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On the Genesis of the Georgina Basin Phosphorites, Northwestern Queensland

by

F. de Keyser

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APPENDIX: Discussion of the evidence relating to the diagenetic silicification of carbonate beds.

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ADDENDUM

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After this Record had been completed, a sample of the evansite (?) rock described in page 11 was forwarded to AMDEL, where Dr. N.A. Trueman carried out a series of tests on the rock and the mineral. The results were inconclusive, and the original identification of the mineral as evansite (?) could not be disproved. However, Trueman's suggestion that the mineral may be a highly unusual, strongly hydrated form of variscite with hitherto undescribed optical and physical properties (e.g., isotropic character, and R.I. less than 1.490) is an interesting possibility in view of the fact that some pellets seem to show intergradation with a birefringent mineral (possibly variscite), and that in the clusters of zoned variscite the various zones show differences in R.I., optic sign, and degree of birefingence.

Reference:

TRUEMAN, N.A., 1969 - The mineralogy and petrography of an aluminium phosphate rock from Duchess, Queensland, with reference to the occurrence of evansite.
The Austr. Mineral Devel. Laboratories, Rept. MP 4080/69 (unpubl.).

SUMMARY

The phosphorites in the Georgina Basin, discovered in 1966, are essentially biogenic replacement deposits formed in very shallow water in semi-enclosed basins, estuaries, lagoons etc. Enrichment of originally low-grade phosphatic sediments took place by means of reworking during sedimentation, followed in places by relative concentration as a result of early diagenetic processes, and commonly by residual concentration during short periods of regression and probably also during the Cainozoic weathering cycle. It is possible that submarine exhalative-hydrothermal action was partly responsible for the alteration and replacement by changing the pH of the environment and by introducing some of the elements required. There is very little likilehood that upwelling currents have played a role in the formation of the phosphorites.

INTRODUCTION

A major phosphate field was discovered in northwestern Queensland in 1966 (Russell,1967) (Fig. 1). The phosphorites are associated with a Middle Cambrian suite of sediments comprising cherts, black siltstones and siliceous shales, and limestones. Further testing by drilling is continuing, but estimates of reserves so far published suggest that close to 2000 million long tons of phosphate rock with a cut-off grade of 18 percent are present.

The phosphorites and associated sediments were deposited in the shallow Georgina Basin, which is about 960 km long and up to 480 km wide and contains Cambrian and Ordovician marine sediments.

GEOLOGICAL SUMMARY AND DESCRIPTION OF THE PHOSPHORITES

The only published account of the geology of the phosphate deposits is that of Russell (1967). The general outline of the regional Cambrian geology as known before the discovery of the phosphorites is contained in a series of Explanatory Notes to the published 1:250,000 Geological Map Sheets (Carter & Opik, 1961, a,b; Noakes, Carter & Opik 1959), and in papers by Opik (1956,a,b, 1960). Some of the ideas expressed in these publications are in need of revision, but although a number of reports have been written to bring the geology up to date, none of then have yet appeared in print. The most recent comprehensive compilation of the geological knowledge of the Georgina Basin is that by K.G. Smith (in press).

Figure 2 diagrammatically shows the relationships between the various formations in the phosphatic areas in northwestern Queensland. Basically, the lithological succession from bottom to top is as follows (Fig. 2):

(a) basic volcanics with some quartzite beds near the top. Local occurrences only.

(b) an irregular layer (not everywhere present) of sandstone, grit, conglomerate, basal breccia. Thickness 0'-35'.

(c) dolomite and dolomitic limestone with and without nodules and layers of chert. Overlain by, and interfingering with, the chert beds of unit (d).

(d) uneven-bedded chert, nodular chert, siliceous siltshale, lenses of limestone with chert nodules. Units (c) and (d) together are more than 500 feet thick in places of maximum development. The phosphorites are associated with the rocks of unit (d)

(e) bedded or flaggy quartz siltstone and fine sandstone with some thin-bedded chert.

(f) grey bedded limestone, silty limestone, marl, some chert. This unit comprises several formations defined mainly on fossil content.

(g) sandstone, or dolomite.

There are two main types of phosphorite: a primary biogenic, pelletal phosphorite, and a secondary, very fine-grained phosphorite (termed "microsphorite" by local company geologists) commonly associated with planes of disconformity and other time breaks. A dense, massive, high-grade variety probably is the secondarily-enriched product formed by leaching of phosphorite (mainly the microsphorite type, but also pelletal phosphorite) during short periods of regression in the Cambrian and during later, mainly Cainozoic weathering cycles.

The pelletal phosphorites are accumulations of collophane pellets, ovoids, lumps and aggregates, phosphatized fossil fragments, and rounded flakes of thin collophane layers, set in a calcareous or cherty matrix (Fig. 5). They grade into low-grade phosphatic siltstone, limestone, or chert.

The "microsphorites" consist of creamy, yellow, or white, very fine-grained phosphatic material or phosphatic siltstone, in which the phosphate content is difficult to estimate visually. It is thought that these "microsphorites" were derived from originally pelletal deposits by extreme attrition in high-energy near-shore environments. The derived, secondarily-enriched massive variety is dense, heavy, generally brown-coloured, crypto-crystalline high-grade rock cementing breccia fragments, developed as modules, or present in pockets or massive outcrops of rather superficial formations.

The phosphorites, particularly the high-grade dense varieties, may show "brain-type" weathering surfaces, and are commonly coated with a characteristic bluish or pinkish white phosphate "bloom".

The pelletal phosphorites are widely distributed in the south-eastern region of the Georgina Basin, in the Duchess and Ardmore districts. They decrease towards the north, until in the Lawn Hill district virtually all phosphorite is of the microsphorite type or its derived, massive variety.

In the following pages, the discussion will be centred first around the question of the made of formation of the various phosphate particles, after which the factors controlling their natural enrichment will be reviewed.

GENESIS OF THE PHOSPHATE DEPOSITS

Formation of the phosphate particles.

Phosphate particles, usually composed of crypto-crystalline carbonate-fluor apatite and other, secondary, phosphate minerals, could be formed in a number of ways: by replacement; by direct biogenic precipitation; by accretion on pre-existing phosphate minerals; by solution and secondary re-precipitation; or by direct inorganic chemical precipitation. The crypto-crystalline isotropic or weakly birefringent phosphate minerals are commonly collectively referred to as "collophane".

Petrographic examination of the Queensland phosphorites has established that replacement and probably biogenic precipitation were the main processes, and that accretion and re-precipitation also played a role. No proof could be found for direct chemical precipitation. This is of some importance in view of the popularity of the theories of upwelling marine currents with resulting chemical precipitation. As we shall see later, there is no need to have recourse to upwelling currents to explain the phosphate deposits in the Georgina Basin, on the contrary, the palaeogeographical conditions were highly unfavourable for the establishment of a system of upwelling currents.

Replacement by apatite of other substances has been commonly observed under the microscope, and the feasibility of the process has been demonstrated in the laboratory. Recently d'Anglejan (1967) suggested a replacement mechanism for the formation of phosphate in the north-eastern Pacific area. In the Georgina Basin, the apatite replaced carbonates present in the form of fossil fragments and probably calcareous muds, but elsewhere in the world replacement of silica or clay by apatite has also been observed.

The intensity of replacement of the skeletal fossil fragments varies from initial or partial to almost wholly (Figure 9-15), and it is a small step to assume that a great number of structureless collophane pellets were derived in this fashion even though the last vestiges of their skeletal origin have disappeared. It is most likely that faecal pellets, too, served as objects of replacement, for, although typical faecal internal structures are only very rarely seen, such structures are easily destroyed during lithification and phosphatization.

d'Anglejan (1967) hinted that there could be a genetic relationship between fine-grained calcareous oozes and the formation of phosphate. He advocated a replacement origin whereby phosphate is substituted for carbonate in the structure of calcium carbonate minerals composing skeletal fragments or calcareous oozes; during the replacement part of the carbonate minerals would go into solution, and the increasing carbonate ion concentrations could control the rate of replacement.

Direct biogenic precipitation, probably or possibly accompanied by replacement, is suggested by various features observed in thin section.

Firstly, fossil fragments when not broken down and comminuted commonly show infillings of impure collophane (Figs. 17,18). This collophane is identical in appearance with the collophane that occurs as thin laminae or lenses, not more than 1 or 2 mm thick, in the sediment (Fig. 19). These thin collophane layers usually appear to mark micro-diastems, visible only with the help of hand lens or microscope, but characterized by very abrupt and undulatory surfaces occasionally almost forming cut-and-fill structures. The collophane is stained brown by organic pigment, contains specks and dust of opaque material and minute inclusions of carbonate, sericite, or quartz. The brown organic staining, and the common association with fossil fragments, suggest that the collophane is the product of some organic process possibly the decay and decomposition of organic tissue, during which micro-environments were created with pH and Eh values different from the surrounding regional environment, and favourable for the formation of carbonate-fluor apatite. The inclusion of minute specks of sericite, quartz, and opaque matter, and the presence of the micro-diastems, suggest that the collophane layers were formed during periods in which carbonate precipitation was inhibited so that little material was deposited, with the result that scarce fine detritus, normally a rare accessory component in the deposits, could be relatively concentrated. The specks of carbonate in the collophane laminae could be either a primary admixture, or else the remains of phosphatized carbonate in a fine lime mud.

These thin collophane laminae may possibly have been formed as a result of the establishment of thin algal mattes on a sediment floor during periods of little sedimentation. Not only would such algal mattes trap fine carbonate mud, but algae also have a naturally high phosphorus content, and during their decomposition the freed phosphorus could first have been absorbed on the carbonate particles in the mud, later to become combined with calcium from the lime mud to form carbonate-fluor apatite. The extremely fine grain size of the lime mud may have promoted the process.

Direct evidence of the former presence of algae is scarce in thin section. However, it is possible that algal structures were destroyed during the phosphatization, and this assumption is supported by the fact that in some thin sections, where the pellets and fragments are extensively altered not to apatite, but to the aluminium-phosphate mineral evansite, algal filaments are commonly and clearly preserved, next to other fossil fragments (Figs. 43-45). Perhaps this type of alteration of the pellets and fragments did manage to preserve in fine detail whereas normal phosphatization tended to destroy; the proportion of fragments of recognizable organic origin is far greater in the evansite pellets than in the apatite ones.

The algal filaments in the evansite phosphate rock are commonly filled with an opaque substance, and it is possible that the opaque specks in the collophane laminae and in the fossils represent broken up and finely comminuted algal remnants.

During periods of increased agitation, the collophane laminae were broken up into fragments which eventually become rounded into pellets. Microscopical examination shows the various intermediate stages of this process.

In conclusion, the assembled evidence, though perhaps not conclusive, suggests that the formation of "collophane" in the Georgina Basin phosphorites was largely biogenic.

Accretion on pre-existing phosphate pellets is visible in some thin sections especially of phosphorites that appear to have been extensively reworked. In some cases a clear collophane centre is surrounded by murky, darker layers of impure collophane containing a cloud of carbonate dust as well as opaque material, much of which may be organic pigment. In other examples the roles are reversed, and an impure collophane centre is surrounded by clear collophane free of inclusions. A microprobe test carried out on the latter example showed traces of Si and Fe in the calcium phosphate matrix of the impure centre, confirming the presence of minute quartz and opaque iron dust in the core.

Figure 20 shows another form of accretion, thouth rarely seen in the Georgina Basin deposits: a lump of pelletal phosphorite surrounded by an enveloping layer of collophane.

Solution and re-precipitation. The formation of apatite by leaching and subsequent re-precipitation is commonly observed in the dense residual phosphorites or phosphate nodules that mark diastems or disconformities, Figure 21 illustrates very well the habit of these apatite crystallites which grew in the interstitial space between fused phosphate pellets. In Figure 21 the phosphate may have been derived from pelletal material in the same bed. There is also an instance where basal Cambrian sandstone, itself not phosphatic at all, does contain similar apatite-filled interstices, and it seems obvious that the phosphatic solutions here were derived from the phosphate beds directly overlying the sandstone, by leaching and downward percolation.

These examples show that, contrary to common opinion, apatite is soluble under certain conditions, can be mobilized and transported in solution, and be re-precipitated elsewhere. The process, however, is here quantitatively of minor importance.

Direct chemical precipitation of carbonate-fluor apatite as a result of the effect of upwelling currents is a well-known theory, and probably needs no further explanation. Briefly the theory involved the action of upwelling, phosphate-rich marine currents leading to the inorganic chemical precipitation of apatite on shelving bottoms, where the pH of the ascending cold water rises as their temperature increases and the partial pressure of CO_2 decreases. The optimum depth range of precipitation is placed between 50 and 200 metres by Kazakov (1937), but between 200 and 1000 metres by McKelvey et al (1952).

No proof could be found in thin section for an inorganic chemical precipitation of the Georgina Basin phosphorites, nor were the palaeogeographic conditions (very shallow water over very wide areas, and presence of obstructions) suitable for the creation of a system of upwelling currents. On the contrary, the evidence strongly favours an estuarine formation somewhat along the lines described by Pevear (1966) for the U.S.A. Atlantic coastal plain phosphorites.

Formation of the phosphorite deposits.

Several factors influence the accumulation and concentration of phosphate particles, and if they all combine favourably, phosphorites of economic grade may be formed.

The factors are: biological activity; absence of clastic detritus; suitable palaeogeographic conditions; secondary concentration of the particles during sedimentation, diagenetically, or by later processes of enrichment.

Biological activity. Obviously the more intense biological activity is, the more intense the formation of phosphate particles is likely to be, other factors being equal. Biological activity is at a high level in areas where upwelling marine currents bring up nutrient-rich water from ocean depths to the surface, or in near-shore estuaries and basins where nutrients brought in from the adjoining land can be concentrated.

There was an abundance of life during the deposition of the Georgina Basin deposits: not only are coquinites fairly common in places, but much more abundant and ubiquitous are silicified beds of micro-ooquinite (Figs. 32-35) in which the fossil fragments are worn and rounded to small pellets less than 1 mm across. It is a fact that in the Georgina Basin these micro-coquinites are almost exclusively restricted to the phosphate-bearing formations. The skeletal nature of the pellets is usually clearly recognizable under the microscope.

Amount of detritus. Even where phosphate particles are formed in abundance, a normal supply of detritus is sufficient to dilute the concentration of phosphate particles considerably. It is necessary therefore for clastic sedimentation to be as slow as possible. Where this condition is fulfilled, phosphate deposition needs to compete only with other biogenic products of sedimentation such as cherts and most carbonate rocks.

In the Georgina Basin, the phosphorites are associated with cherts and limestones and some fine-grained siltstone, while sandstone and other coarse clastics are typically absent.

Palaeogeographic conditions. Negligible clastic sedimentation is only possible under the right palaeogeographical conditions, the main one being the presence of a morphologically old source land of low relief and low elevation, where the rate of erosion is at a minimum. Another requirement is a coastal configuration which prevents, or at least strongly hinders, the loss of phosphate particles to the open sea, and allows them to accumulate within the limits of a restricted area. Semi-enclosed water bodies such as lagoons, estuaries, restricted basins, sea arms, and shallow platforms studded with islands and submarine banks, fulfil this requirement.

The palaeogeographical conditions in the Georgina Basin were extremely favourable during the lower Middle Cambrian. Firstly, there was an old, worn, tectonically inactive Precambrian land surface from which little clastic matter could have been derived. This surface was in many places broken by a later, lower surface of erosion up to 200 feet or so below the level of the former, and which formed the sea floor for the succeeding Middle Cambrian marine incursions (Fig. 22). Precisely what height the sea level reached is not known, but the total absence of any trace of Cambrian remnants on the older and higher Precambrian surface would suggest that the Cambrian sea may not have extended much beyond the margins of the embayments formed by the later and lower surface of erosion. If this assumption is correct, the depth of deposition of the phosphate-bearing strata connot have been greater than a very few hundred feet at the most.

