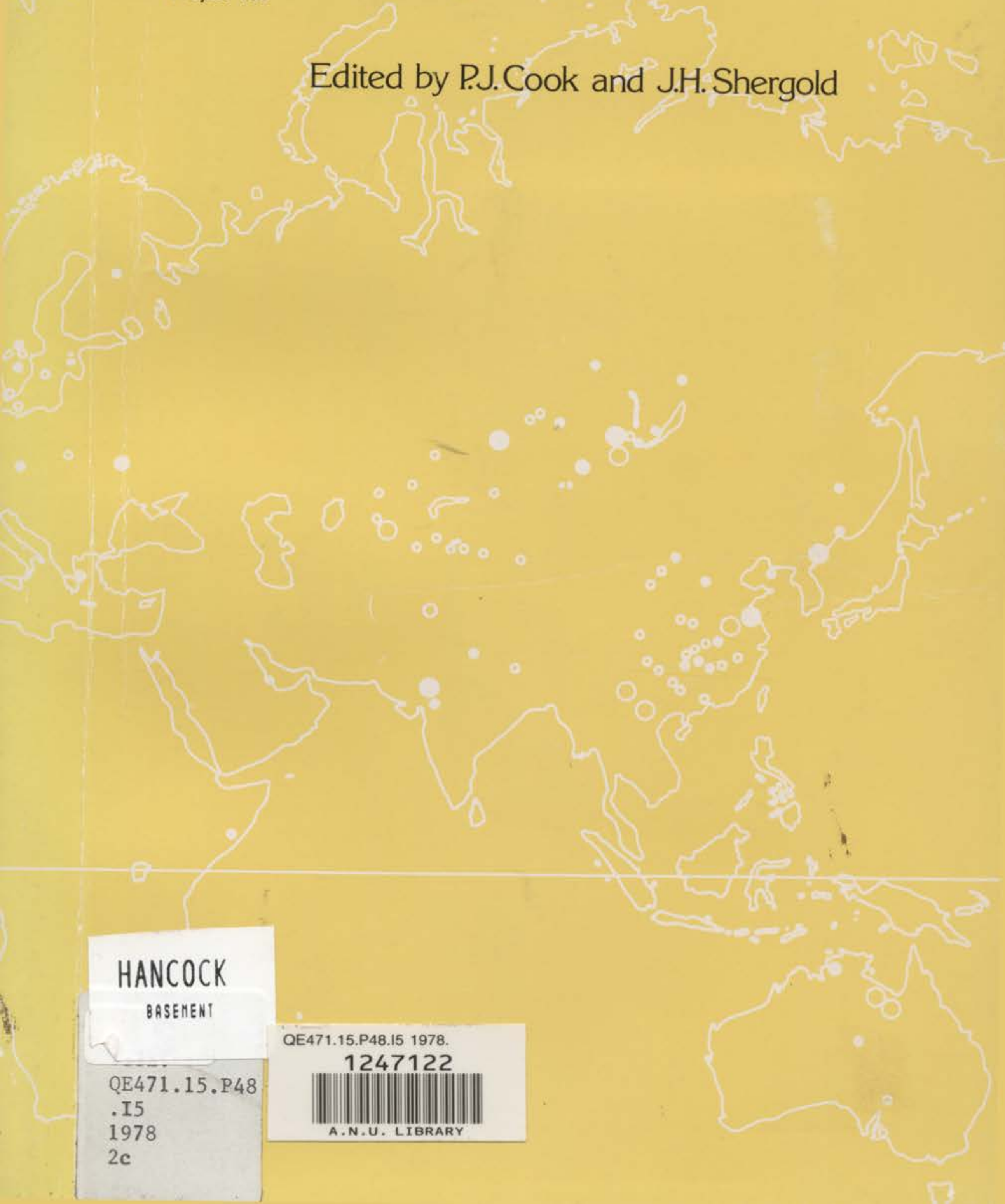
IUGS UNESCO

Project 156

Proterozoic-Cambrian Phosphorites

Edited by P.J. Cook and J.H. Shergold



This book was published by ANU Press between 1965–1991.

This republication is part of the digitisation project being carried out by Scholarly Information Services/Library and ANU Press.

