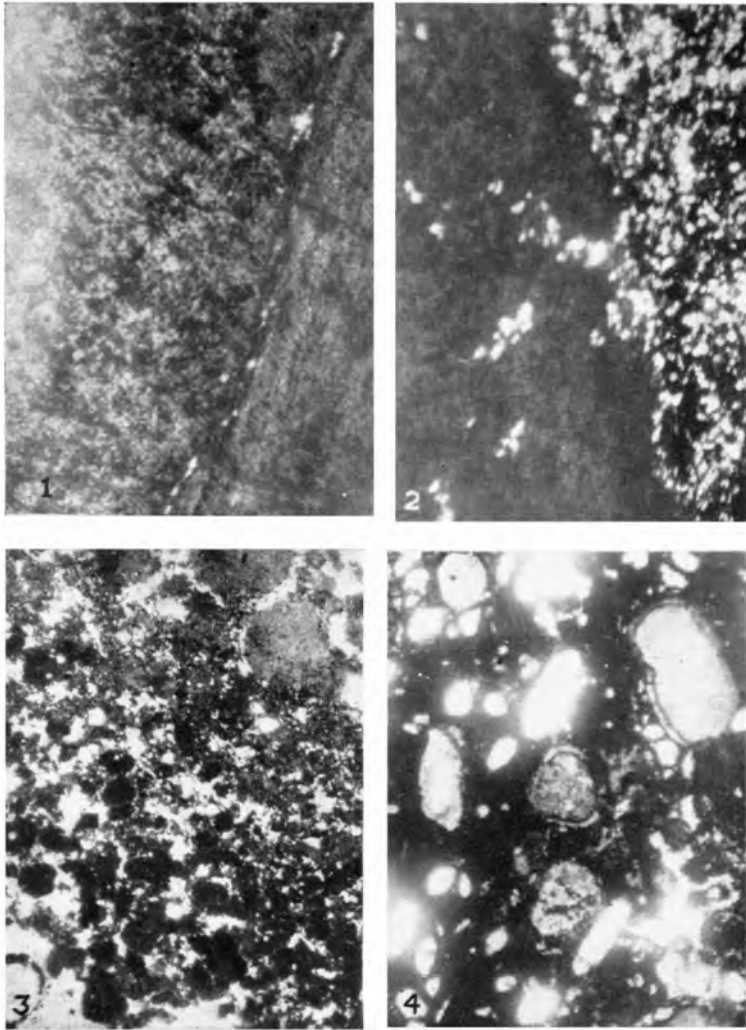
FIGS. 1-5 : 1, Polished specimen across bedding of granular phosphorite from Maldeota area showing greyish-black phosphate specks associated with calcareous material and traversed by numerous veins of calcite; 2, Crude but distinct lamination in arenaceous rocks of the lower Tals; 3, Polished specimen across bedding of phosphorite showing plates of phosphates in calcareous matrix; 4, Polished specimen along the bedding of phosphorite showing the nature of platy material of phosphates in calcareous matrix; 5, Polished specimen across the bedding of nodular phosphorite from Midland area.

these phosphorite varieties, however, does not mean that phosphate mineral will not occur in types or varieties other than those mentioned above; the name only signifies the preponderant type.

The varieties that these phosphorites predominantly comprise include granular or pelletal, platy, lenticular, nodular, bedded, and bedded-massive, characterised by cubicular fracture (*see* Table I). Oolitic phosphorite is rather uncommon. In Pari-Tibba area, the leaching away of the calcareous matrix has resulted in a powdery