Secondly, the outline of the later, lower surface of erosion and, therefore, of the Middle Cambrian sea, was determined by the structural and lithological features of the Precambrian basement. In this case, the tectonic structure was characterized rather by a predominance of synclinal and basinal elements over anticlinal and domal forms; the lithological succession shows an alternation of soft siltstone and schist with hard, competent sandstone and quartzite. These factors combined to produce, during erosion, a chain of synclinal depressions with eroded cores, and separated by narrow ridges of resistant rock types. After inundation by the Middle Cambrian seas, this landscape was, of course, transformed into a chain of semi-enclosed, shallow and restricted marine basins, lagoons, estuaries, and embayments; even where more open gulfs and bays existed, the sea floor in these must have shown a series of submarine ridges and sills which would impede or hinder free bottom water circulation and tend to retain any phosphate accumulations formed.

These conditions existed mainly in the northern and central regions; the situation in the Duchess district in the south is slightly different in that the depth of deposition may have been slightly greater, and the depositional basin was larger and open to the deep ocean. The possibility that upwelling currents may have been active here is therefore not to be altogether excluded.

Palaeolatitude. Sheldon (1964) found that the formation of phosphate deposits, past and present, has been restricted to the warmer regions of low latitude and palaeolatitude, and he ascribed this to the greater loss of CO_2 in warm waters, with the accompanying rise in pH, which promotes the precipitation of apatite, Another explanation could be that phosphates may be genetically associated with calcareous deposits (see, for example, d'Anglejan, 1967) so that the distributional realm of carbonate sediments - the warm regions of low latitude - automatically controls that of phosphorite.

Whatever the explanation, there appears to be a palaeolatitudinal control of phosphate distribution, which sould be taken into account in exploration programmes.

The climate over the source areas of phosphorite deposits was probably lateritizing - elements like silica, magmesium, calcium, and also phosphorus are then carried in solution to the sea in great abundance.

Secondary enrichment. When all the conditions described above are favourable, the best that can be expected is the formation of a low-grade phosphatic rock. High-grade phosphorites are produced only when phosphate accumulations are concentrated by secondary enrichment. This can be brought about in a number of ways.

(a) Concentration during sedimentation can take place under the influence of wave action and traction currents, whereby particles of different size and shape and of different specific gravity are concentrated into separate fractions. The winnowing of fine mud and silt from mixed sediments so that clean, well-sorted gravels and sands remain while the fines are removed and deposited elsewhere, is a very common example.

In the Georgina Basin, a very shallow depth of deposition is indicated by the presence of laterally-linked hemispheroidal type algae in parts of the Thorntonia Limestone, and probably also by the irregularly bedded chert sequences with their undulatory bedding plane surfaces: this may have been a result of wave action. The extreme rounding of the fossil fragments in the micro-coquinites also points to a high-energy environment and, hence, shallow-water conditions. The sorting effects associated with such shallow environments can be clearly seen in certain coquinites: some of them consist almost exclusively of accumulations of cheeks and pleura of trilobites, whereas others contain very abundant cranidia and pygidia. Some friable, only loosely coherent, well-sorted, high-grade pelletal phosphorites are probably end-products of such sorting processes in which winnowing, pellet shape, and specific gravity may all have had a hand.

Another form of residual concentration is described by d'Anglejan (1967) who suggested that "phosphorite deposits would form partly through the residual accumulation of phosphatized calcarenites" owing to the fact that much associated calcareous matter seems to go into solution simultaneously with replacement by apatite.

(b) Diagenetic concentration is another factor which has been effective in some of the Georgina Basin deposits. This has been studied in the Duchess area, where low-grade phosphatic limestone has been upgraded by leaching of carbonate under simultaneous partial replacement by silica. As this view has met with opposition from some other geologists who have examined the material, the argument is presented in detail in the Appendix.

(c) In some areas, concentration of phosphate apparently took place during slight regressions of short duration, whereby deposits probably emerged just above sea-level to present a low swampy landscape studded with lakes and bogs. These hiatuses in the stratigraphical column along the shores of the Georgina Basin are characterized now by rubble or breccia zones heavily stained by iron and manganese oxides, and commonly richly phosphatic. The phosphate in these zones is thought to be largely secondary, as it is a solid, dense, brown collophane rock cementing fragments of broken chert and probably also fragments of original phosphate rock, the pelletal structure of which is now difficult to recognize because of the cementation. It is in these secondary phosphate rocks that one finds the secondary apatite crystallites to be very common (Fig. 21), illustrating the effects of solution and re-precipitation. Common also are phosphate nodules built up of the same dense brown collophane.

In other places, the hiatuses are represented by smaller and larger pockets of phosphatic, massive, soft siltstone. In the Lady Annie area, phosphatic siltstone ("microsphorite") in one locality appears to occur in pockets over an old karst surface of Thorntonia Limestone. The pockets are lined by strongly ferruginous-manganiferous zones forming the bottom and sides of the pockets. Part of the phosphate at least may represent the residual accumulation of phosphate derived from dissolved slightly phosphatic Thorntonia Limestone.

SECONDARY PROCESSES

Post-sedimentary processes recognized in thin section include:

1. phosphatization of carbonate material (fossil fragments, lime mud);
2. silicification of carbonate and phosphate;
3. grain growth ("recrystallization") of sparry carbonate cement;

4. calcification of chalcedony, quartz, phosphate, glauconite;

5. fluoritization?

6. formation of alunite and the secondary phosphate minerals wavellite, variscite, mota-veriscite, crandallite, turquois, and evansite (?)

Most of these processes are imcomplete, and even rudimentary in places, but phosphatization of carbonate, and in part silicification of limestone, have been important factors in the formation of the phosphate deposits. (see Appendix).

Whereas the majority of the processes listed above are of a purely diagenetic nature, the fluoritization(?) and the formation of many of the secondary phosphate minerals and of alunite may have been caused, partly by submarine fumerolic emanations. This possiblility is discussed in more detail in a later section.

Generally the phosphatization of carbonate is one of the earliest events, and may have taken place almost contemporaneously with sedimentation. This was followed by silicification (figs. 24-29), still at a time when the sediments were unconsilidated and could accommodate changes in volume by settling and warping without rupturing. Silicification is particularly noticeable in the micro-coqinites, and often leads to complete chertification, resulting in a rock composed of chalcedony and micro-crystalline quartz. In thin sections where coarse chalcedony is present two varieties of chalcedony are commonly found an earlier, length-fast type usually with spherulitic texture, and a later, length-slow type filling the remaining interstices between spherulites.

Cherts formed by silicification of carbonate rocks appear to show one or more of the following features: scattered fine carbonate dust being the last vestige of the original rock; ghost remains of fossil fragments; presence of dolomite rhombs or outline offormer dolomite rhombs; and a dirty appearance in thin section due to the presence of innumerable unidentifiable small specks and crystallites.

The next diagenetic stage probably was one of "recrystallization" of carbonate matrix in limestones by rim-cementation and grain growth (Figs. 36-38, 7-8). At the same time, carbonate veinlets were formed by secretion and mobilization along developing cracks and joints.

It is interesting to note that some veinlets traversing both chert and limestone parts in the same section occasionally contain mineral fillings in accordance with the composition of the adjoining host rock, i.e. they are filled mainly with chert in the chert rock, and with carbonate in the limestone, which seems to confirm a secretionary origin. The fact that the carbonate in the veinlets is commonly syntaxial with sparry calcite "recrystallized" by grain growth, and with rim cement, suggests that the recrystallization and the formation of veinlets were penecontemporaneous processes, wholly taking place at a time when lithification was in full progress.

The marginal replacement of collophane pellets, quartz grains, etc. by calcite (or perhaps, the marginal solution of pellets and grains with subsequent filling of the corroded margin space by calcite) is assumed to have been closely associated in time with the period of carbonate "recrystallization" and vein filling, or to be of even later date.

Fluorite, a rather common interstitial mineral in many of the phosphorites in the Georgina Basin, has also been observed in thin section as pseudomorphs after dolomite rhombs (Fig. 40).

The formation of alunite and the secondary phosphate minerals crandallite, wavellite, variscite, meta-variscite, turpuoise, and evansite (?) may have been a diachronous process, possibly in part of submarine hydrothermal-exhalative origin. This seems to be indicated in the thin-sections (Fig. 49) of an altered rock sample from Mount Murray (Duchess district), in which clean-cut veinlets of pure wavellite and some variscite traverse the rock, and are usually adjoined by a contact zone in which original collophane or evansite pellets have been completely silicified and wavellite occurs disseminated. In other layers of the same rock, alteration to wavellite is more uniformly penetrative-disseminated, and variscite and meta-variscite varieties (and possibly other obscure secondary phosphate minerals) have built up zoned-radiating clusters around Al-Fe-rich nuclei from which the alterations progressed centrifugally in zoned fashion towards Al-rich (but Fe-poor) margins (Figs. 46-49). In the central parts of a few of these clusters, the outlines or original pellets can still be recognized, although apparently the whole mass of pellets and matrix has been simultaneously metasomatized.

In the least altered portions of the rock the original pellets (clearly of biogenic origin) are still present, but are composed of evansite(?1) instead of the usual collophane. It may be that original collophane was subsequently altered to evansite(?), but the very good preservation of algal filaments and other organic structures suggests that the evansite(?) is a primary replacement of carbonate fragments.

Another secondary but unknown phosphate mineral(2) has replaced collophane pellets in thin zones in the cherty portions of the replaced limestone bed described in the Appendix.

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(1) Evansite ($2AlPO_4 . 4Al(OH)_3 12 H_2O$?) meets all the observed optical, compositional, and X-ray diffractometer characteristics. It is amorphous (hence not picked up by the X-ray diffractometer), isotropic, has a low refractive index of about 1.48 (negative relief!), and is an aluminium-phosphate compound. Electron microprobe analysis of the pellets revealed a composition essentially of P and Al, with a little Fe (impurities?) and locally considerable Si, though patchy and irregular (probably signifying beginning silicification of the pellets). The normal Shapiro test failed to show phosphate, but the mixed-acid method indicated approximately 8-10% P_2O_5.

(2) The optical properties resemble those of alunite, though the birefringence seems a bit high (second-order green). The mineral is length-fast, and optically positive, with a 2V ranging from uniaxial(?) to clearly biaxial. Electron micro-probe analysis showed a composition of calcium phosphate, but no fitting mineral species could be found in the literature.

Turquoise is found in thin seams and joints in phosphorites in the Duchess district apparently restricted to faulted areas, e.g. at Mount Murray.

Alunite was identified microscopically as well as by the X-ray diffractometer from samples in the Duchess district, and again, seems to be restricted in occurrence to faulted areas (Fig. 41).

SOURCE OF THE PHOSPHORUS

According to the upwelling-current theory, the source of the phosphorus required to form the phosphate deposits is the cold water of the ocean deeps. This is not applicable to the Georgina Basin, where the palaeogeographical configuration did not favour the establishment of a regime of upwelling currents.

Another source of phosphorus is often sought in submarine basic volcanism. Although this possibility is not to be excluded in the case of the Georgina Basin, where the base of the Cambrian sequence is in places formed by basic volcanics, and where there is some evidence for hydrothermal alteration of phosphorite, it is not necessarily the only, or best, answer.

According to Bushinsky (1964), and others, the phosphorus in near-shore deposits could have been supplied by the rivers. Judging from figures given in Strakov (1962), and taking an average river with a water discharge of one million acre-feet per annum, some 30 million tons of phosphorus could easily be discharged into the sea by one such river over a geologically short period of one million years; re-calculated to phosphate rock with a grade of 20% P_2O_5, this would be equivalent to some 375 million tons of phosphate rock per million years. If this phosphorus is trapped in semi-enclosed basins, no other source of supply seems to be required for the formation of phosphorite. An especially favourable condition should be a lateritizing climate in the source areas, by which elements like silica, magnesium, calcium and also phosphorus are leached from the soil and transported to the sea in great abundance.

However, even without a significant supply by rivers, organisms can extract phosphorus from the average, under-saturated concentrations available in normal sea water. The sea is an inexhaustible reservoir, and any phosphorus lost to organisms would be replenished by fresh sea water brought in by surface currents.

It is contended in this paper that the Georgina Basin phosphorites were formed by a combination of biogenic processes and replacement of carbonate material, and it is therefore not necessary to demand unusually high concentrations of phosphorus to start off with. A supply of rivers, the oceanic reservoir, and the paleogeographical traps, are sufficient in this case to account for the amounts of phosphorus fixed in the phosphorite deposits.

THE POSSIBILITY OF SUBMARINE HYDROTHERMAL INFLUENCES

It is tempting to consider the possibility that the localized but intensive alterations of phosphatic rocks to secondary phosphate minerals, as well as part at least of the silicification and leaching of limestones, may have been the result of submarine fumarole activity along the major fault systems. This possibility is certainly feasible: volcanism is known to have been active during the lower or early Middle Cambrian (extrusion of Colless Volcanics and Peaker Piker Volcanics), and the last vestiges of this volcanism during the Middle Cambrian could have been represented by submarine fumarole springs along fault lines. It has been noted that all the known occurrences of alteration are situated along the major fault zones in the Duchess district, and the features shown in Figure 49 are highly suggestive of hydrothermal effects.

The submarine emanations could have acted in the following manner: exhalative CO_2 would have decreased the pH of the sea water locally and warmed the water causing it to rise until equilibrium was reached. The water could then have spread out laterally and, upon encountering calcareous sediments, would have effected a partial or total solution of the limestone. At the same time, the low pH would have favoured the precipitation of SiO_2. The observed fact (Fig. 49) that total silicification of a rock, including phosphate pellets, occurs in zones adjacent to cross-cutting hydro-thermal (?) veinlets of wavellite, suggests that part at least of the silica required for the chertification which is so common in the Beetle Creek Formation was of exhalative-hydrothermal origin.

It is difficult to assess how much of the Al and Fe necessary for the formation of the secondary phosphate minerals could have been derived from the same exhalative source. Certainly the original biopelsparite cannot be expected to have had a high content of these elements. It is a fact that the thin-sections of the altered rock sample from Mount Murray (Fig. 49) show the development of aluminium-phosphate pellets (Figs. 42-45) instead of the usual collophane pellets.

The few examples of alunitization (Fig. 41) and fluoritization (Fig. 48) observed from the Duchess district are located along fault zones, and for this reason are thought also to be the result of hydrothermal activity.

CONCLUSION

The investigation of the Georgina Basin phosphorites has shown that they most probably are biogenic replacement deposits formed in very shallow water, and that the concept of upwelling currents and associated inorganic chemical precipitation of phosphate does not apply to the Georgina Basin. The search for phosphate deposits in general, therefore, should not be based exclusively on the upwelling current theory, but should also take into account other palaeogeographical conditions, including the morphology of the borderland and basement, and the possibility of entrapment in semi-enclosed, shallow-water basins.

However, the feature which the major primary, marine phosphate deposits in the world, whatever their genesis, most often have in common appears to be their association with chert, carbonates, and (black) shale, and the recognition and delineation of this lithological suite should therefore be one of the first steps in any systematic exploration programme. The empirical association of phosphorites with regions of low palaeclatitude should also be taken into consideration before expensive exploratory work is carried out.

ACKNOWLEDGMENTS

Discussions with others have been very helpful in drawing my attention to certain discrepancies and forcing me to search for more convincing arguments in support of some of the theories described in the foregoing pages. I express my gratitude, therefore, to Dr. N.A. Trueman (A.M.D.E.L.), Mr R.T. Russell (Broken Hill South Ltd.), Dr P.J. Cook, and Mr. A.D. Haldane (both B.M.R.).