This project aims to make past scholarly works published by The Australian National University available to a global audience under its open-access policy.

IUGS
UNESCO
IGCP
Project 156

Proterozoic-Cambrian Phosphorites

First International Field Workshop and Seminar on Proterozoic-Cambrian Phosphorites, held in Australia, August 1978

Editors
Peter J. Cook,
The Australian National University, Canberra

John H. Shergold,
Bureau of Mineral Resources, Canberra

Sponsored by:
The International Geological Correlation Programme,
Project 156 of UNESCO-IUGS
and Australian, Indian, and United States Science & Technology Agreements

National Library of Australia
Cataloguing-in-Publication entry

Cook, P.J., Shergold, J.H. (Editors)
Proterozoic-Cambrian Phosphorites.
Papers given at a UNESCO sponsored conference held in Australia in 1978.
Bibliography
ISBN 0 7081 1159 9
1. Rocks, Sedimentary – Congresses. 2. Phosphate rock – Congresses. I. Cook, Peter John, ed. II. Shergold, John Helsby, joint ed.

552.5

Printed by Canberra Publishing & Printing Co. Pty. Ltd.

Preface

We began thinking about an international project on phosphorites in early 1976, and during that year solicited the views of scientists in many countries. On the basis of an overwhelmingly favourable response, a project to study phosphorites, particularly focussing on those of Proterozoic-Cambrian age, was submitted to the International Geological Correlation Programme. It was formally accepted as IGCP Project 156 in early 1977. Since then, co-ordinators have been appointed and national working groups set up in a number of countries to encourage research programmes. Additionally, several national meetings and one regional meeting have been held. However, it was clearly necessary to convene meetings which would bring together scientists from many countries to discuss the similarities and differences between the various deposits. It was considered that field workshops would be essential to the success of the Project as it is frequently at the outcrop or the mine that the most meaningful discussions take place. The international field workshop in the Mount Isa region and the subsequent seminar at Magnetic Island were conceived as the first of several such meetings which will be held in various countries. The ultimate aim of such meetings is to bring about not only an understanding of Proterozoic-Cambrian phosphogenic provinces, but hopefully also lead to the critical analysis of existing genetic models and perhaps ultimately to a new understanding of the genesis of phosphorites.

Fifty eight scientists representing twelve nations (Australia, France, India, Malaysia, New Zealand, Pakistan, People's Republic of China, Republic of South Africa, Thailand, United Kingdom, United States of America, and the Union of Soviet Socialist Republics) attended the inaugural meeting, and we are encouraged by this response which we consider augers well for the future of the Project.

This volume has been published within only a few months of holding the inaugural Field Workshop and Seminar. We felt it absolutely essential to do this in order to disseminate the information as quickly as possible, to ensure that Project 156 maintains its momentum. This speed of publication has only been achieved through the co-operation of the contributors and of those involved in the production of the volume and we express our thanks to all these people.

Peter J. Cook, John H. Shergold
Editors and Co-Project Leaders

Acknowledgements

During the past year we have drawn upon the assistance of many organisations and individuals who together made the field workshop and seminar possible. We are most grateful for this assistance and we look forward to working with them in the future.

We gratefully acknowledge the following organisations, without whose support this field workshop and seminar would not have been possible: –

Adelaide & Walleroo Fertilizers
(financial assistance)

Australian Development Assistance Bureau
(financial assistance for scientists from developing countries)

Australian Fertilizers Ltd.,
(financial assistance)

Australian National Commission for UNESCO
(publication assistance)

Australian National University
(organisational support)

BH South Ltd., and subsidiaries
(field and organizational support)

Bureau of Mineral Resources
(organisational support)

Department of Science
(financial assistance under the US-India-Australia Science and Technology Agreements)

Geological Survey of Queensland
(field support)

Ian Potter Foundation
(financial assistance)

ICI Australia
(logistic support)

IGCP-IUGS
(financial assistance)

Indian Department of Science and Technology
(financial assistance under science agreement)

International Mineral and Chemical Company
(financial assistance)

Mount Isa Mines Ltd
(field support)

U.S. National Science Foundation
(financial assistance under science agreement)