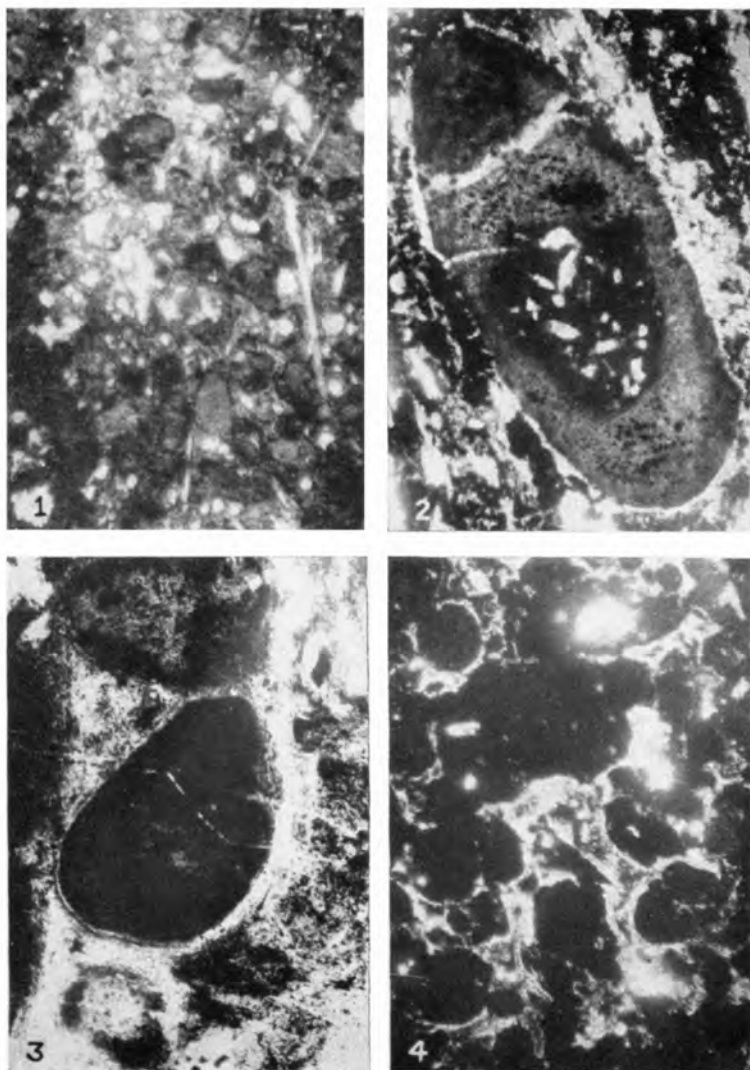


FIGS. 1-4. (All Figures are from thin sections, plane Polarised light, $\times 25$): 1, Variegated phosphate grains in dolomite matrix; 2, Fragments and pellet of phosphate in dolomite matrix; 3, Granular phosphate showing the nature of phosphate grains in dolomite matrix; 4, Part of phosphate lenticle with abundant angular grains and needles of siliceous matter similar to that of the matrix.



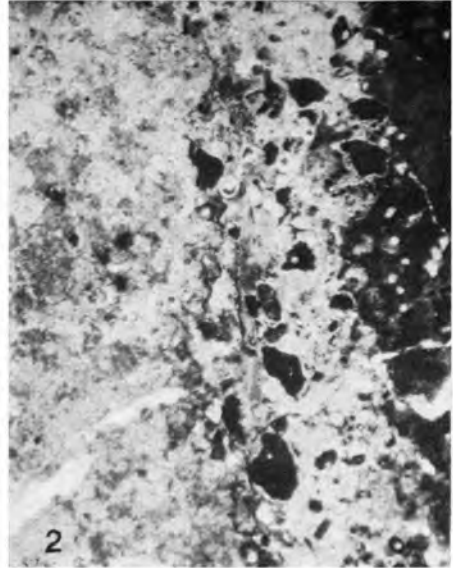
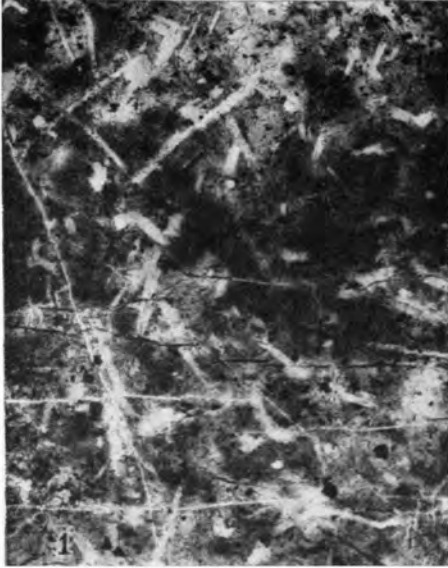
FIGS.1-4. (Figures 1 and 2 are from polished sections under oil immersion, $\times 80$, and Figures 3 and 4 are from thin sections, plane polarised light, $\times 30$): 1, Part of a phosphate lenticle in contact with the groundmass, showing replacement by pyrite, appearing as shining grains along the contact zone. The darker areas of the lenticle appear as the carbonaceous assimilations; 2, Part of a lenticular phosphate showing the extent of replacement by pyrite; 3, Adjustment of a lenticular body and corroded pellets in phosphate matrix with mainly siliceous material. A calcium carbonate pellet partly replaced by phosphate appears in the left lower portion. The noteworthy feature is that the lenticle comprises several small to minute mostly rounded pellets compacted with granular material similar to the matrix. The phosphorite shows bleaching of the lenticles, pellets, and the matrix; 4, Anisotropic phosphate pellets surrounded by two layers of opaque and anisotropic phosphates, occurring in a carbonaceous shaly matrix with angular grains and lath-like material of siliceous nature.

product, named powdery phosphorite. Of all these different phosphorites, the granular or pelletal, platy, lenticular, and bedded-massive are the most prevalent. The occurrence of these varieties is not in any way restricted to any of the particular areas, but is prevalent throughout. It can be considered to be in a way more dependent on the facies change, and other related depositional factors.



FIGS. 1-4 : (All Figures are from thin sections, plane polarised light, $\times 30$) 1, Loosely dispersed, anisotropic pellets, appearing with a thick dark periphery and several angular to sub-angular grains, needles of siliceous material embedded in phosphatic groundmass similar to the pellets; 2, An elongated pellet of phosphate characterized by two zones, occurring in phosphatic shale; 3, Phosphate pellets in phosphate groundmass. Note absence of any inorganic mineral grains; 4, Isotropic phosphate pellets compacted with anisotropic phosphatic clayey material in phosphatic nodule.