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APPENDIX

DISCUSSION OF THE EVIDENCE RELATING TO THE DIAGENETIC SILICIFICATION OF CARBONATE BEDS

Most of the evidence revolves around the interpretation of the nature of spherical bodies of phosphatic biopelsparite limestone (with about 7% P_2O_5) about 6 inches across, "floating" in a bed of cherty phosphorite (with some 20%-21% P_2O_5) (Fig. 23). The following features can be observed:

> bedding is much more clearly visible in the limestone bodies than in the cherty rock, and cross-lamination can be recognized; separate bedding planes in adjoining spheres can be correlated; bedding in the cherty rock is faint, cross lamination cannot be rocognized, and bedding planes wrap around the limestone spheres; in some of the spheres the bedding may be at an appreciable angle to that in the surrounding cherty bed; relatively thick (a few mm) carbonate laminae free of pellets in the limestone bodies usually correspond to thinner chert laminae free of pellets in the siliceous bed (Fig. 24) except at the lower and upper edges of the spheres where the deflection of the wrap-around bedding planes in the cherty bed becomes so strong that the continuity is disrupted; collophane pellets in the limestone bodies are commonly marginally replaced by carbonate, whereas in the cherty bed the pellets appear to be relatively unaffected; thin zones of collophane pellets in the cherty rock are replaced by a moderately birefringent, optically positive, secondary calcium phosphate mineral, whereas no such replacement has been observed in the limestone bodies.

Some geologists favour the concept that the spherical limestone bodies are concretions ~~correlations~~ of carbonatized siliceous phosphorite. They base this on the marginal replacement of collophane pellets in the carbonate bodies as against the apparently unaffected pellets in the cherty bed. However, this hypothesis is rejected here on the following grounds. Firstly, the marginal replacement of pellets by carbonate takes place in virtually all the limestone beds in the area; in other words, it takes place also in primary biopelsparite beds, and is considered to be a late-diagenetic effect (see page 11) having nothing to do with wholesale carbonatization of a sediment. Such late-diagenetic re-mobilization of carbonate is also evident in the veinlets of carbonate cutting both the limestone bodies and the cherty bed. The phenomenon cannot be taken as proof for a carbonatization of the silica beds.

Secondly, there is a large volume increase in the carbonate bodies as compared with the silica beds. This is indicated by the deflection and wrapping-around of the cherty bedding planes, by the difference in P_2O_5 content, and by the difference in thickness between pellet-free laminae in the spherical bodies and their matching counterparts in the cherty bed. The volume increase is of the order of 4 to 6 times, as measured by taking the difference in thickness between pellet-free laminae in the spherical bodies and in the surrounding cherty bed.

Such a volume increase would lead to considerable stress in the cherty phosphorite surrounding the spheres and would presumably act in all directions. The wrap-around structure in the cherty bedding planes, however, shows no sign of lateral pressure effects, and there is no reason why the volume increase should have acted in a vertical sense only.

It has also been denied by some that the pellet-free laminae in the spherical bodies are matching equivalents of similar laminae in the chert bed, and that the precise juxtaposition is purely coincidental. Far too coincidental, surely, to be accidental! The main reason why the pellet-free laminae in spheres and chert rock have not been accepted by some as matching equivalents is the fact that those in the cherty phosphorite contain small impurities, whereas those in the carbonate spheres are relatively clear. It will be shown later why this argument is not necessarily valid.

It is difficult to see how carbonatization of a rock in which bedding is not distinct, can lead to an end product in which the bedding is very pronounced, precisely reproduced or even improved, complete with cross-lamination, especially when one takes the considerable volume increase into consideration. Even microscopically the carbonate bodies are seen to be clearly bedded whereas the pellets in the chert are usually in disorder. Another argument used by supporters of the carbonatization theory is that a silicification process under partial leaching of carbonate would lead to collapse structures or at least total destruction of fine bedding laminae in the "original" siliceous phosphorite. This may be so under atmospheric leaching conditions, but need not apply to submarine processes during which the leaching and replacement could take place by uniform diffusion.

Finally, carbonatization of an originally cherty phosphorite in which fossil fragments are relatively scarce, would not lead to a rock in which calcareous fossil fragments are more common. Furthermore, the carbonate spheres contain small chalcedony spherulites, rare grains of glauconite, and other earmarks of an original limestone deposit.

For these reasons, the suggestion that the spherical carbonate bodies in the cherty phosphorite bed are due to carbonatization of the chert, must be rejected.

Another suggested explanation of the carbonate bodies involved physical transport of the spheres from elsewhere, downslope, the argument being that the inclined dip in some of the spheres indicated rolling on a sloping sea floor. This is quite untenable because of the close correlation between bedding planes in adjacent spheres, because of the matching juxtaposition of laminae in the spheres and the surrounding cherty phosphorite, and because of the scarcity of inclined bedding, horizontal bedding being the rule. The writer believes that the movement can be explained as a settling effect, and here again the silicification theory is preferable to the carbonatization theory because, if the latter were valid, one might expect to find sinuous or kinky bedding planes in the spheres corresponding to repeated settling movements during growth of the nodules. Settling during silicification, on the other hand, when the stage was reached where the original limestone bed had been reduced to free "floating" spheres, of course does not disturb the shape of the bedding planes in the spheres.

All observed facts can be easily explained by a process in which an original phosphatic biopelsparite was partly dissolved, partly replaced by silica. The result is a decrease in volume, with an increase in phosphate content due to the relative concentration of phosphate pellets; fading of the originally sharply defined bedding planes; development of wrap-around bedding planes; and production of inclined spheres in places, due to settling. The chert usually contains carbonate dust representing the last vestige of the original limestone. Carbonate particles found in the chert are mostly dolomite rhombs, and these may either represent dolomite originally occurring with the calcite if the original limestone bed, or they may be new-formed crystals created during the leaching of an original magnesian limestone.

In thin section, the chert has a dirty appearance due to the presence of disseminated dusty impurities. Although this consists partly of residually concentrated original detrital material such as quartz and mica, most of it comprises newly-formed crystallites of impurities originally contained in the calcite of the limestone, such as Mn and Fe. This "dirty" appearance is of course also found in the pellet-free laminae in the chert, which has been the main reason for some to consider these laminae to be deposits unrelated and unconnected with the corresponding pellet-free laminae in the carbonate spheres.

Identical phenomena were seen in small chert lenses occurring in primary biopelsparite beds in the same general area (Fig. 25). It is evident that this chert is a replacement body, as parts of the lens extend into adjoining bedding layers and even curve back. In thin section one again observes the "dirty" appearance, the dolomite rhombs, the fine carbonate dust, and, in addition, a buffer zone of abnormally fine-grained chert against the limestone, comparable with a "chilled border" effect in igneous rocks (Fig 26). This buffer zone is found only in the cross-cutting chert areas, and does not seem to be present where chert and limestone join along a bedding plane, the explanation being that the zone heads the frontal wave of silicification, and has no reason to form along the bedding planes.

Finally, again in the same area, the relationship existing between a certain biopelsparite bed and an overlying cherty phosphorite adds further evidence for the silicification theory. The lithologies of both beds are identical to those of the carbonate spheres and cherty phosphorite discussed above. The cherty phosphorite is deposited on what at first glance seems to be the scoured surface of the limestone bed, and exhibits bedding planes that "sag" into the "scoured" parts of the limestone. However, close examination again reveals the presence of features discussed above, notably the correspondence between pellet-free laminae. If carbonatization of chert had taken place, the carbonate must have risen uniformly from below, and the process of replacement must have stopped at some distance from the sediment surface. Surely it is more logical to accept the fact of silicification of the limestone bed, acting from the surface downwards, and as a result of diagenesis.

As to the factors which determined the silicification, little is known. Siever (1962) states that conditions for replacement of carbonate by silica can be related to localized areas where the pH is lowered at an early diagenetic stage by the addition of CO_2 by bacterial decomposition of organic matter. The dissolved carbonate could be removed by diffusion. At the sites of organic decay, the solubility of silica is lowered because of adsorption on organic matter as well as because of adsorption of organic matter on silica, whereas in surrounding areas without much organic content the solubility is higher. The concentration gradient leads to diffusion and finally precipitation in the form of chert nodules. In the Duchess area, the silicification of limestone beds could possibly have taken place along similar lines, but on a larger scale. Studies by Broken Hill South Ltd have shown that the facies distribution at the time of phosphate deposition was probably as follows: a silty facies close to the old shore lines, siliceous phosphorites on the more elevated parts of the shelf and on the crests of submarine banks, and "limestone" in the troughs. It should be pointed out, however, that the limestone group includes genetically different varieties, and that the "trough" limestones are represented only by the dark, micritic, generally fetid types, whereas coarser-grained, light-coloured biopelsparites occupied the higher slopes of shelf and submarine banks and, initially, probably also large parts of the elevated shelf areas and the crests of the banks. It is here in these well-aerated regions that decomposition of organic matter (which, in the biopelsparites, was abundant to begin with) was a rapid and complete process, thus lowering the pH,dissolving calcite, etc. In the troughs, biological activity was less intense, and decomposition furthermore was slower and less complete. The un-silicified biopelsparites between these extremes occupied a transitional position, and exhibit the signs of incomplete replacement.

The possibility of submarine fumarolic action having played a role in the silicification of limestone in the Georgina Basin is discussed on page . Such fumaroles could have lowered the pH and may have supplied much of the SiO_2.

In the Duchess district the highest-grade bedded phosphorites are represented by the siliceous phosphorites. This is probably partly owing to enrichment during the silicification, but consideration must also be given to the palaeo-topographical position of these phosphorites on elevated parts of the basin, where biological activity and sedimentary concentration in a high-energy environment were more likely to occur than in the quiet deeper parts.

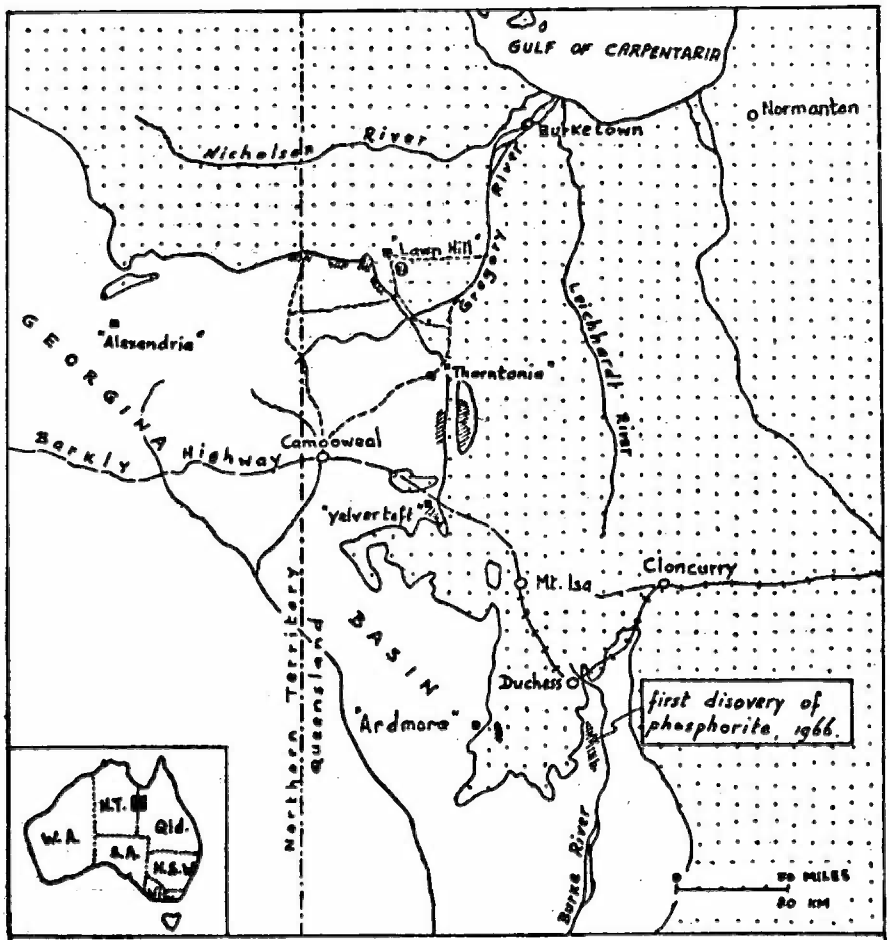
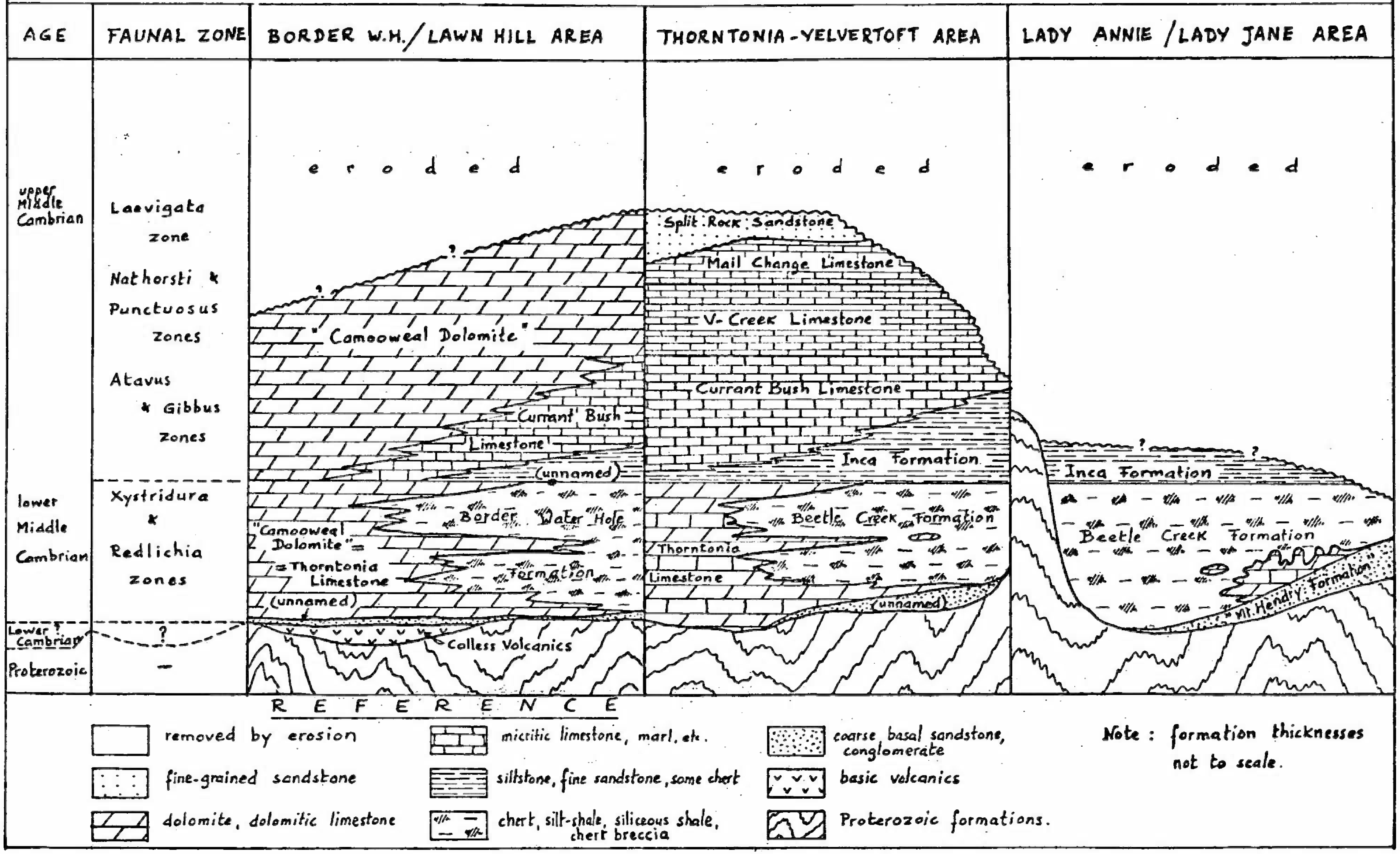


FIGURE 1 - LOCALITY MAP, EASTERN GEORGINA BASIN.