Institut Mondial du Phosphate, Paris
(financial assistance)

In addition, the support of many individuals has been vital in making the meeting a reality. In particular, we would like to acknowledge the following:—

Dr D.M. Banerjee, University of Delhi

Mr J.N. Casey, Bureau of Mineral Resources

Mrs K. Gibbs, Australian National University

Professor L.B. Gustafson, Australian National University

Mr D. Hackett, ICI Australia

Professor P.F. Howard, Macquarie University

Mr P.W. Pritchard, formerly of IMC

Dr R.P. Sheldon, U.S. Geological Survey and East-West Center

Mr P. Southgate, James Cook University of North Queensland

Mr P. Stoker, Mount Isa Mines Ltd

Staff of the BH South group of companies.

We would also like to express our thanks to those participants of the Seminar who acted on our behalf as Chairmen and Secretaries of the various Sessions, and who provided the syntheses of the discussions provided below: Dr D.M. Banerjee, Dr W.C. Burnett, Mr A. Driessen, Professor L.B. Gustafson, Professor P.F. Howard, Dr G.H. McClellan, Mr A.J.G. Notholt, Professor A.R. Palmer, Mr P.W. Pritchard, Dr S.R. Riggs, Mr M.W. Sandstrom, Dr R.P. Sheldon, Dr M. Slansky, Mr P.N. Southgate, Dr H.H. Veeh, and Professor A.M. Ziegler.

J.H. Shergold publishes with the approval of the Director, Bureau of Mineral Resources.

Contents

The Field Workshop

Compiled by *Peter J. Cook* and *John H. Shergold*
with assistance from the Staff of the BH South group of companies

Introduction

The inaugural Field Workshop of the International Geological Correlation Programme Project 156 was held in the Mount Isa region of northwest Queensland between August 14-20, 1978. The aims of the Workshop were to demonstrate the stratigraphy and depositional environments of the Queensland phosphate deposits, to seek similarities and differences between these Middle Cambrian deposits and Proterozoic and Cambrian deposits elsewhere in the world, and to co-ordinate opinions on the nature of depositional environments, phosphogenetic processes, nomenclature of phosphorites and the post-depositional history of phosphate deposits.

During the Workshop, participants examined the Middle Cambrian phosphatic sediments in the Ardmore, Duchess and Lady Annie districts, on the eastern margin of the Georgina Basin (Figs 1, 2). They considered the regional, structural and stratigraphic setting of the deposits, the various types of phosphorite, their primary sedimentary structures, diagenetic features, and the manner in which the phosphorites are related to other sediments.

The Proterozoic (Carpentarian) sediments which underlie the Cambrian phosphatic sequences were also examined during the Workshop, at surface in the Mount Isa Valley, underground in Mount Isa Mine, and again at surface in the Lady Annie area. The purpose of this was to provide an opportunity to examine an unmetamorphosed Proterozoic sequence which has depositional features in common with sediments of similar age in Asia, e.g. the phosphatic stromatolitic sequence of Rajasthan, India. Although base metal mineralisation is not of course the primary interest of Project 156, the two topics are not entirely divorced. Areas of overlap include the high phosphorous values found in some stratiform deposits and the association of evaporites and organic-rich sediments with both base metal deposits and phosphorites. Consequently, it was also decided to briefly examine stratiform base metal mineralisation at Mount Isa during the Field Workshop.

Because the Workshop provided the initial catalyst for the ensuing Seminar, and the Georgina Basin phosphorite deposits were used there as a point of reference for discussion and comparison with deposits elsewhere, it is considered appropriate to include in this volume a brief account of the geology of the Mount Isa region to aid readers who did not receive copies of the Workshop guidebook issued to participants. For the most part, this account consists of already published information although in places new observations made during the course of the Workshop, and new data provided by BH South Pty. Ltd, are also incorporated.