The phosphorite matrix has also been observed to be weakly to moderately phosphatic, perhaps more phosphatic in very fine grained varieties. The matrix comprises (i) carbonate of lime, very fine-grained, fine-grained, or medium grained, (ii) siliceous, very fine-grained, and fine-grained, (iii) fine to ultra-fine particles



FIGS. 1-4 : (All Figures are from thin sections, plane polarised light). 1, Bedded massive phosphorite, showing infilled parallel joint planes, $\times 40$; 2, Bedded phosphorite showing the band of spherulites in the phosphate groundmass, $\times 30$. 3, Phosphate pellets with anisotropic phosphate rims in anisotropic phosphate groundmass relatively free from detrital matter, $\times 30$; 4, Concentric-layered phosphate pellets occurring in a phosphate rich band associated with siltstone, $\times 30$.

of clayey nature, (iv) clayey and shaly matter intermixed, or (v) phosphatic materials.

The lamination in the phosphorites is crude, though distinct in calcareous and siliceous varieties, and fine to sharp in those with ultra-fine particles of clayey or phosphatic material. The lenses and laminae, richer in carbonaceous matter are fine-grained, and this could also show the relation between phosphorite deposition and the nature of the prevailing oceanic currents.

The petrographic nature of the different megascopically-ascertainable varieties of phosphorites appears in the following pages, while Pls. VIII to XI illustrate the general microscopic nature of these different varieties. All photomicrographs are from thin sections, except Pl. IX, Figs. 1, 2, which are from polished sections in oil immersion.

Fragmental Phosphorite—Irregular fragments of phosphate mineral upto one mm. in size are quite commonly seen in micro-sections of certain phosphorites, and are restricted mainly to those with calcareous matrix. Sporadic pellets may also be occasionally distributed, as shown in Pl. VIII, Fig. 2. In optical characters, the fragments are in no way different from the pelletal bodies, and contain angular grains and specks of calcareous material. Sporogenous matter, and woody material also contribute to these phosphorites.

Granular Phosphorite—Friable to medium hard, greyish-black to blackish, with fine granular spotted appearance, and without any significant variations in the granularity and texture, this phosphorite is typical of the area (Pl. VII, Fig. 1). Thin to thick veins of calcareous or siliceous material traverse along the joints, and fissures, as well as fracture planes. It analyses as much as 23 per cent P_2O_5 .

Opaque, rounded to sub-rounded, ellipsoidal, lath-like with sub-rounded edges, oblong-shaped, ovular, and aggregated ovular grains of structureless nature, occur within 2 mm. diameter, form 30 to 70 per cent of the rock. Pl. VIII, Figs. 1, 3 illustrate the general microscopic nature of the grains forming the rock. The periphery of the individual grains may be smooth, crenulated, dentate or carved out. The individual phosphate grains contain variable proportions of quartz, calcite, chert, or mica, which are abundant in some of the grains and absent in others, may be rounded or have remained angular. These grains may or may not be always similar to those forming the groundmass, which will ultimately suggest the periods of their phosphatization, and phosphorite formation.

The matrix of the phosphorites is fine, granular, microaphanitic, and composed either of carbonate of lime, being either calcite or dolomite, or both, or of silica, as quartz and chert. The phosphorites with calcareous matrix, on its leaching out, yield powdery phosphorite; this residual product obtained from the N.M.D.C. Incline, Pari-Tibba area, analysed 30 per cent of P_2O_5 . Microscopically, it is composed of the phosphate grains with abundant carbonaceous material that might have ultimately leached out from the associated carbonaceous shale strata.

Phosphate grains also appear in a phosphatic groundmass compacted with (i) material similar to the phosphate grains or pellets, but much lighter in colour, being dark yellowish-brown, brownish, greyish or greyish-black, depending upon the content of carbonaceous material present (Pl. X, Fig. 3; Pl. XI, Fig. 3), (ii) clayey matter of ultrafine to fine particles of kaolinite or illite mixed with grains of chert, quartz, carbonate of lime, and iron minerals (Pl. X, Fig. 4), or (iii) shaly

matter, characterised by common occurrence of minerals, like quartz, chert, carbonate of lime (Pl. IX, Fig. 4).

There are obvious gradations in the increase of grain size laterally and/or vertically. A pelletal phosphorite may eventually grade into a lenticular or platy variety. The phosphate bodies are almost invariably set with their longer axis along the bedding plane of the rock.

Plate X, Fig. 2 shows a pellet of elongated shape in a phosphatic groundmass of shaly nature in the beds associated with the phosphorites. The pellet is characteristic in two zones, the inner carbonaceous-rich, and the outer thicker anisotropic zone with cracks well-developed prior to compaction. Granular carbonaceous matter pervades the outer zone. A very thin anisotropic rim also surrounds the pellet.

Pl. XI, Fig. 3 shows isotropic and anisotropic phosphate pellets in very light coloured anisotropic phosphate matrix. Each of the pellets is surrounded by a very thin rim of anisotropic phosphate mineral. The nature of the pellets, surrounding oxidized rims, and groundmass will be more clear from Pl. X, Fig. 3, under high magnification. Very thin layering of the phosphate groundmass encircling the pellets is prominently seen. The removal of the carbonaceous matter from the pellets and dispersal in the matrix is more apparent. This process of removal has uncovered the colloid-like appearance of the phosphate material. The minute granular blackish aggregates flanking around the phosphate grains on the left indicate the process of removal and concentration in the triangular space formed by the three pellets compacted.