○ Township
■ Homestead
—— Highway
------- Access road, track
+—+—+ Railway
phosphate deposit
⬚ Basement rocks and alluvial plains outside the Georgina Basin.

FIGURE 2 - SUMMARY OF STRATIGRAPHIC RELATIONSHIPS, NORTHEAST GEORGINA BASIN



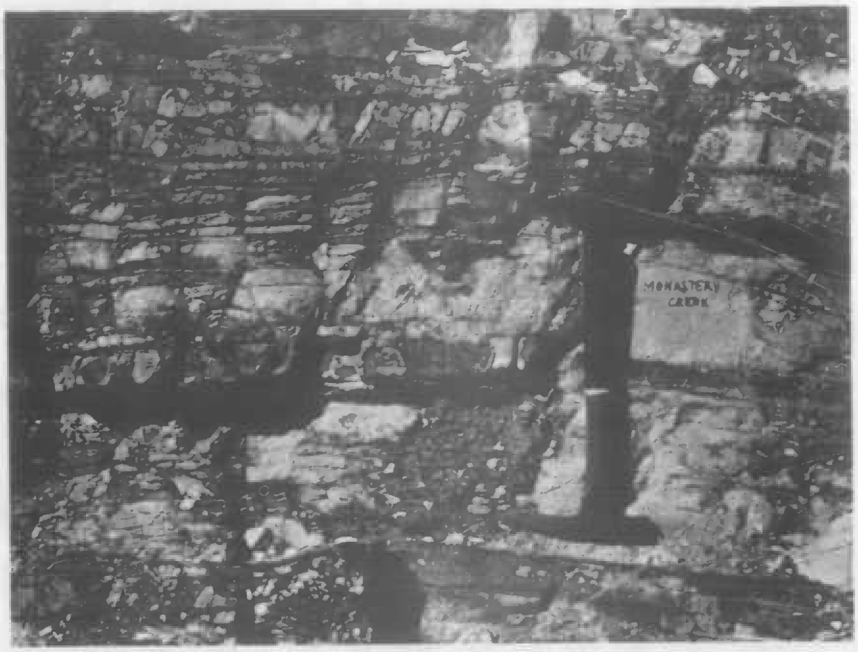


Figure 3: Typical outcrop of phosphorite in the Duchess district. Beds of siliceous phosphorite and phosphatic siltstone, and thin laminae of chert.

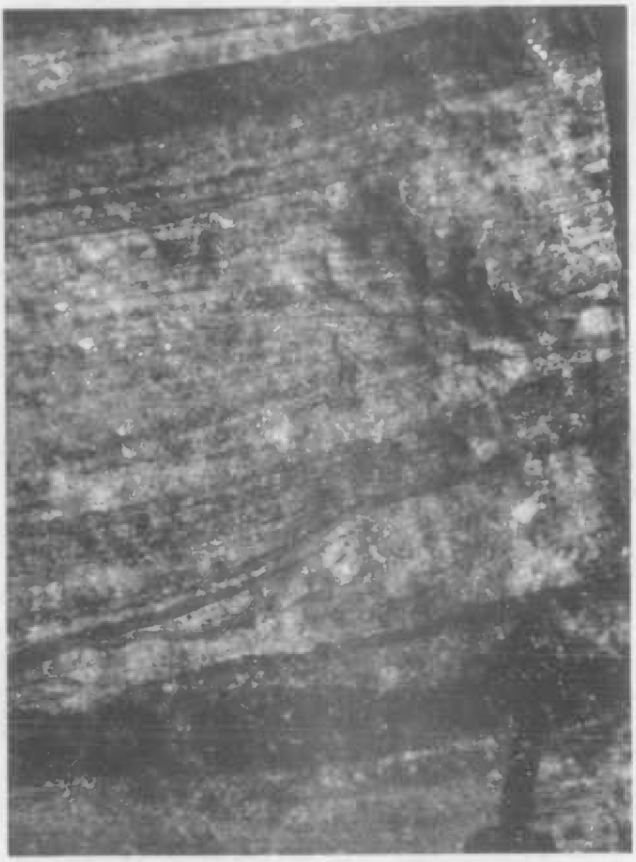


Figure 4: Cross-bedded phosphatic biopelsparite or low-grade phosphorite, Duchess district. Pellet-rich zones are light coloured.

Figure 5: Well-developed pelletal phosphorite, typical of Duchess district.

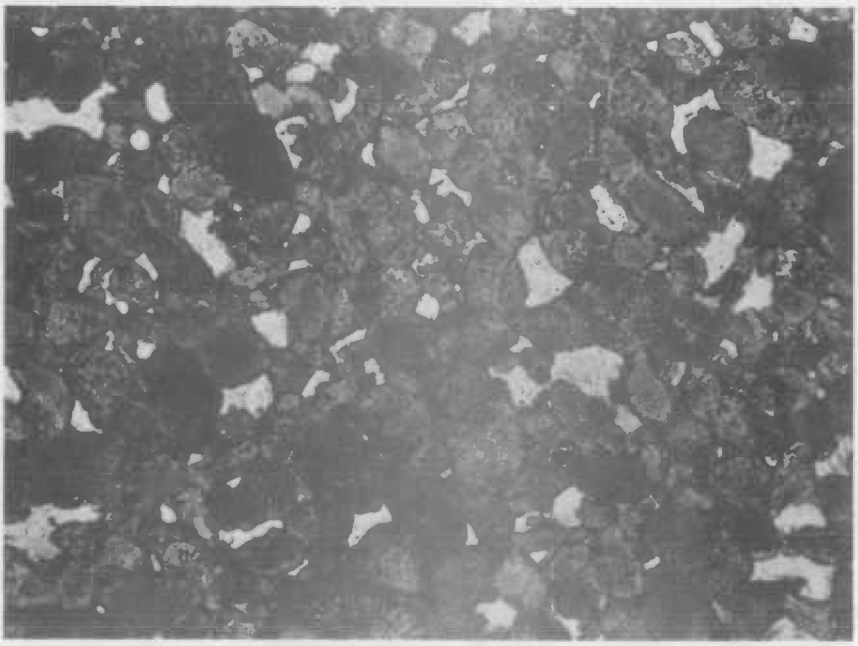


Figure 6: Photomicrograph of high-grade pelletal phosphorite. High concentration probably due to winnowing during sedimentation, possibly also to some leaching of carbonate matrix. x 100

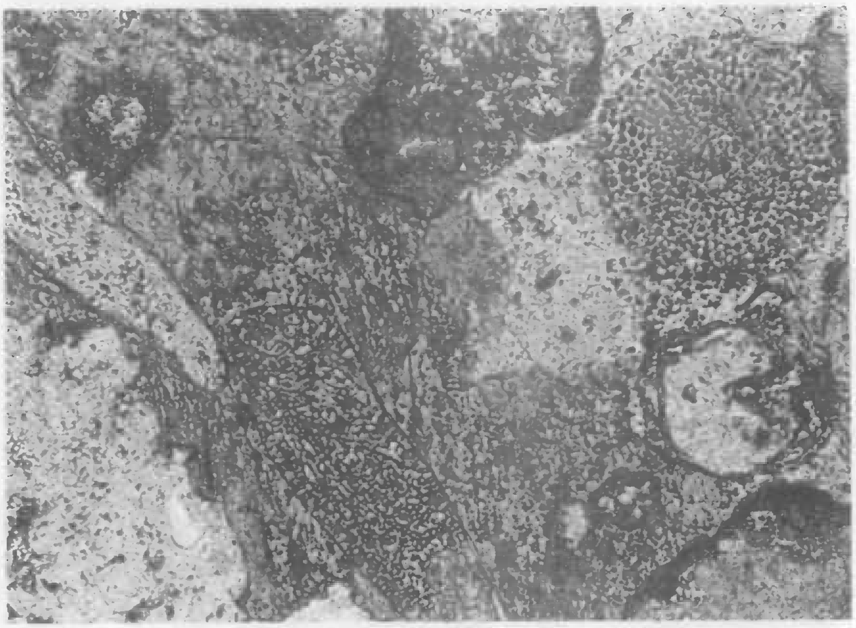


Figure 7: Fossil fragments in coarse sparry calcite. Photomicrograph of a coarse-grained biopelsparite. Ordinary light. See also Figure 8. x 150

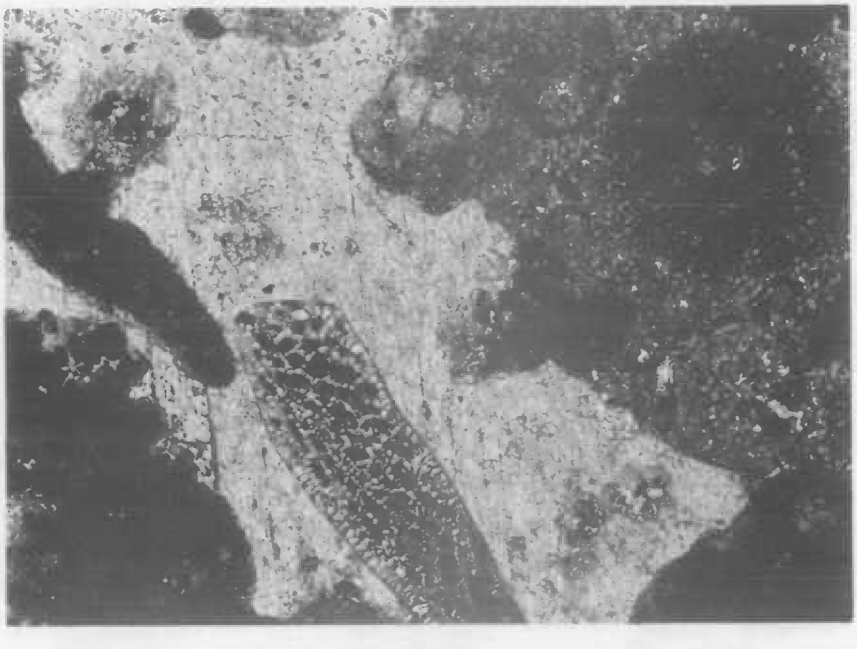


Figure 8: As Figure 7, but crossed nicols. Partial phosphatization (black patches) in fragments in lower centre of photograph, complete phosphatization in long fragment on left margin (black). Irregular, marginally replaced pellets (black) elsewhere, and circular section of partly phosphatized skeletal fragment in top right hand corner. x 150

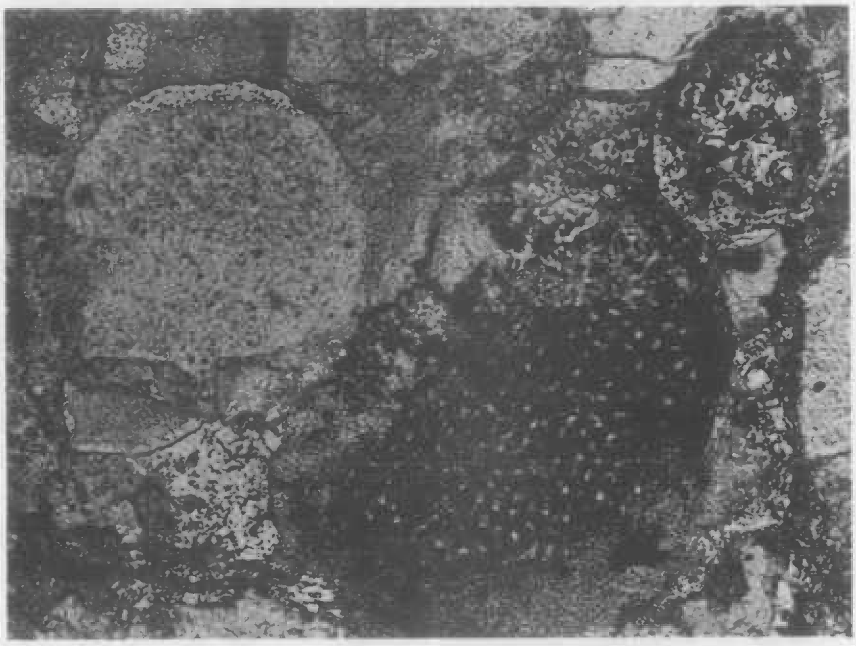


Figure 9: Photomicrograph of partly phosphatized fossil fragments in biopelsparite. See also Figure 10. Ordinary light. x 60

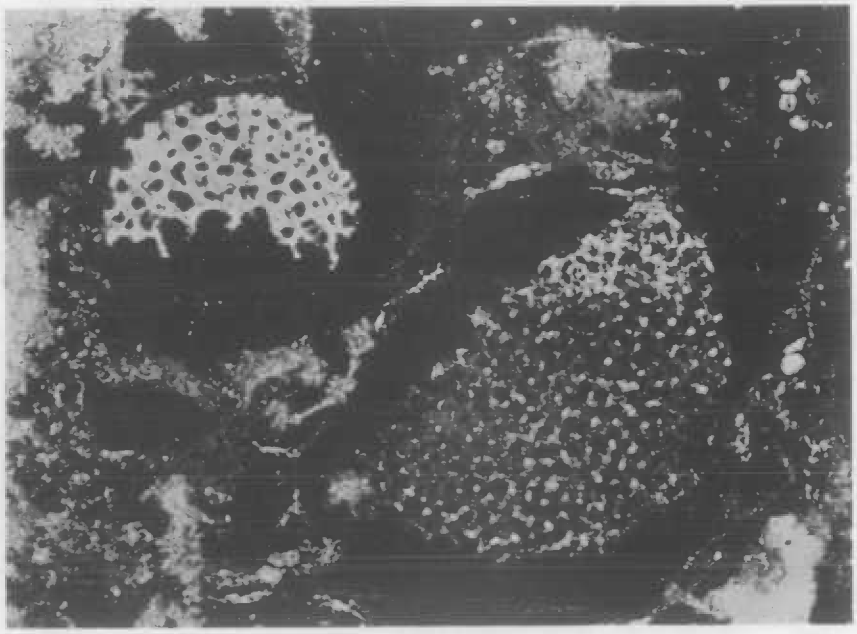


Figure 10: As in Figure 9, but nicols crossed. Skeletal derivation clearly visible owing to remaining calcitic framework. x 60.