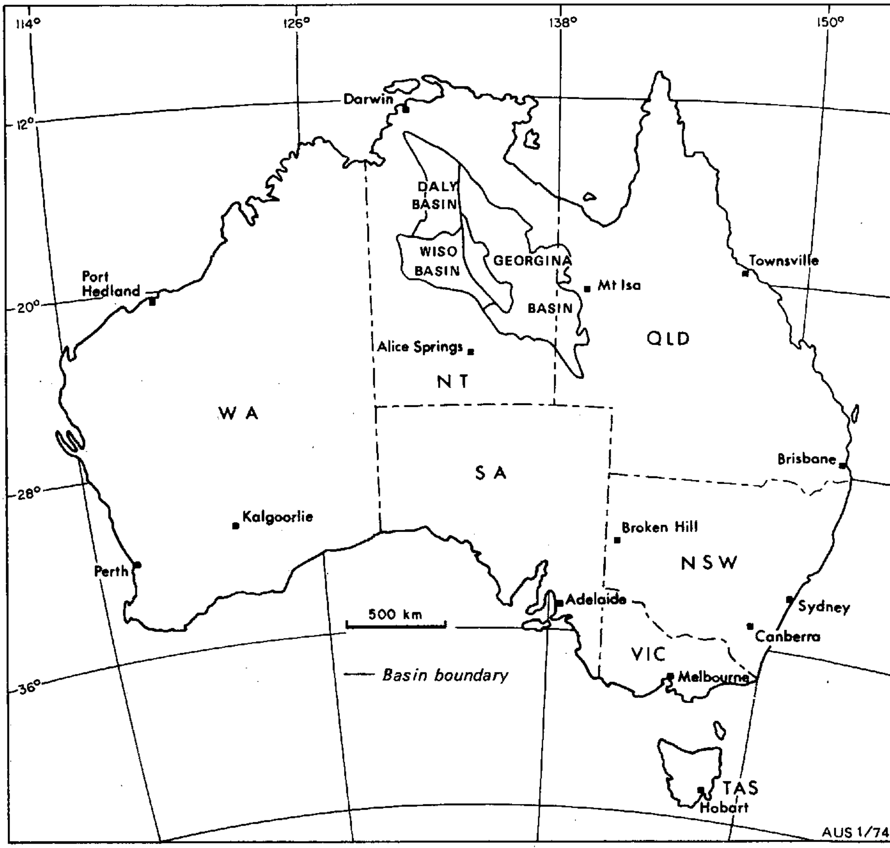


Fig.1 Location of the Georgina Basin

Synthesis of Regional Geology

Proterozoic

The Precambrian rocks of the Mount Isa region are mostly referrable to the Middle Proterozoic (Carpentarian), with ages between 1600-1860 m.y. (R. Page, pers. comm.). To the west of Mount Isa, Carpentarian sequences are overlain by younger Proterozoic sediments of the South Nicholson Basin, considered to have an early Adelaidean age (1000-1400 m.y.). Both Carpentarian and early Adelaidean sedimentary basins are unconformably overlain by younger sediments of the Georgina Basin, which contains rocks varying in age from latest Proterozoic (late Adelaidean) to mid-Ordovician.

The oldest rocks of the Mount Isa region form a basement inlier, some 300 km long and 30 km wide, known as the Kalkadoon-Leichhardt Block. This basement succession comprises acid volcanics, ash flows, metabasalts and quartzites of the Tewinga Group and the Argylla Formation. To the east and west, the Kalkadoon-