Pl. IX, Fig. 4 shows phosphate grains surrounded by a quite thick anisotropic phosphate layer in a shaly groundmass. The phosphate layers surrounding the grains are of isotropic and anisotropic nature alternatingly. The carbonaceous shale groundmass has several speck-like granular and lath-like quartz.

Platy Phosphorite—Plates upto 2 cm., along the bedding, and 1 to 2 mm. across the bedding, and even more in lenticular sheets have been noted. It is only very rarely that the plates and lenticles are oblique to the bedding. The lenticles have tapering edges while the plates are thin sheet-like and may even have abruptly-ending edges. Pellets and nodules also appear distributed sporadically in the matrix. Pl. VII, Figs. 3, 4, show polished specimens of phosphorite. The P_2O_5 analysed 20 per cent.

Microscopically, the main phosphate mineral appears dark greyish to blackish and is isotropic. Pl. VIII, Fig. 4 shows part of a phosphate lenticle, which is characterised by abundant angular and needle-shaped quartz, forming its inherent proportion. Pl. IX, Fig. 3 shows a lenticular phosphate in association with pellet of phosphate. The lenticle is composed of very small phosphate grains of more or less rounded form, intimately associated with siliceous material. In general, such phosphorites have the matrix composed of siliceous material or of carbonate of lime. The accessories include limonite, goethite, pyrite, apatite, carbonaceous matter, and glauconite.

Pyrite forms an abundant mineral constituent of phosphorites at places, and is recognizable as specks, grains and clusters, replacing the phosphate bodies and the phosphatic groundmass. Pyrite has been found to be incorporated after the formation of phosphorite, as a replacing mineral. The replacement is to such an extent that the rock is composed at times mostly of pyrite. Very fine

disseminations of pyrite in phosphate lenticles, plates, and pellets form one of the most tedious beneficiation problems. The nature of pyrite distribution in phosphorites will be clear from Pl. IX, Figs. 1, 2. In Fig. 1, pyrite is replacing the phosphate along the matrix boundary, while in Fig. 2 it is seen as having intensely replaced the phosphate. The groundmass also shows pyrite as very fine disseminations, seen as shining grains. Such phosphates have to be totally discarded for improvement by beneficiation techniques. But those having pyrite as an accessory mineral can be beneficiated depending on the practicability of whether and to what extent pyrite can be removed away after being converted into pyrrhotite. This conversion by heat is essential since pyrite as such has no magnetic properties and can be removed only as pyrrhotite, after transformation by heat.

Nodular Phosphorite—Only one band of the nodular phosphorite (Pl. VII, Fig. 5) has been observed in the area, and the same also does not hold any economic significance at all owing to its small extent near Midland, Mussoorie. The phosphorite showed around 14 per cent, the matrix as 16 per cent, and the nodules as 30 per cent P_2O_5 .

The nodules vary in size from 2 mm. to 8 mm. across. Microscopically, the nodules are isotropic, rounded or ellipsoid, with usually smooth or fibrous pattern of the periphery. Quartz, calcite, mica, and cherty matter are commonly seen in the nodules. The matrix is of carbonate of lime.

Nodular phosphorite with cherty matrix is also recorded. It also has lenticular and pelletal phosphates. The phosphate mineral is isotropic, periphery crenulated, and shows oxidized rims. The matrix is of siliceous material, very fine-grained in nature, and shows wavy extinction.

Bedded Phosphorite—Layers of bedded phosphate alternate with clayey or shaly bands. Microscopically, the phosphates are lenticular to platy, persistent, structureless, and interbanded with phosphatic, weakly phosphatic, or non-phosphatic shaly layers. Thick bands of phosphatic material show spherulites with an opaque interior and a colourless anisotropic rim in the light greyish phosphate groundmass, as shown in Pl. XI, Fig. 2. The matrix is occasionally composed of fine clayey or shaly matter, admixed with carbonaceous matter. The fractures, cracks, and joints are infilled by secondary pseudo-dendritic limonitic matter. Pl. X, Fig. 1 shows another photomicrograph of the bedded phosphorite, in which loosely-dispersed phosphate grains of greyish colour, and having a thick dark outer rim forming the periphery, occur in the phosphate matrix, dispersed with angular grains, needles, and splinters of siliceous material.

Bedded massive phosphorite—Greyish-black to jet-black in colour, and characterised by massive bedded appearance, these phosphorites break into cubicular or rectangular pieces, on the slightest handling. This physical character reminds the author of the characteristic so similar to vitrain, but distinguished by its botanical origin. Calcareous, siliceous, and limonitic permeations commonly traverse these phosphorites across their bedding, along the joint planes and along the fracture zones. Of the different phosphorites met with in the area, these phosphates persistently show a high percentage of P_2O_5 from 33 to 35.