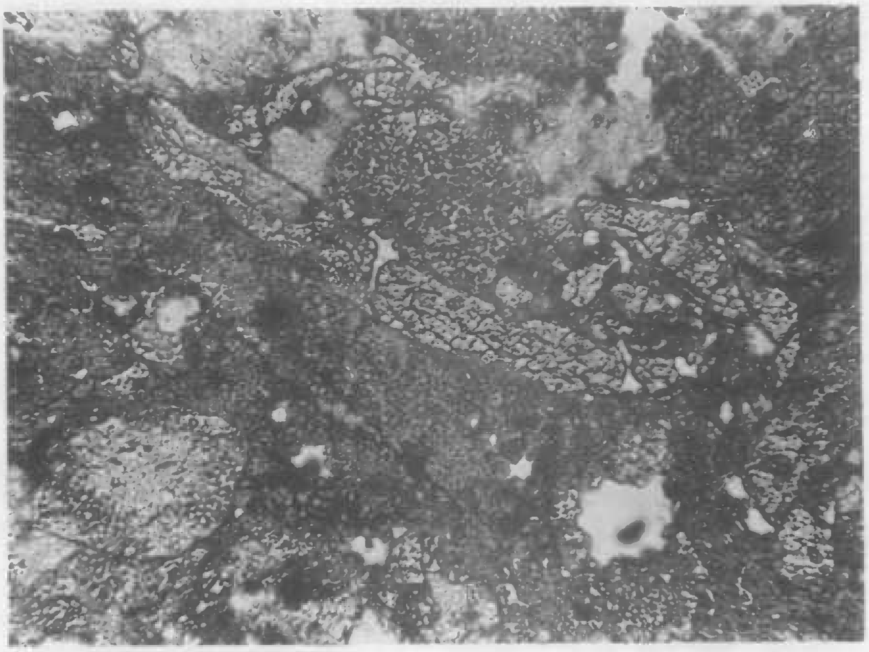


Figure 11: High-grade phosphorite, composed of completely phosphatized fossil fragments, in many of which the skeletal texture is still recognizable in places. Photomicrograph, ordinary light. x 60

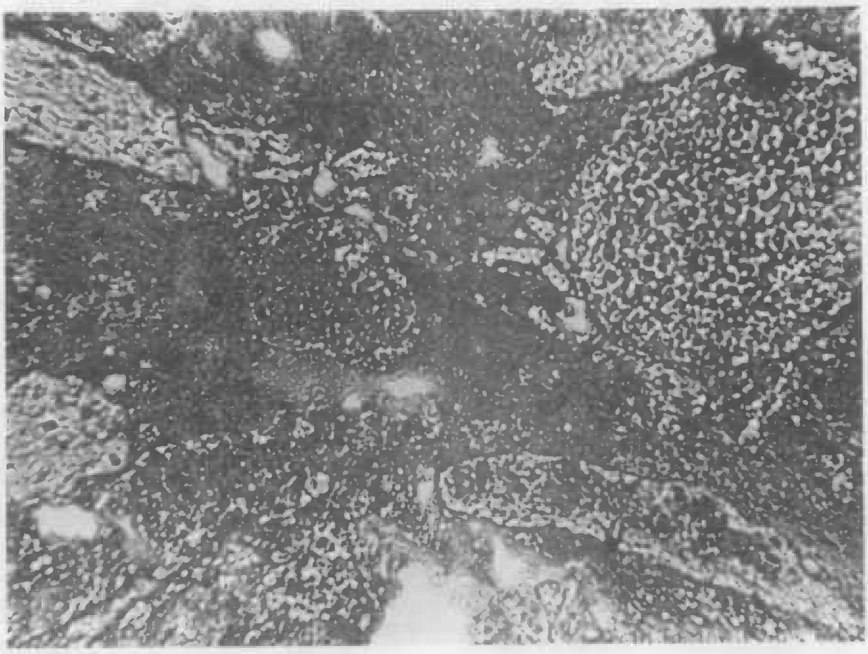


Figure 12: High-grade phosphorite composed of completely phosphatized fossil fragments. Photomicrographs ordinary light. x 100.

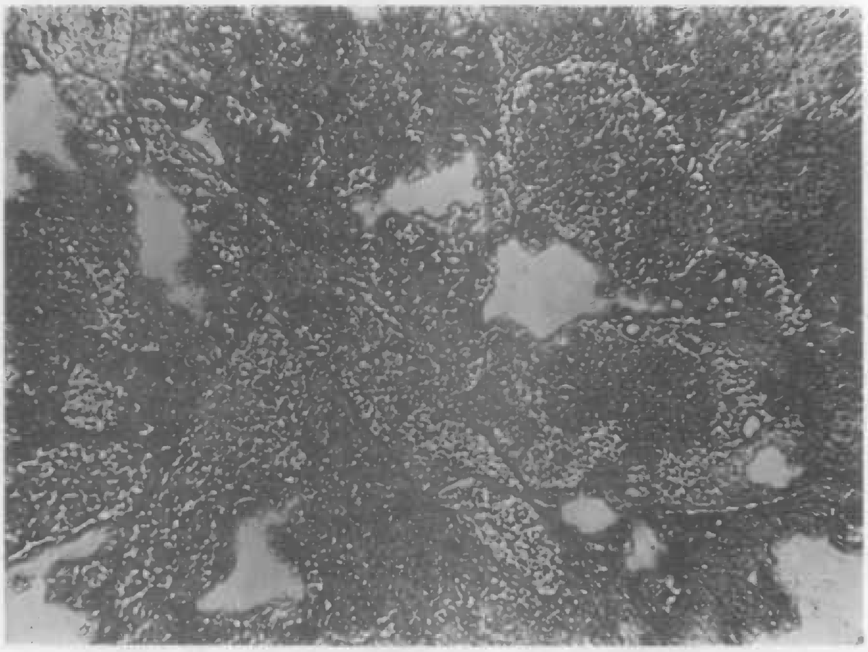


Figure 13: High-grade phosphorite composed of completely phosphatized fossil fragments. Photomicrograph, ordinary light. x 60.

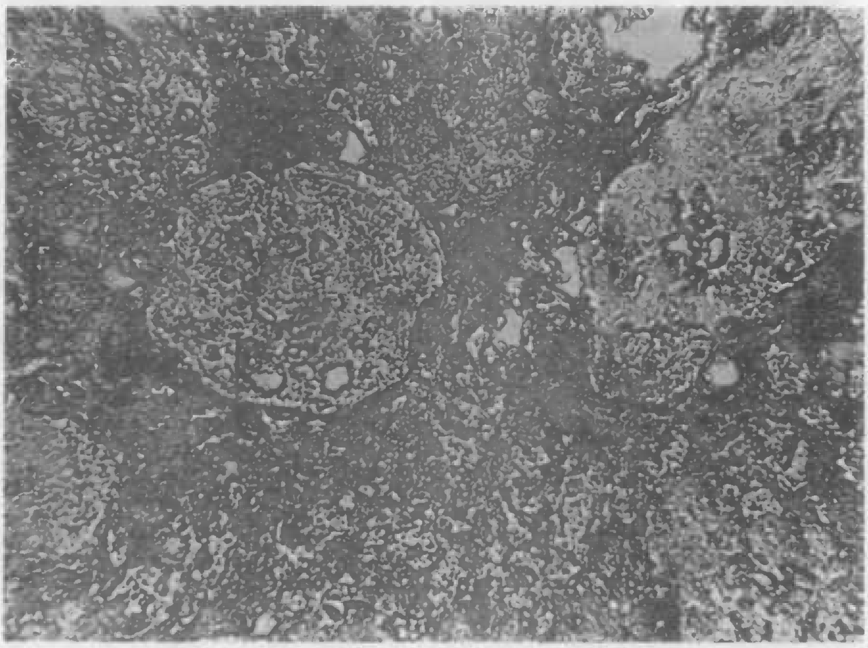


Figure 14: High-grade phosphorite, composed of completely phosphatized fossil fragments. Skeletal texture is almost totally destroyed, and out of context these fragments would probably not have been recognized as being phosphatized fossils. Photomicrograph, ordinary light. x 60.

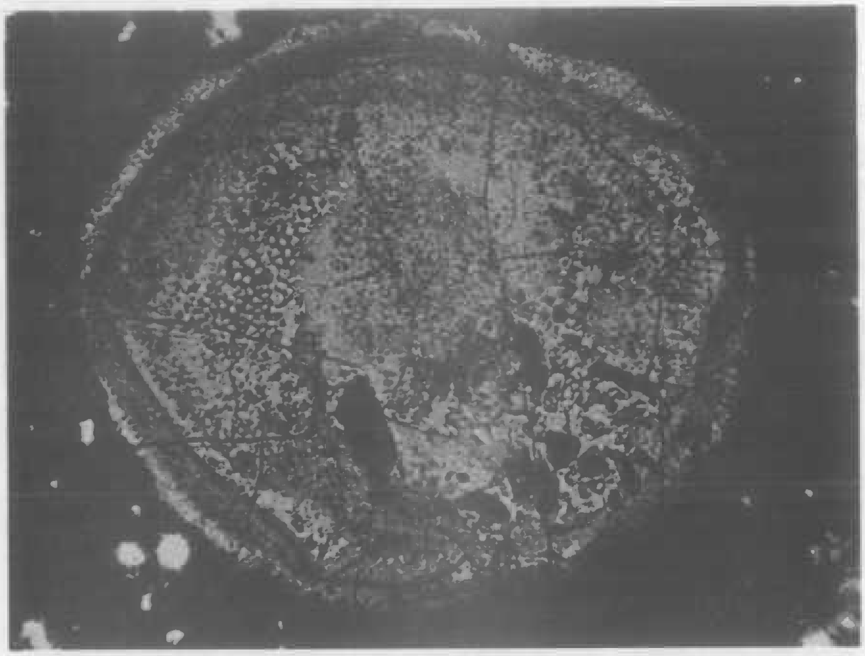


Figure 15: Photomicrograph of phosphate pellet in ferruginous phosphorite. Skeletal texture just recognizable in left portion of pellet. Accretionary rim around pellet. Black ground is goethite. Ordinary light. x 100

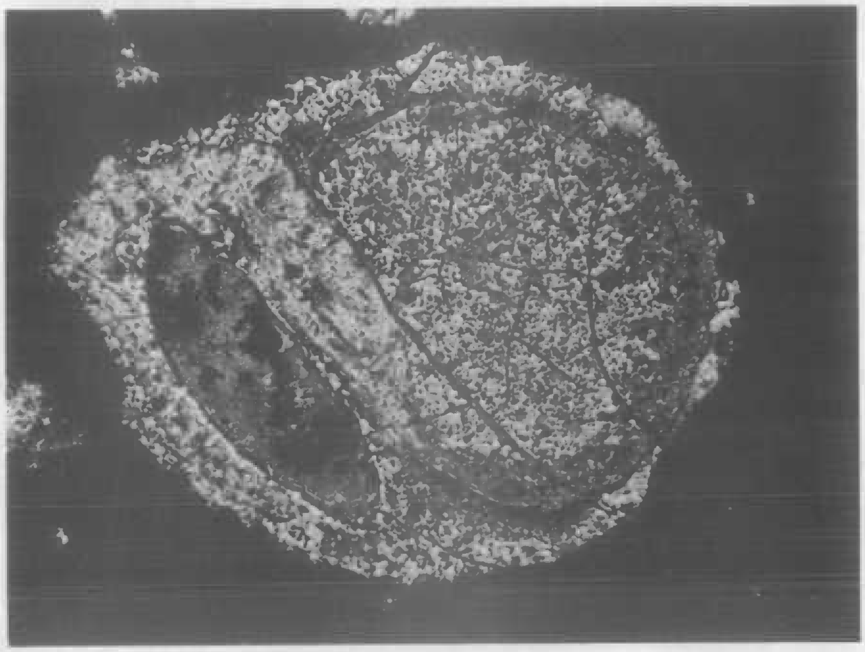


Figure 16: Photomicrograph of phosphate pellet in ferruginous phosphorite. The pellet is a composite structure consisting of an older pellet and a glauconite grain (dark grey area with black blotches) enveloped in an accretionary mantle of collophane. Ordinary light. x 100.

Figure 17: "Collophane"-filled section of a trilobite in a biopelsparite. Photomicrograph, ordinary light. x 35.

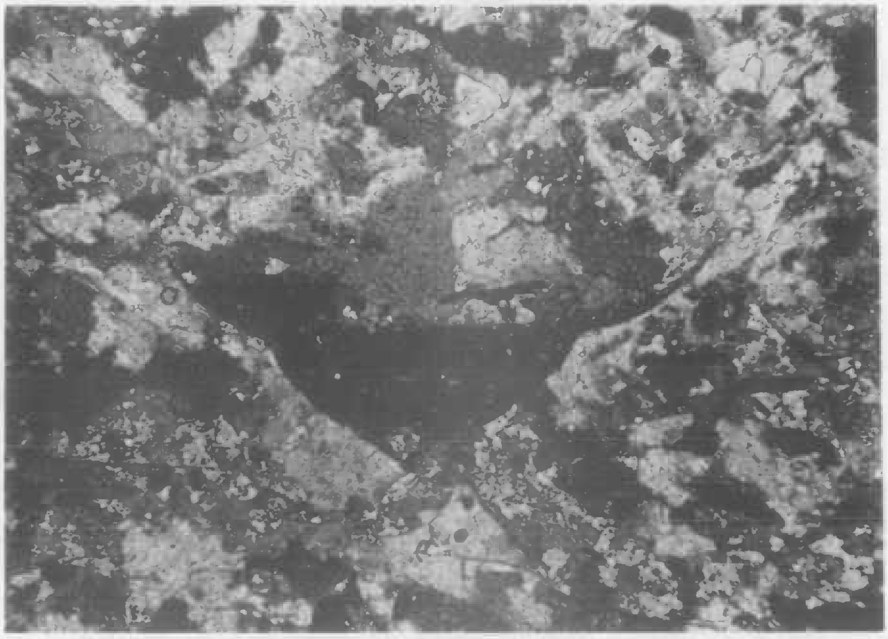


Figure 18: As above, nicols crossed to show isotropic collophane filling and pellets, and the sparry calcite matrix. x 35.

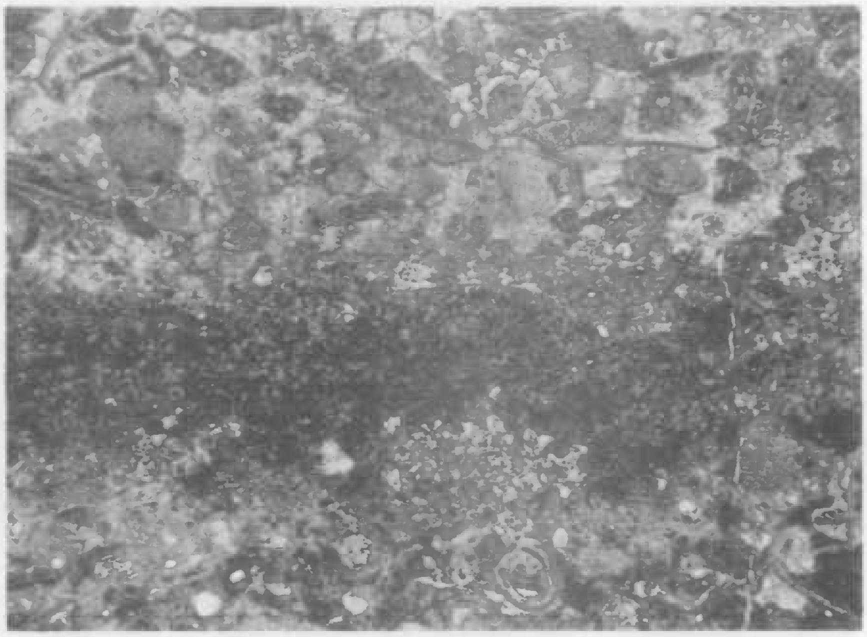


Figure 19: Biopelsparite with thin layer of "collophane" (dark grey, mottled) Photomicrograph, ordinary light. x 35.