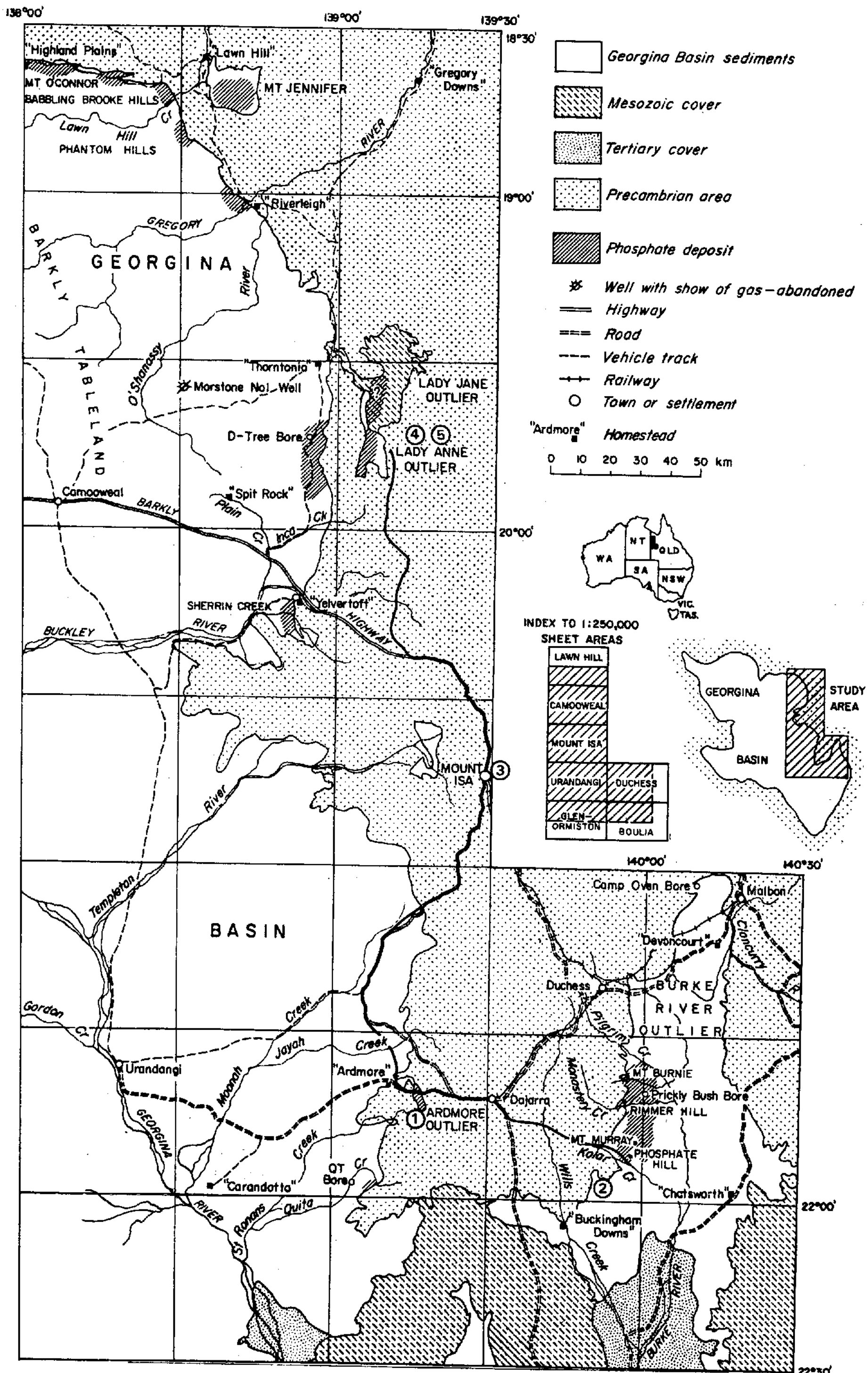


Fig.2 General route taken during field workshop:
to Day 1 August 15th
Day 5 August 19th