Microscopically, the phosphorites have dark brownish to greyish phosphates with occasional chert, quartz, and micaceous grains, needles and splinters, and

also calcareous grains, pyrite, and limonite. The groundmass appears as if compacted from a colloidal state. Anisotropic splintery and fragmentary phosphate is also seen. The cubicular fracture is characterised more or less by its amorphous form, breaking into similar pieces along the weaker closely-placed joint planes, so conspicuously seen in Pl. XI, Fig. 1. These planes are infiltrated by calcareous permeations. The phosphorites are apparently different and conspicuous from the other petrographic types in optical characters and composition and their origin is also possibly due to very different agencies, when compared to the other prevalent varieties.

Oolitic Phosphorite—Concentrically-layered, alternately isotropic and anisotropic phosphate bodies, occur sporadically. True oolites are in fact uncommon. Pl. XI, Fig. 4 shows a few phosphate bodies with layered appearance. This phosphate band is in association with phosphatic siltstone.

Phosphatic nodules—Phosphatic nodules were first reported in the Midland area by King (1885). The occurrence of the nodules has now been established over a larger part of the Lower Tals at different localities.

The phosphatic nodules occur in variable sizes up to 65 cm. along, and 40 cm across the bedding, but those around 5 cm. are the most prevalent, associated with shaly horizons. The smaller nodules have a higher proportion of P_2O_5 content, which has fast decreased in the larger and bigger ones.

Microscopically, the smaller nodules show granular isotropic phosphates with irregular periphery, and are set in a phosphatic anisotropic groundmass. Many of the larger phosphatic nodules have fine-grained amorphous phosphatic material in the central portion surrounded by a carbonate layer, and in turn layered by shaly matter. Still others show a nucleus of silica or of carbonate of lime with concentric phosphate material layered around them. In other larger nodules, the shaly matter with accumulations of carbonaceous material is dominant, and no phosphate grains or minerals are seen to compose the rock. Pl. X, Fig. 4 shows the nature of pellets of phosphate marked by a thin anisotropic layer around each of the grains, and compacted by an anisotropic phosphatic clayey material.

X-RAY DATA

The mineral composition based on X-ray data appearing in Table II indicates the composition of rock to be of hydroxyfluorapatite as the major constituent and quartz and calcite as trace and scarce, respectively. The petrographic studies indicate the presence of opaque or isotropic and anisotropic varieties; X-ray data confirms hydroxyapatite. Thus, it leads to point out that many of the phosphatic pellets may be of collophanite or francolite and may have absorbed carbonaceous matter making it opaque. The granular phosphorite analysed 1.27 per cent total water, 8.83 per cent P_2O_5 , and 0.97 per cent F, while the bedded-massive phosphorite showed 1.39 per cent total water, 34.18 per cent P_2O_5 and 3.21 per cent F. (Chemical analysis by Chemical Division, G.S.I.). The question regarding the identification of "hydroxyfluorapatite" and "hydroxyapatite" is interesting: the former has been reported in three samples and the latter in two samples; "the powder spacing data for the apatite constituent in both the samples are similar indicating similar structural character of apatite in them."

The X-ray data has not revealed the presence of any clay minerals. Petrological studies indicate the presence of limonite, goethite and pyrite occasionally in many of the samples, the presence of which is detrimental to the effective utilization of these phosphorites in the fertiliser industry.

TABLE II

Mineral composition of Phosphorites based on X-ray diffraction pattern data

Name of the rock	Locality	Constituents as identified by X-ray analysis
Pelletal Phosphorite ¹ (variegated pellets in calc. matrix)	Maldeota, Dist. Dehradun.	Hydroxy-fluorapatite-major Quartz — trace, Calcite — scarce
Bedded massive Phosphorite ¹ (characterised by cubicular fracture)	Near Bagi, Dist. Tehri	Hydroxy-fluorapatite-major Quartz — trace Calcite — trace
Phosphatic nodule ¹ (Compacted pellets, grains, etc., in phosphatic matrix)	Maldeota, Dist. Dehradun.	Hydroxy-fluorapatite-major Quartz — trace
Granular Phosphorite ² (calcareous matrix)	Maldeota, Dist. Dehradun.	Dolomite — major Hydroxyapatite — minor
Bedded massive Phosphorite ² (characterised by cubicular fracture)	Maldeota, Dist. Dehradun.	Hydroxyapatite — major Quartz — trace

Analysts : (1) Dr. B. B. Mukherjee, (2) Dr. S. D. Lalit, Mineral Physics Section, Central Petrological Laboratories, Geological Survey of India, Calcutta.

It may be worthwhile mentioning certain significant points of X-ray studies of carbonate fluorapatites. In this connection Altschuler and Cisney (1952) have presented certain interesting facts. It has been shown that they are a structurally-distinct variety, different from both fluorapatite and hydroxyapatite. Thompson (1954) has found that X-ray powder patterns of phosphatic material from the Phosphoria formation match the type pattern of the carbonate-bearing fluorapatite showing the same difference from fluorapatite or hydroxyapatite as the carbonate-bearing fluorapatites.