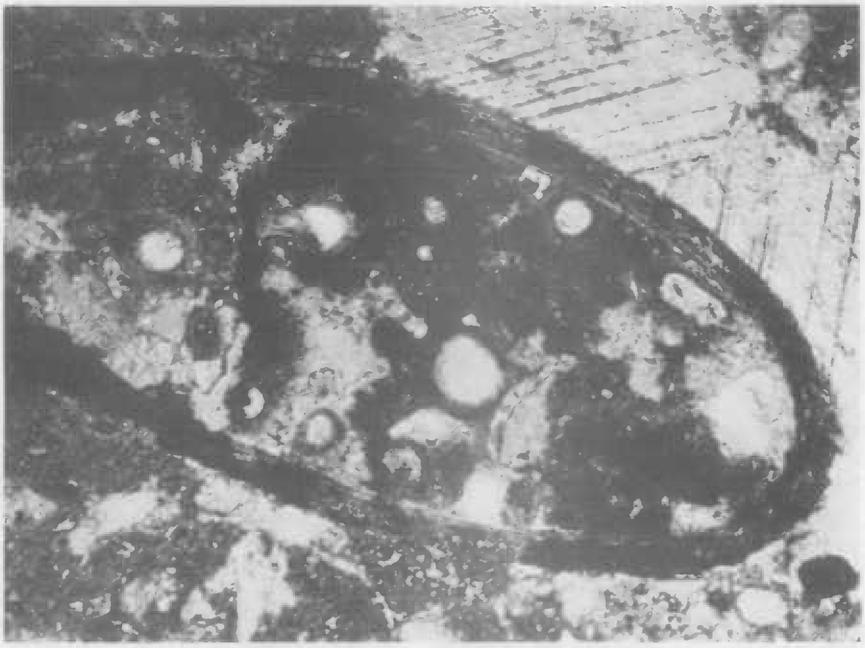


Figure 20: Rounded lump of phosphorite surrounded by an envelope of collophane, Photomicrograph, crossed nicols. x 35.

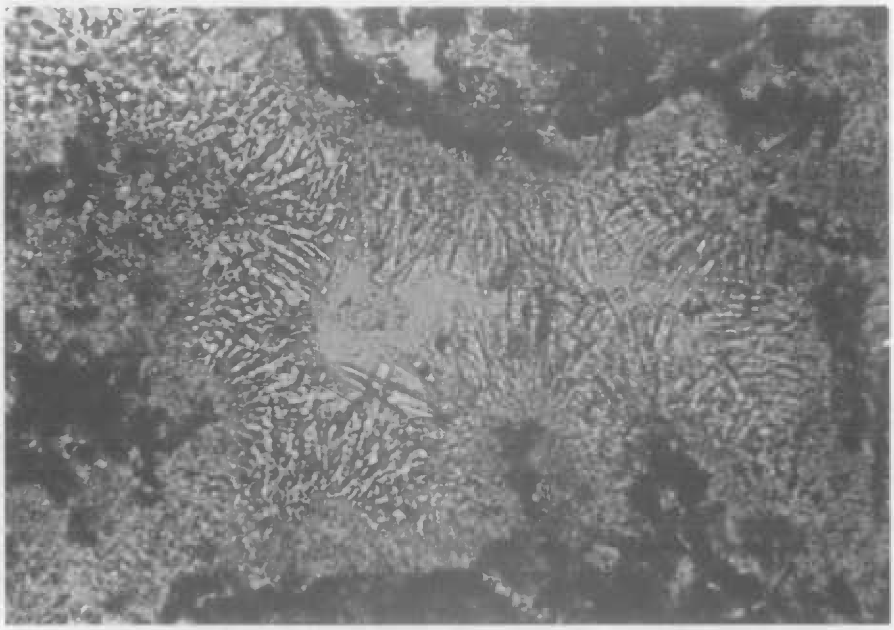


Figure 21: Minute crystals of clear apatite, precipitated from solution into interstitial voids in residual phosphorite. Photomicrograph, ordinary light. x 300.

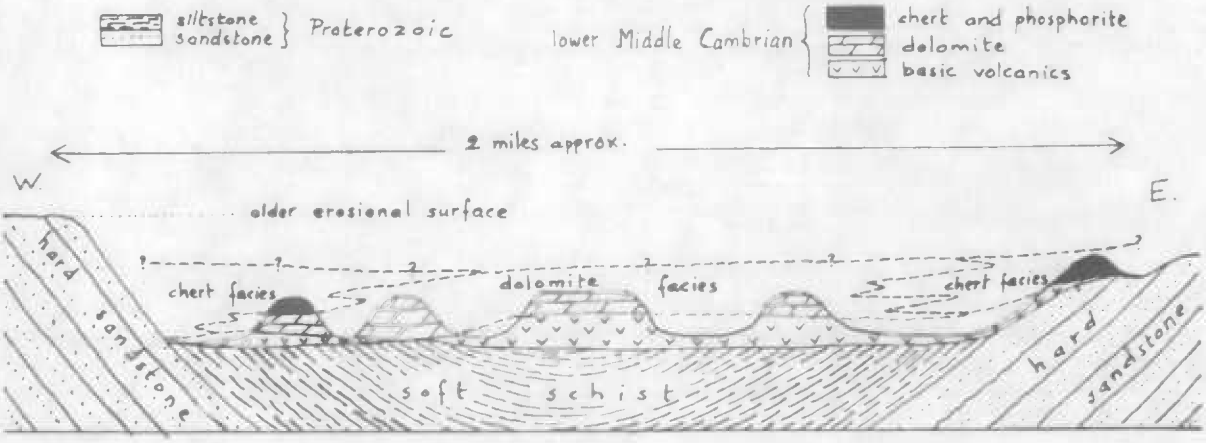


FIGURE 22 — Diagram showing the two pre-Cambrian erosion surfaces, and the facies distribution in the lower Middle Cambrian deposits, 12 miles southwest of Lawn Hill.

Figure 22: Diagram showing the two pre-cambrian erosion surfaces, and the facies distribution in the lower Middle Cambrian deposits, 12 miles southwest of Lawn Hill.

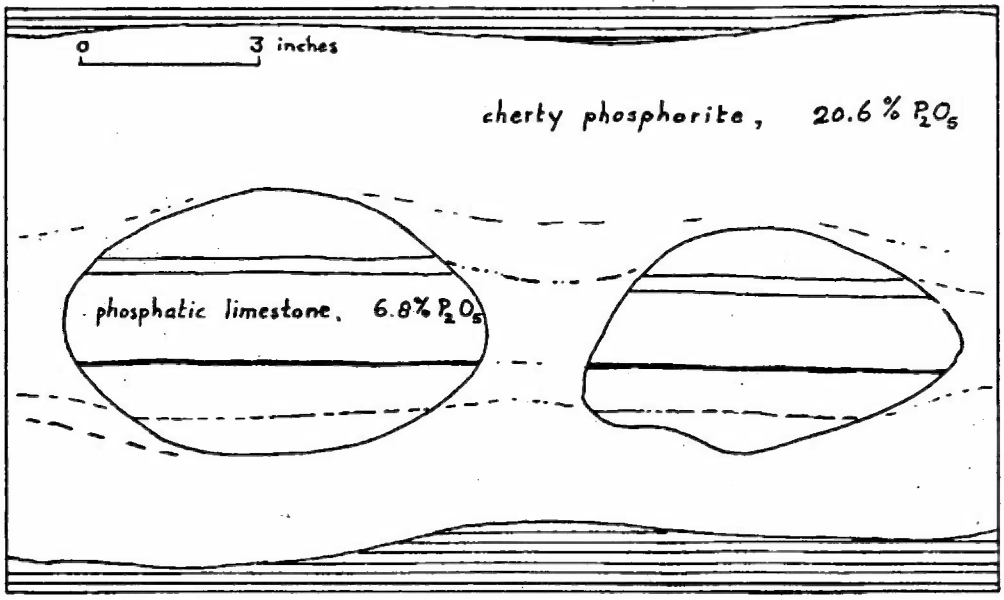


FIGURE 23 — Spherical remnants of biopelsparite in cherty phosphorite bed. For explanation see text.

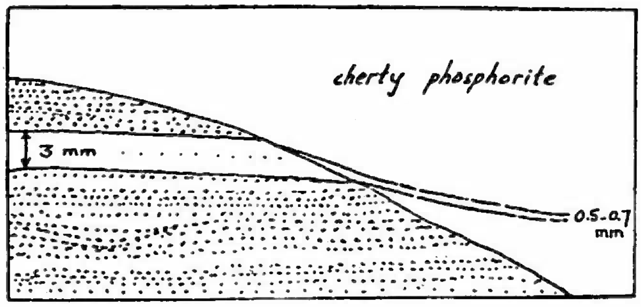


FIGURE 24 — Detail of Fig. 23, showing decrease in thickness of pellet-free laminae at transition from limestone to chert.

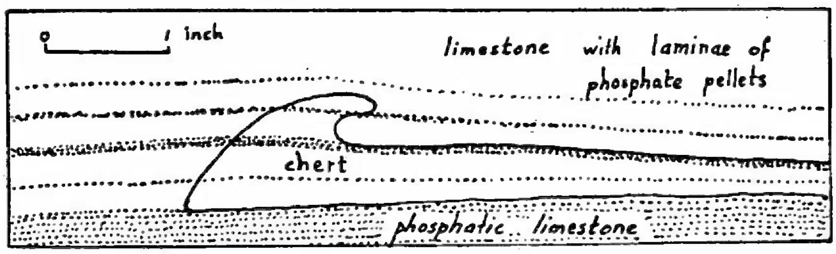


FIGURE 25 — Chert nodule produced by silicification of limestone. Laminae of phosphate pellets remain unaffected.

FIGURE 26 Chert replacing limestone. Note carbonate dust in centre of drawing, and border zone of very fine-grained chert. (After photomicrograph of detail of Figure 25)

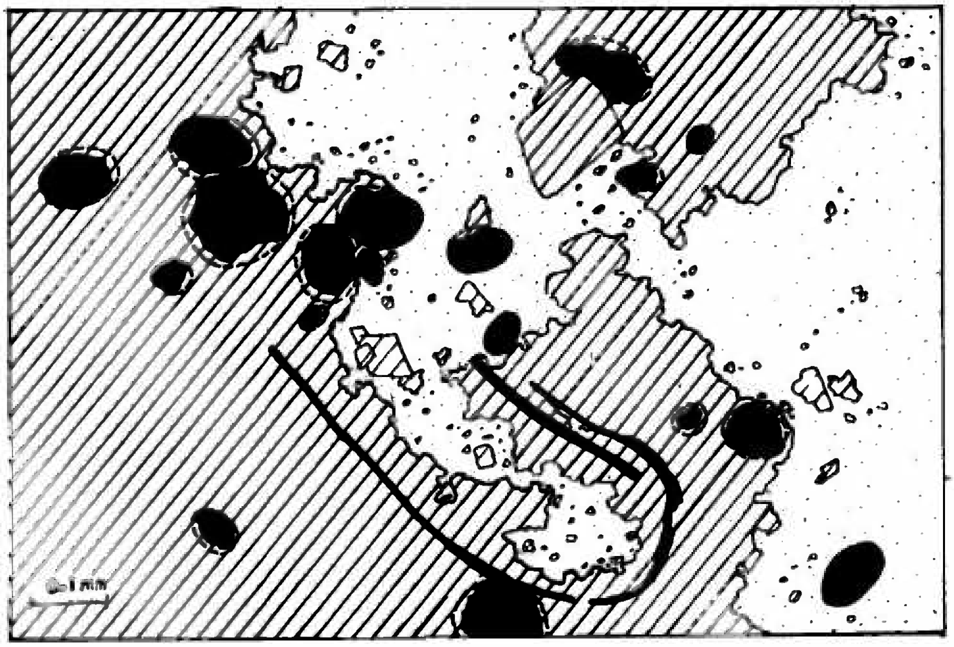


FIGURE 27 Chert replacing limestone. Also note marginal corrosion of phosphate pellets, and transected fossil. (After photomicrograph)

● collophane pellets
☐ chert.
▨ sparry carbonate.
░ extremely fine-grained chert.

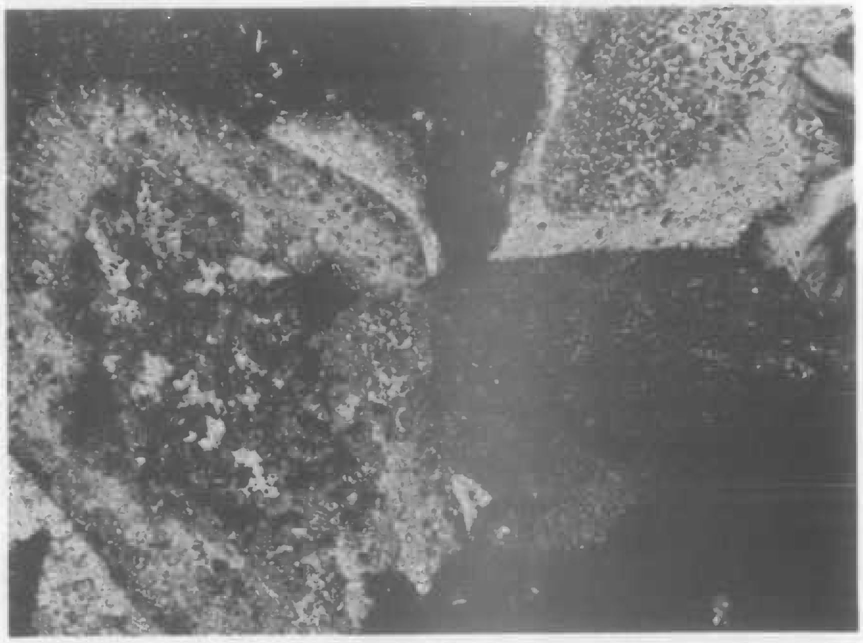


Figure 28: Silicification of fossil fragment, starting from the interior. Note presence of carbonate dust remaining in the chalcedony, and the partial phosphatization (black spots) along the margin of the fossil fragment. Photomicrograph, crossed nicols. x 150.

Figure 29: Silicification of originally carbonate ovoid (?). Note irregular remains of calcite (all with the same optical orientation) and some carbonate dust in the patchy mass of chalcedony. Photomicrograph, crossed nicols. x 100.

Figure 30: Completely silicified carbonate rock, showing limonite(?) - rimmed outlines of silicified dolomite rhombs in a silicified matrix, and some faint ghost remains of rounded skeletal debris. Photomicrograph, ordinary light. x 100.

Figure 31: As above, nicols crossed. Note carbonate dust throughout the chalcedony-quartz groundmass, and the range in size of the quartz and chalcedony grains. the outlines of the former dolomite rhombs can be recognized, with difficulty, by their limonite rims. x 100.

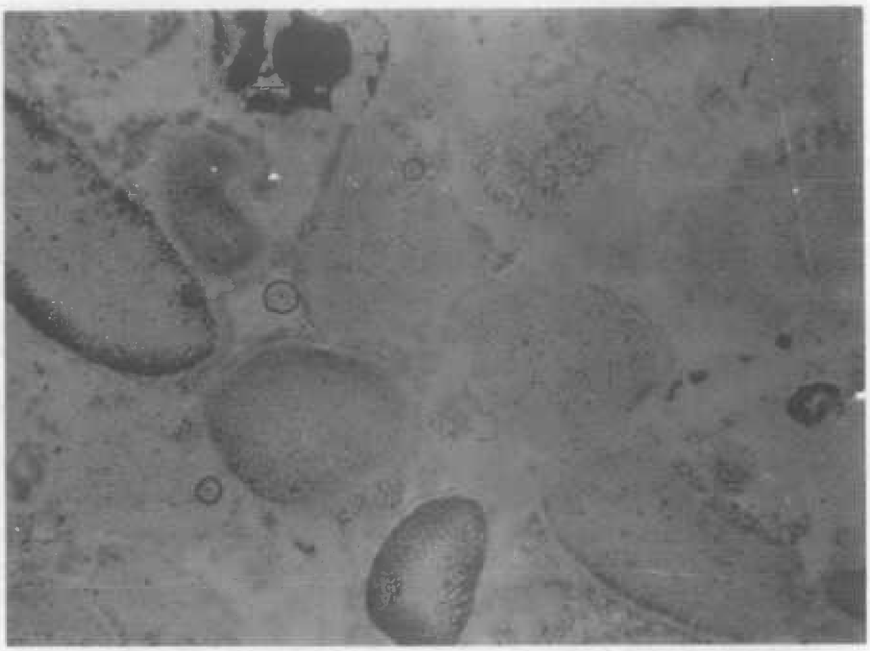


Figure 32: Silicified micro-coquinite. Skeletal nature of the fragments still clearly recognizable in ordinary light owing to part-preservation of phosphatized skeletons (dark rims) and probably organic pigment. Photomicrograph, ordinary light. x 35.