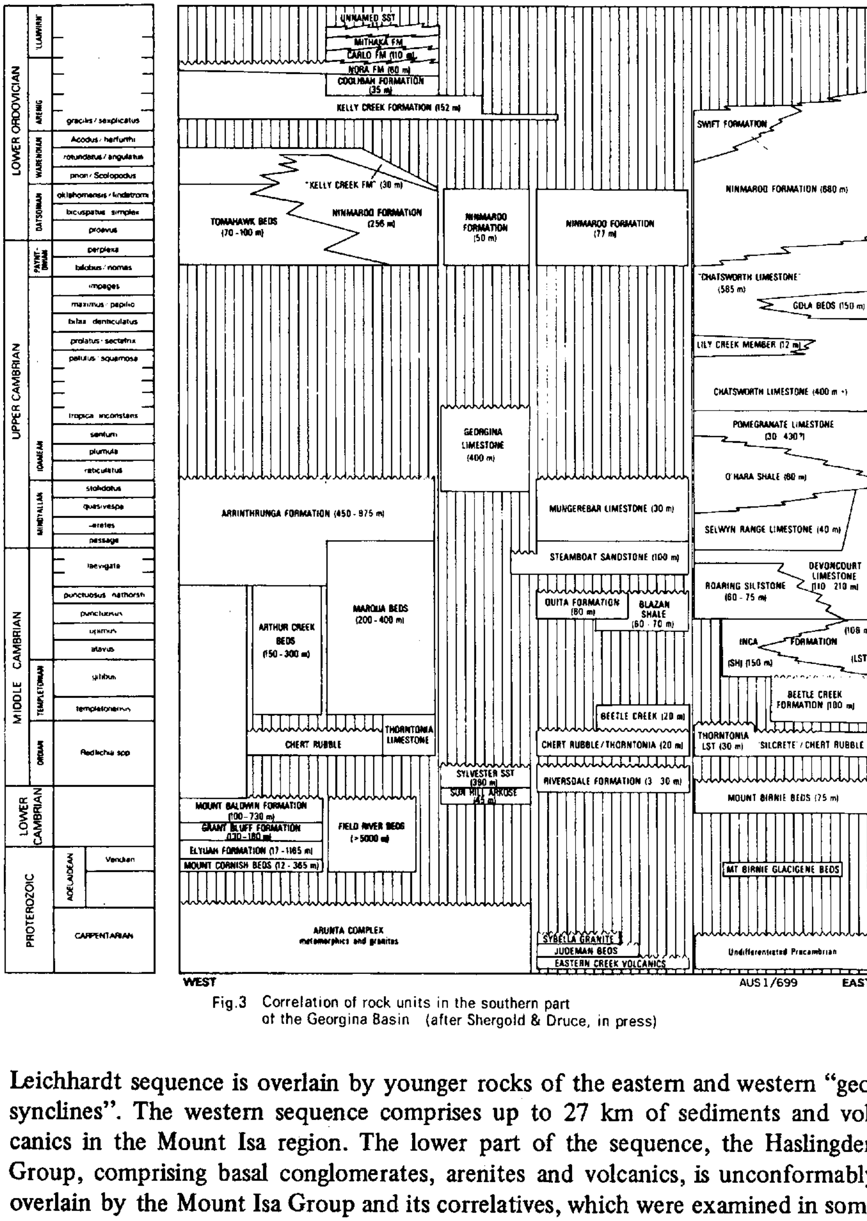


Fig.3 Correlation of rock units in the southern part of the Georgina Basin (after Shergold & Druce, in press)

Leichhardt sequence is overlain by younger rocks of the eastern and western "geosynclines". The western sequence comprises up to 27 km of sediments and volcanics in the Mount Isa region. The lower part of the sequence, the Haslingden Group, comprising basal conglomerates, arenites and volcanics, is unconformably overlain by the Mount Isa Group and its correlatives, which were examined in some detail in the Mount Isa Mine, in the Mount Isa Valley, and in the Lady Annie area. At Mount Isa, where the group is about 5000 m thick, the sequence comprises a coarse arenaceous unit at the base (Warrina Park Quartzite) followed by more lutaceous/calcareous units, including the Urquhart Shale – a particularly important unit because it is the host rock of the stratiform Ag-Pb-Zn deposits of the Mount Isa and Hilton Mines (Table 1). The Mount Isa sequence comprises for the most part fine grained, finely laminate siltstones, claystones, calcareous claystones and calcilutites. The discovery by McClay and Carlile (1978) of gypsum pseudomorphs in the Silica Dolomite, a facies equivalent of the Urquhart Shale, indicates either hypersaline depositional or post-depositional conditions occurred in at least part of

Table 1 Mount Isa Group sequence of the Mount Isa Valley (after Derrick 1974).

Unit	Approx. thickness (m)	Rock type
Magazine Shale	200	Calcareous shale, some pyrite.
Kennedy Siltstone	300	Siltstone, feldspathic quartzite.
Spear Silstone	170	Dolomitic siltstone, shale, albite marker.
Urquhart Shale	900	Ferruginous pyritic laminate dololutite K-rich tuff; Cu, Ag, Pb, Zn ores.
Native Bee Siltstone	800	Dolomitic siltstone, minor tuffs.
Breakaway Shale	1000	Grey shale, minor siltstone.
Moondarra Siltstone	1200+	Dolomitic siltstone, shale.
Warrina Park Quartzite	70-700	Orthoquartzite, feldspathic cross-bedded quartzite, conglomerate, minor siltstone.

the sequence. To the north of Mount Isa, in the Paradise Creek-Lady Annie area (Fig. 2), rocks of the Paradise Creek Formation believed to be equivalent in age to the Mount Isa Group (Cavaney 1975), are stromatolitic. This predominantly calcareous and partly siliceous (e.g. Esperanza Chert) sequence provides good evidence of shallow water hypersaline depositional conditions.