RADIO-ACTIVITY

The Geiger Counter readings indicate a maximum of five times the background value on certain phosphorite outcrops and specimens. The higher background values are notable in Maldeota and Pari, Tibba areas and have been successful in locating sizeable phosphorite bands in other areas, e.g. Durmala. It has been noticed that there is a general increase in the background value with increased concentration of the phosphates. Moreover, the deposits with clay-sized matrix show higher values than those with siliceous or calcareous matrix. It is also of interest that the value increases with greater occurrence of larger-sized lenticles or plates of phosphatic material. Besides proving the economic or academic value of the

presence of Uranium, the data accumulated will provide guidelines for interpreting the mode and nature of distribution of Uranium, nature of association in the different varieties and its variations with size of the phosphatic minerals and the variations over the synform of the then existing conditions of environments, when detailed investigations are taken up for their Uranium values.

Undoubtedly, the source of Uranium is related to the marine origin of phosphorites. Marine phosphorites contain 0.005 to 0.03 per cent uranium (McKelvey and Nelson 1950), and most high grade deposits contain more than 0.01 per cent. The Marble Falls phosphorite showed 0.017 per cent U_3O_8 content (Barnes 1954). Phosphatic limestones and associated black shales are weakly uraniferous. "Much of the uranium was derived from sea water at or shortly after the deposition of rocks. The phosphorites being more permeable than the associated rocks, more of the uranium may have been derived from later solutions or redissolved and redeposited by them by direct precipitation as chemical adsorption. That uranium content varies in phosphorites of similar P_2O_5 content, may arise in part from the differences in the uranium content of the sea water at the time of deposition, but the most significant variations probably result from the differences in the pH, Calcium and Carbonate ion concentration of the source water, the length of time phosphate particles are exposed to the sea before burial, and their post-depositional history (McKelvey *et al.* 1956).

The absorption could not be as perfect for the phosphorites of matrix other than those with clayey or shaly nature, in view of the ultra-fine size of the particles. This is deduced from the laboratory studies carried out on different specimens and correlated with the microscopic nature of each of the specimens. Those with phosphatic groundmass and ultra-fine matrix showed higher background values on the Geiger Counter than those with finer or coarser matrix. Detailed correlative investigations in such beds are likely to reveal significant uranium anomalies.

It will be worthwhile presenting here views of certain relevant interest by workers on this aspect. With regard to the beneficiation of uranium in phosphorite, Igelsrud *et al.* (1948) pointedly state that uranium cannot be beneficiated in phosphorite by the usual methods of ore beneficiation or by infra-sizing, elutriation, or floatation in liquids of appropriate specific gravity, and the amount of uranium dissolved on acid treatment of the phosphorites is proportional to the amount of phosphates dissolved. McKelvey and Nelson (1950) observed that all marine phosphorites contain less than 0.01 to 0.02 per cent Uranium; this is of syngenetic origin, being derived from sea water, either by direct precipitation or as an inorganic uranium salt, or by the selectivity of organisms of substances for which it has an affinity. It is likely that the uranium was concentrated by selectivity of organisms, since it is mostly associated with carbonaceous shales.

In a later paper, McKelvey and Carswell (1956) state that the uranium content in a rock directly varies with the apatite contents present therein. The uranium content increased by supergene processes at the base of the zone (Altschuler 1953). The uranium in the leached zone could be a concentrated product of once thicker section of slightly phosphatic, clayey quartz sand (Cathcart 1956).

The size of the phosphatic pellets and concentration in them of uranium is yet another study. The size of the pellets possibly reflects the length of time required

for them to form or the conditions under which they were formed. Thus, longer the period required for a pellet to form, or longer it was in contact with the sea water, it might have absorbed more uranium from the sea water. Thompson (1954) carried out correlation studies between pellet size and uranium content and found no obvious relationship between the concentration of uranium and size measurements. The determinations showed little relation between uranium concentration and pellet size. But it is not unlikely that the shape and size of the pellets has considerably changed since their formation to arrive at any such definite conclusion.

The the content of uranium seems to have been governed/influenced, according to McKelvey *et al.* (1956), by the length of time the phosphate grains are exposed to the source solutions, by the uranium content of source solutions, by the size of phosphate grains, and by the permeability of the phosphatic beds. These could also explain the lower uranium content of the more calcareous phosphorites.

That apatites deposited under reducing conditions generally contain twice as much uranium as the phosphorite found under oxidising conditions, is brought out by Sheldon (1959).

Geosynclinal facies are obviously richer in phosphorites than the platform facies. The uranium content of phosphorites increases roughly with increasing phosphorite content. Geosynclinal facies thus have higher uranium content.

GENESIS OF THE PHOSPHORITES

The petrographic studies on Mussoorie phosphorites lead to three significant observations, i.e. (i) phosphate minerals are profusely pervaded by the carbonaceous matter, (ii) the main phosphate mineral has quite commonly a rim of another phosphate mineral, the peripheries are oxidized at places and are not universally smooth, (iii) of all the associations of different rock-forming minerals with the phosphates, the siliceous matter is in very fine-grained association, besides the clayey ultra-fine particles, and (iv) specks of pyrite are frequently seen, and the beds are intensely limonitized. These are certain basic intricacies to create beneficiation problems.