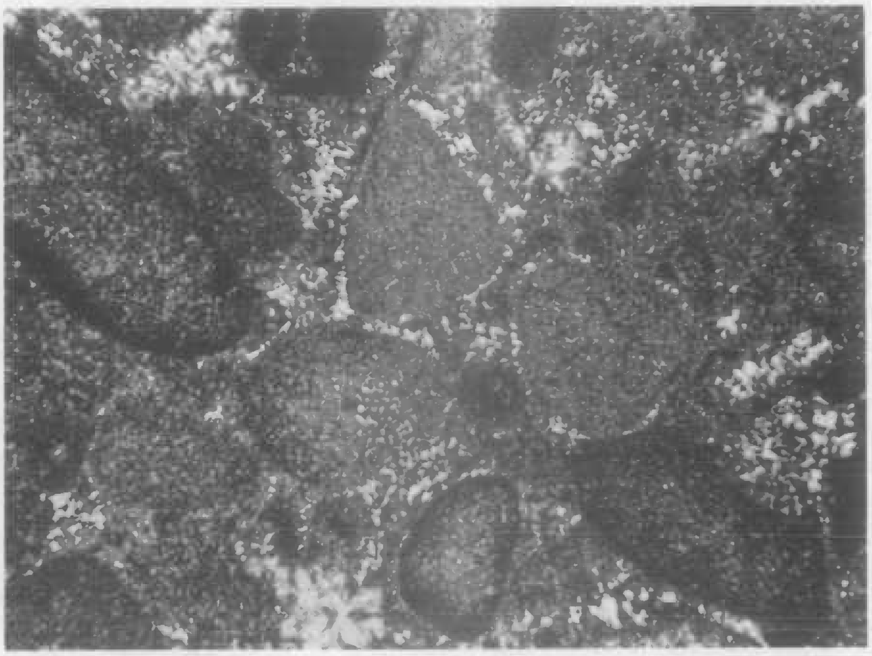


Figure 33: As above, nicols crossed, to show the structures of quartz-chalcodony aggregates composing the fragments and the interstitial matrix. x 35.

Figure 34: Silicified micro-coquinite. Skeletal textures of the rounded phosphatized particles still obvious. Silicification not as far advanced as in Figures 32 and 35. Photomicrograph, ordinary light. x 35.

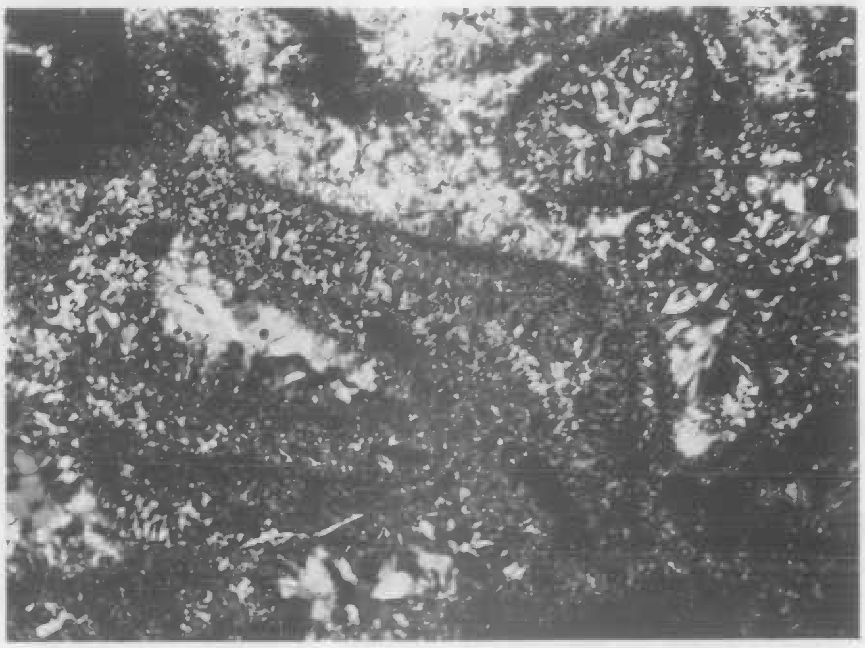


Figure 35: Completely silicified micro-coquinite. Crossed nicols to show up the ghosts of the former particles, which are no longer visible in ordinary light. Photomicrograph, crossed nicols. x 35.

Figure 36. Biopelsparite showing the effects of syntaxial rim cementation, grain growth, etc. Calcite veinlet running from right bottom to top left is scarcely visible but is indicated by the displaced fragments of broken particles. Photomicrograph, ordinary. light. x 60.

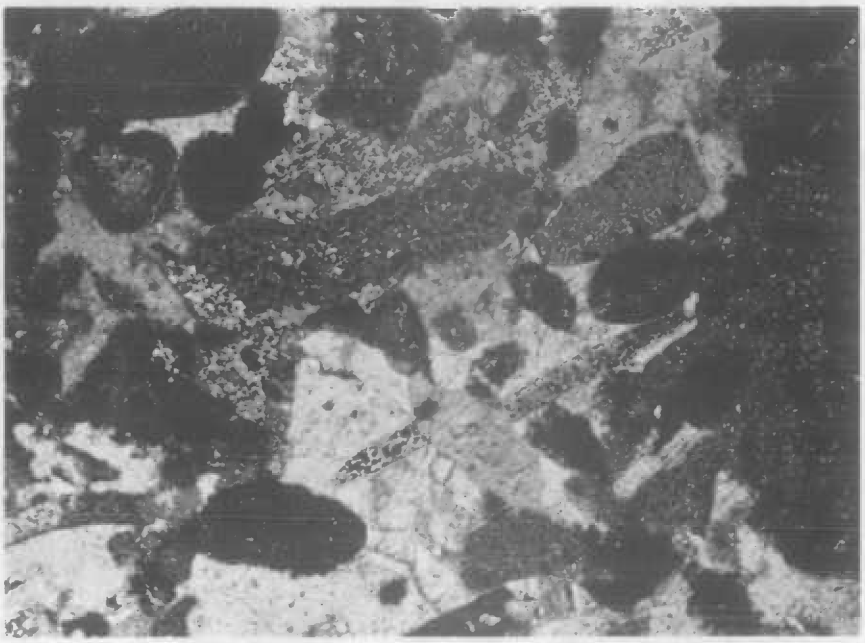


Figure 37: As above, nicols crossed, to accentuate some of the features mentioned. Note also various degrees of phosphatization. x 60.

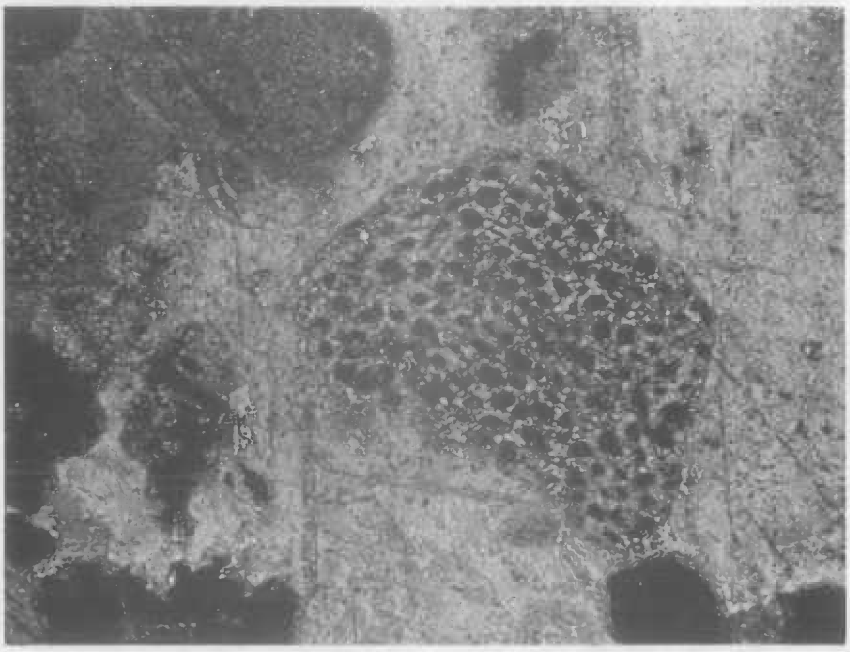


Figure 38: Partly phosphatized fossil fragment surrounded by syntaxial rim cement. Isotropic "collophane" pellets elsewhere in the picture are commonly marginally replaced by calcite. Photomicrograph, crossed nicols. x 60.

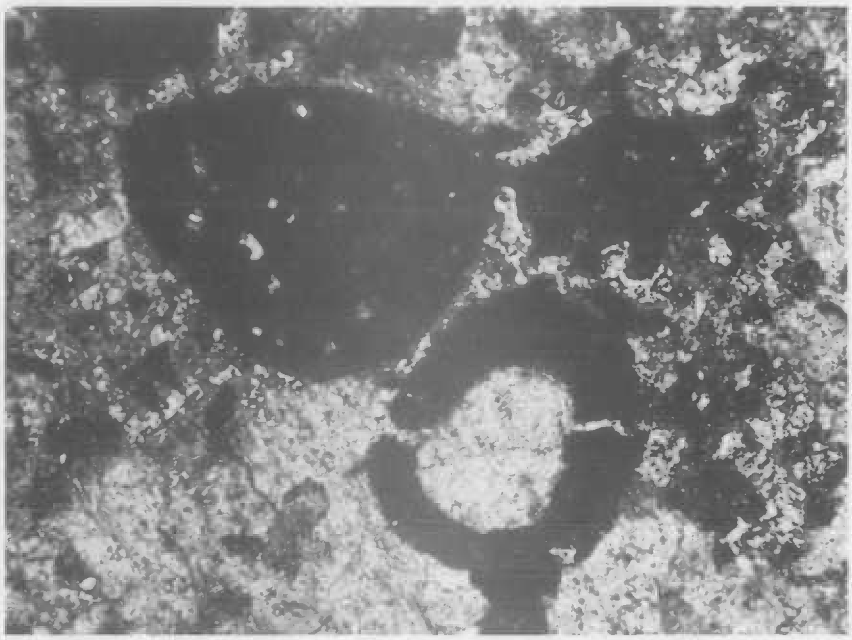


Figure 39: Collophane pellet internally replaced (?) by calcite. Photomicrograph, crossed nicols. x 150

Figure 40: Fluorite(?) pseudomorphic after dolomite rhombs in chertified limestone fragment. The mineral is clear, isotropic, and has appreciable negative relief. Photomicrograph, ordinary light. x 100.

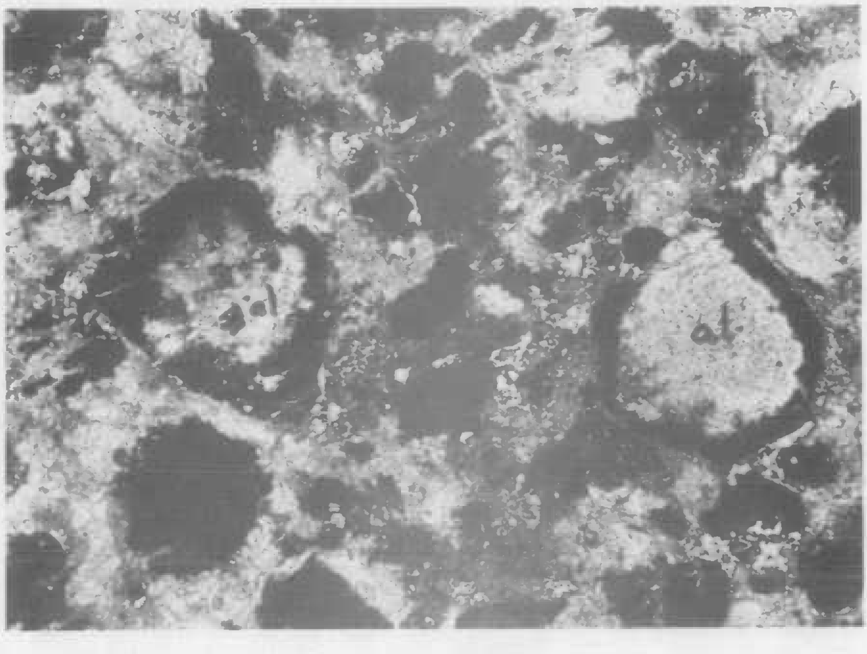


Figure 41: Phosphate pellets internally replaced by alunite (al). Note also the marginal replacement of some of the phosphate pellets by calcite. Photomicrograph, crossed nicols. x 100.

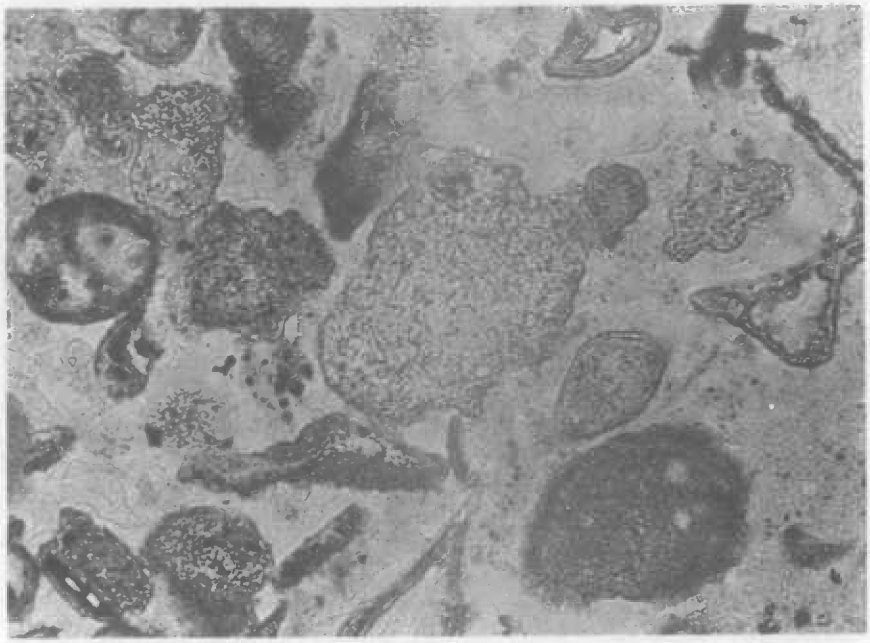


Figure 42: Pellets and fragments of an aluminium phosphate, probably evansite. Biogenic origin recognizable in some of the fragments, the central one containing sponge spicules(?). Chert matrix. Photomicrograph, ordinary light. x 100.