It is thus very difficult to find the collophane free from other substances, and the latter are so intimately associated that mechanical separation is very difficult and often impossible.

These phosphorites are essentially shallow water deposits. In this connection, some of the relevant indications, similar to those given by Bushinski (1964), are (i) smooth and more or less worn condition, apparently due to rolling of phosphorite nodules and associated pebbles, (ii) presence of sand grains of various origin and of arenaceous phosphorite material (iii) occurrence of angular and worn fragments, (iv) indication of bedding, (v) alternation of phosphorite layers with shallow marine sands of pebbly sands or their direct transition, (vi) inclined bedding, (vii) phosphorites with phosphorite sand grains and granules present through the layers, and (viii) phosphorite grains usually showing a thin coating of phosphate of a different nature.

The occurrence of these phosphorites is in a syncline; it has been observed that majority of the thick and rich deposits of phosphorites are formed in synclines, being barren or with very thin phosphatic layers in anticlines (Youssef 1965). In

the southern Algero-Tunisian region, phosphorite formation is in the form of a gulf that communicated with the open sea through two "paths" (Visse 1953). The Taplow deposit of England seems to have accumulated in a pseudo-synclinal trough (Wilcox 1953).

Certain extensive studies with regard to the distribution of phosphorite in several parts of the world, carried out by Sheldon (1964), conclude that it is in low latitudes that environment of marine upwelling is best developed. There is a close correspondence between the low latitudes of young phosphorite occurring at warm latitudes between the equator and the 40th. parallels and the palaeolatitudes, as determined from magnetic studies of ancient phosphorite. The warmer latitudes and the trade wind belts of the past may have been as narrow as present, probably always falling within the 40th parallels.

As regards the origin of the phosphorites, the phosphates were undoubtedly derived from the continental mass, transported by rivers to the sea as calcium phosphate, soluble in water, containing carbon-dioxide, and even in colloidal form. The main and immediate source of silica was also sea water, and the same could have well been derived from the chemical weathering of the continents.

The phosphates develop by replacement. Those replaced are the calcium carbonate masses, pellets, etc., which were originally formed at the sea floor possibly by the movement of tidal currents, ocean currents, and seasonal influx or fluctuations. These bodies rolled along and it must have been for a considerable time that they were exposed to the movement action by the sea water to attain their partly present shapes. The current movement did have little effect on these bodies, once they had gained stationary character under specific environmental conditions. The phosphate content in the oceanic waters permitted replacement of these bodies by the phosphate dissolved in them. Such bodies were, therefore, either completely or partially replaced, and the phosphates had moved from the phosphatic pellets to the matrix.

The processes for further concentration of the phosphates could have been through washing and diagenesis. During washing of the deposits, continued and repeated incessantly by turbulent oceanic waters, the detrital grains could have been removed away from their existing position to further deeper areas, leaving the phosphatic pellets, and other bodies to form the present day bands of phosphorite. Recurrence of such processes largely account for the occurrence of the large number of bands of phosphorite in an area. This also lead to account for the pinching off of the bands and also for the gradation into other varieties of phosphorites, the occurrence of thick phosphorite deposits at localised places and the thinning out in other directions away from the source.

The bedded and bedded-massive phosphorites seem to have formed under other conditions. It is not unlikely that their origin is related to currents that may have swept the basin in the form of sheets. Emerging from deeper to shallower basins or in the direction of the shallower region, they would have gradually released the dissolved load nearer the shallower area, loosing the carbon-dioxide (Youssef 1965).

Coming to the processes responsible for the formation of phosphorite, it may be said that the open ocean, according to Dietz *et al.* (1942), is essentially saturated with phosphate, indicating that an amount equal to the increment is precipitated

each year. The increase in temperature causes precipitation of calcite from the saturated solution of sea water, but this effect is largely because of an increase of pH through the removal of CO_2 (Emery 1946). The controlling factors in the deposition of calcium carbonate and phosphorite are strikingly similar (Krumbein and Garrels 1952).

A rise in pH will saturate the water with respect to apatite. A rise in temperature thus drives off CO_2 , saturates the water also, and the result is a rise in pH (Kazakov 1937). An excellent discussion of the theory of origin of phosphorite similar to, but modified from that proposed by Kazakov (1937), is presented by McKelvey, Swanson, and Sheldon (1953). Warm climate is considered to have prevailed during the deposition of the Phosphatic Chalk of England (Wilcox 1953). Arid climate is also considered to have helped considerably the deposition of phosphorite (Bushinski 1964).

Obviously pH is the most important controlling factor in the phosphorite precipitation. Any environments of low pH are not likely to reach saturation, but increase in pH tends to cause precipitation of calcite. With the increase in pH , and co-precipitation of calcite and phosphorite, the ratio of calcite is very high and that of phosphorite as a trace. Krumbein and Garrels (1942) have suggested that the phosphorite may represent precipitation in restricted basins with relatively low pH . The most common association of Eh and pH satisfying a common framework for them is thus necessary for phosphorite precipitation.

Sheldon (1957), discussing the formation of phosphate deposits of North western Wyoming considers the concentration of apatite is due to (i) a small supply of clastic material, (ii) winnowing out of the clastic material deposited with apatite, and (iii) a physico-chemical environment in which apatite is stable. The pelletal phosphorite seems to have been deposited under conditions of low pH and Eh, carbonate rocks under high pH and Eh, and cherty material being intermediate of the two. His conclusions are that an environment with a pH above 7.8 and an Eh greater than zero existed for the carbonate phase, and with pH less than 7.8 and an Eh less than 0.25 for the phosphorite phase.

Youssef (1965) suggests that phosphates are deposited in a medium whose pH is around 7.8. He considers that the bedded deposits of marine phosphates owe their formation to biochemical mode of formation controlled by the configuration of the sea floor, and "the deposition of phosphate minerals is most probably Eh-independent. Anaerobic conditions are incidental. Restrictions of circulation..... is a necessary requirement for the concentration rather than for the deposition of phosphates."

McConnell (1965) concludes that (i) sea water is almost saturated with respect to a carbonate fluorapatite; (ii) certain analogies are relevant with respect to the biologic processes of teeth, bone, and shell formation; (iii) the biochemical systems can be influenced (*in vitro*) by a common enzyme (carbonic anhydrase); (iv) precipitation may be impeded in cases of apparent supersaturation by some inhibitor; and (v) greater understanding of the processes involved in the mineralization of bones and shells should give clues to the precipitation of the phosphorites.

Emigh (1967) outlines the following conditions for phosphatized beds :

- (i) The more highly phosphatized beds are formed under/below the euphotic zone (av. 100 m.).
- (ii) Relatively slight precipitation of calcium carbonate.
- (iii) Only slow accumulation of detrital material, both organic and inorganic.
- (iv) Appreciable ocean currents to form pellets, and to renew solutions.
- (v) Long periods of time.

In dealing with the origin and genesis of phosphate-bearing strata of Jordan, Reeves and Saadi (1971) state that detrital supply was low during phosphate deposition. The absence of detritus could partially be due to removal of "fines" by wave and current action. Phosphorites are considered to have been deposited through the interaction of three bodies of water; normal shelf sea water, upwelling phosphate bearing water, and, a minor contribution in this particular case from, river water bearing organic detritus. The essential criteria concluded for economic accumulation of phosphorite are: (i) very low detrital supply to prevent dilution of phosphate formed, (ii) sufficiently low pH, and (iii) availability of fairly rich Si and P, slightly acid and cold upwelling waters.

The genesis of the Mussoorie phosphorite is not too dissimilar with, if not akin to, the worked-out facts brought out in the preceding pages. There are a number of varieties of the phosphorite, e.g., granular, pelletal, nodular, lenticular, bedded, and bedded, massive. Their genesis is obviously related to the facies change that the area of deposition witnessed. In other words, they are closely related to the varying conditions of physico-chemical environments that prevailed in the area during the lower Tal period. That strongly reducing conditions prevailed needs no emphasis. The occurrence of pyrite in phosphates, woody matter in phosphorites, presence of black shales, and radioactive phosphorites are all sufficiently suggestive of the strongly reducing conditions, negative Eh and limitations of detrital matter being carried into and mixed with the deposits. But pyrite also occurs as an oxidized variety, e.g., limonite, and this could also be due to alternation of periods of existence of reducing and oxidizing conditions.

CONCLUSIONS

The petrographic studies indicate that (i) the phosphate mineral constituting the phosphorites is masked by carbonaceous matter, has oxidised peripheries, at places, being not uniformly smooth, (ii) there is only one dominant phosphate mineral prevalent throughout, and its characters are best seen when the carbonaceous matter is released, (iii) the phosphate mineral is hydroxy fluorapatite, as indicated by X-ray diffraction pattern data, (iv) the siliceous matrix is very fine grained, calcareous as fine-grained, and clayey as very fine or ultra-fine, (v) pyrite is in intimate association with the phosphates, and has even completely replaced the phosphates at places, (vi) it is difficult to obtain phosphate free from impurities, (vii) the phosphate bodies ubiquitously have detrital particles of quartz, dolomite, chert, mica, clayey matter, and iron minerals within them, which are in many cases different from the composition of the matrix and a highly angular, subangular,

and rarely rounded, and (viii) the different varieties of phosphorites are obviously the direct outcome of facies change.

The Mussoorie phosphorite is significantly different from the world deposits in (i) the dominance of phosphatic lenticles and plates, having tendency to form thin slabs, (ii) the characteristic occurrence as bedded, and bedded-massive deposits, having tendency to form thick slabs, (iii) the abundance of the pelletal (granular) phosphorite and relatively uncommon to rare oolitic phosphorites, (iv) the prevalence of detrital matter as particles and grains in the individual phosphatic bodies, (v) the association of pyrite specks with phosphatic bodies and intense replacement by the same in localised areas, (vi) the very common gradations into different varieties occurring as distinct layers, (vii) the occurrence, petrographically, of variations and of mixed types, (viii) the intense limonitisation of the phosphorites at the outcrop specially, and (ix) presence of sporogenous matter and woody fibres.

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