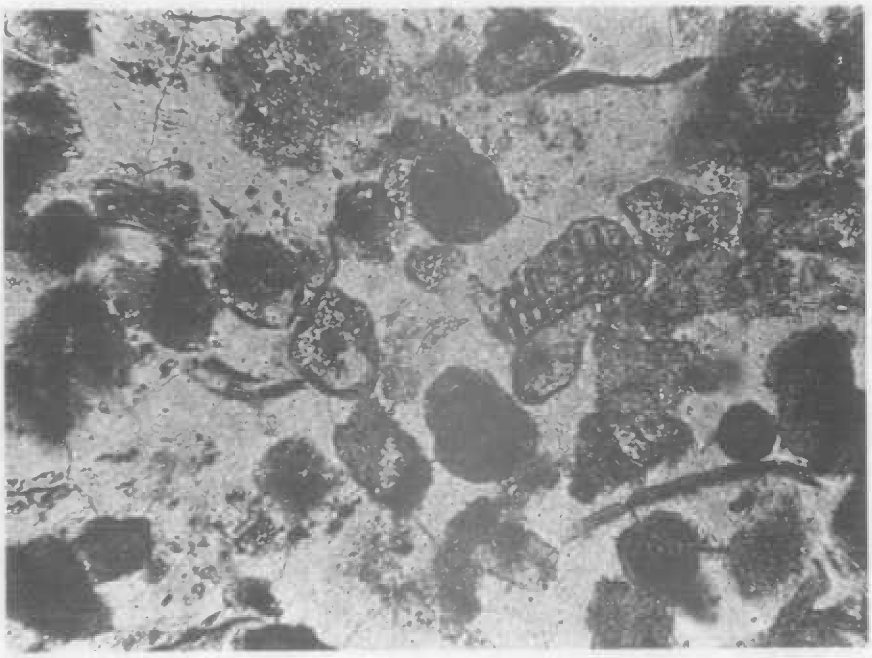


Figure 43: Pellets and fragments of evansite(?) after fossil material, including algae. Chert matrix. Photomicrograph, ordinary light. x 100.

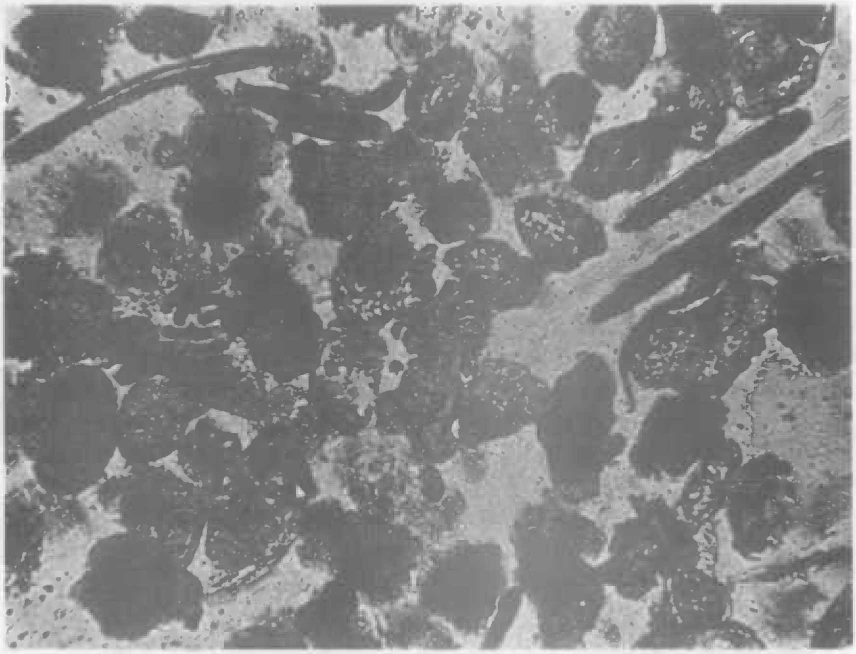


Figure 44: Evansite(?) replacing fossil fragments. Photomicrograph, ordinary light. x 100.

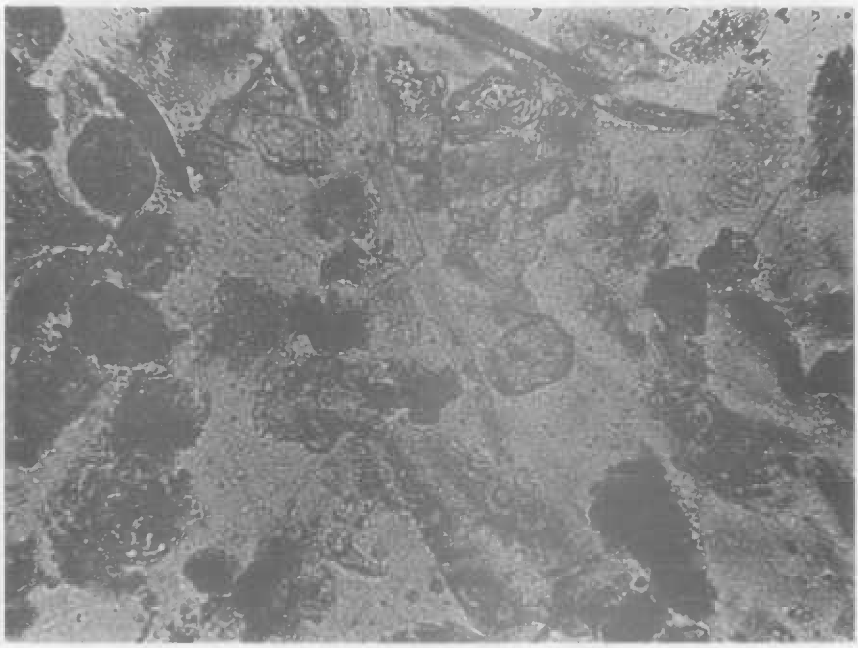


Figure 45: Evansite(?) grains after fossil material. Chert matrix. Photomicrograph, ordinary light. x 100.

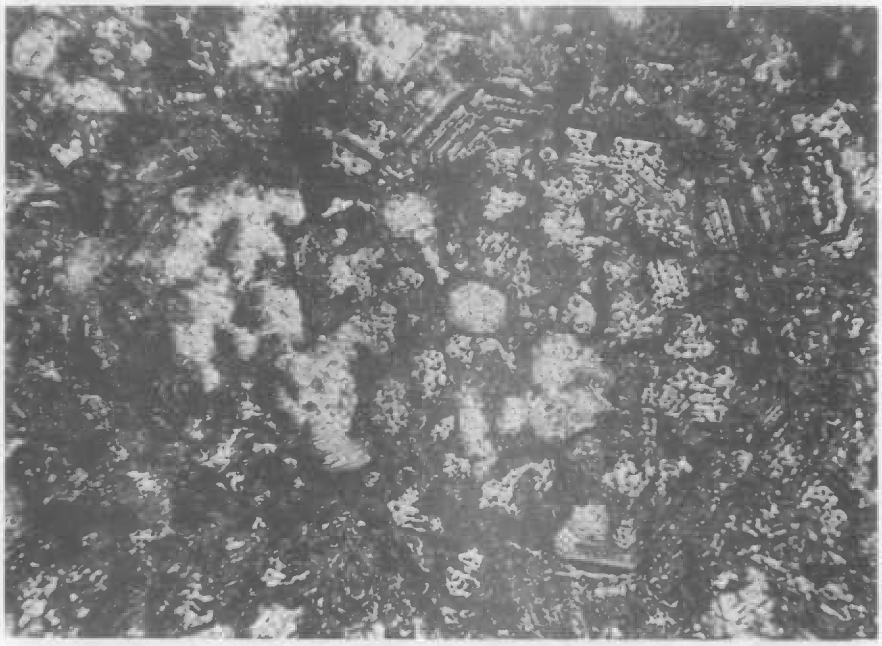


Figure 46: Zoned variscite, meta-variscite, and possibly other Fe-Al-phosphate minerals, forming replacement complex. Original pelletal structure of the rock is still clearly visible in this example. See also Figures 47-49. Photomicrograph, ordinary light. x 60.

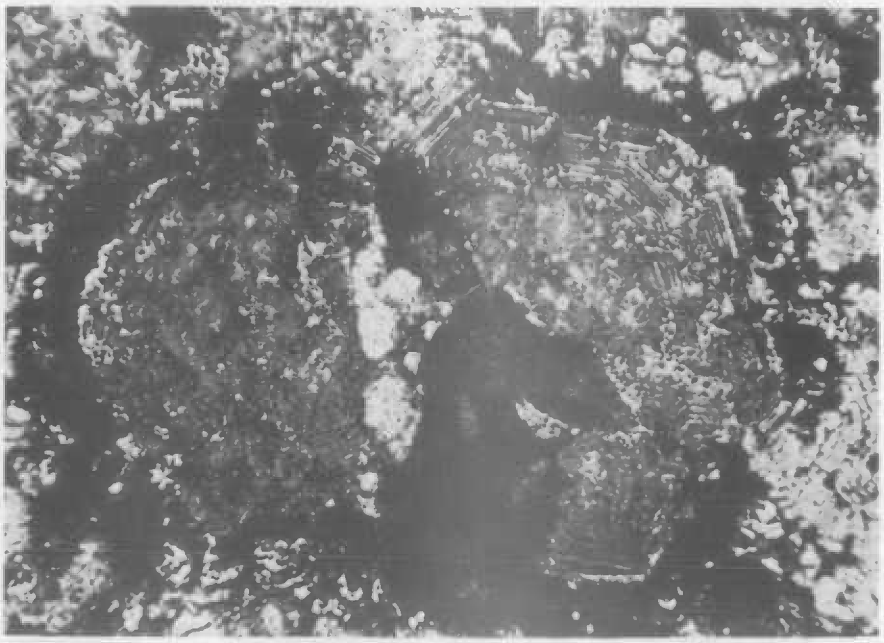


Figure 47: As above, nicols crossed. Original pelletal structure no longer obvious. Note isotropic rim of unknown phosphate mineral. x 60.

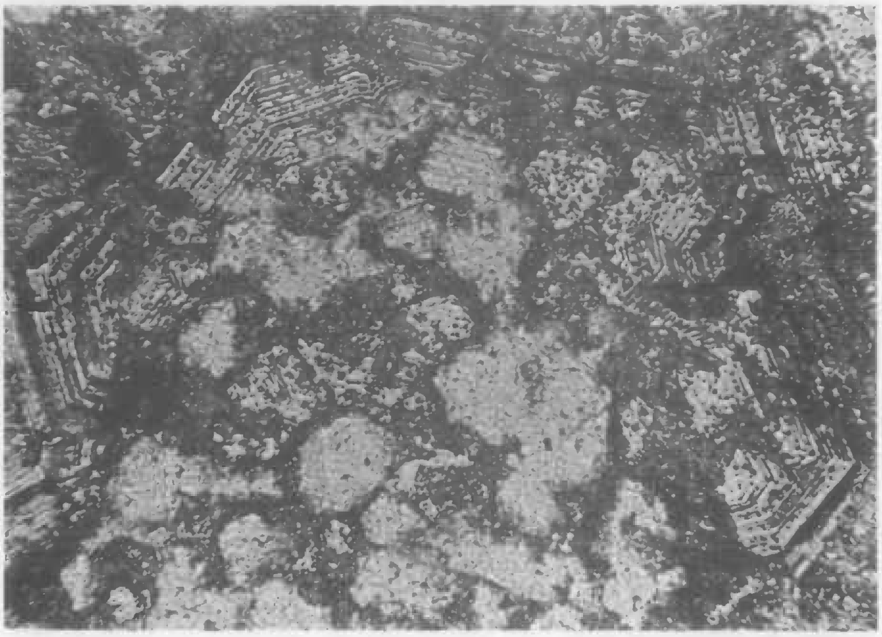


Figure 48: Detail of Figure 46 accentuating zonal structure. Photomicrograph, ordinary light. x 100.

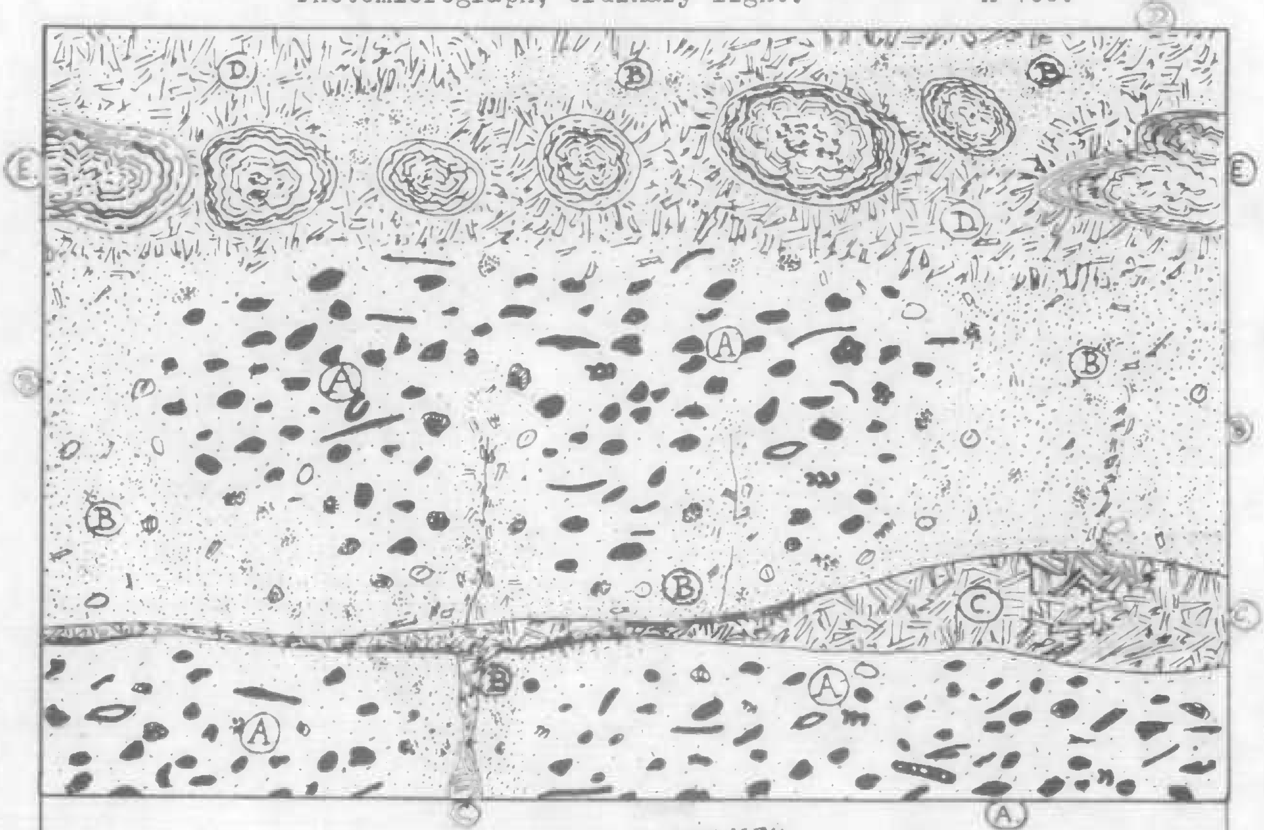


FIGURE 49 – Diagram showing various phases of microscopic alteration in siliceous phosphorite. For explanation, see text. (After thin section 68.63.1003, Mt. Murray, Duchess district).
Magnification roughly 20 x

Area A - Pelletal phosphatic chert, showing pellets of evansite(?) (black) and rare pellets of wavellite and variscite, in chert matrix (stippled).
Area B - Completely silicified rock (densely stippled) with some pellets of wavellite and variscite (blank) and scattered flakes of wavellite in chert matrix.
Area C - Veinlets of wavellite, some variscite, cross-cutting rock.
Area D - Areas mainly of wavellite with interstitial chert.
Area E - Zoned clusters of variscite and other Fe-Alphosphate minerals. Cf. Figures 46-48.