Cambrian

The Carpentarian and early Adelaidean rocks are overlain by sedimentary and thin volcanic sequences deposited on a broad epi-continental shelf, the Georgina Basin (Fig. 1). Shergold and Druce (in press) suggest that the Georgina Basin contains three tectono-stratigraphic units referred to as Tectotopes 1, 2 and 3 (Fig. 3), ranging in age from latest Proterozoic to Ordovician.

Tectotope 1, of Vendian (late Adelaidean) to Early Cambrian (Tommotian) age is composed predominantly of clastic sediments, with some dolomites. The sequence is glaciogenic at the base (Preiss *et al.* 1978), whereas the upper units may be paralic and shallow marine. In the middle part of the Early Cambrian (Atdabanian) the coarser detrital sediments give way to some carbonates. Volcanic rock occur towards the top of this tectotope. Sediments of Tectotope I are best developed on the southern margin of the basin. However, a thin, incomplete section is present in the Burke River Structural Belt to the south of the Duchess (de Keyser 1968, 1973).

Tectotope 2, ranges in age from early Middle Cambrian to Early Ordovician (early Arenigian). It comprises a basal arkosic sandstone (in part fluvial), and some thin volcanics which may in part by synchronous, or in places immediately post-date, the sandstone. The sequence is followed by interbedded carbonates and terrigenous clastics with thin evaporites, claystones, phosphorites and cherts in its lower part. Environments range from supratidal to shallow marine.

Tectotope 3, is confined to the southern and southeastern margins of the Georgina Basin and was not examined during the Workshop. The sequence, which is Early Ordovician (mid Arenigian to ?Llandeillian) in age, comprises some 550 m of arenites with basal carbonate units forming the Toko Group (Kelly Creek Formation, Coolibah Limestone, Nora Formation, Carlo Sandstone, Mithaka Formation and Ethabuka Beds). Phosphorite occurs locally in the Nora Formation (Reynolds & Pritchard 1965).

Table 2 Cambrian units in the vicinity of major phosphate deposits visited during field workshop, Mount Isa region.

Duchess	**Ardmore**	**Lady Annie**
Inca Formation	Blazan Shale	Inca Formation
	Beetle Creek Formation	
Monastery Creek Phosphorite Member	Simpsons Creek Phosphorite Member	Phosphorite
Lower Siltstone Member	Lower Siltstone Member	Siltstone
	Chert Member of the Thorntonia Limestone	
	karst surface	
	Thorntonia Limestone	
Mount Birnie Beds	Riversdale Formation	Mount Hendry Formation
	unconformity	
	Carpentarian rocks	

The attention of the Field Workshop was focussed on the Cambrian rocks of Tectotope 2 in the Ardmore, Duchess and Lady Annie areas (Figs 4, 5, 6). In these areas the sequence commences with a basal sandstone-conglomerate and vari-coloured mudstone unit referred to the Riversdale Formation in the Ardmore area, Mount Hendry Formation in the Lady Annie area, and the upper part of the Mount Birnie Beds in the Burke River area (Table 2). The unit is variable in thickness, reaching a maximum of 30-50 m. It is believed to be in part a fluvial deposit possibly becoming paralic towards the top, where it is dolomitic in places. In the northern and western parts of the basin there are thin (max. 60 m) basic to intermediate volcanics known as the Peaker Piker and Colless Volcanics (Fig. 2) which are probably partly equivalent to the extensive Antrim Plateau Volcanics. Although imperfectly known, their age probably ranges from Early to Middle Cambrian, and they may be in part synchronous with the basal sandstone units. In places, however, the Middle Cambrian carbonates directly overlie the Colless Volcanics and there is no basal sandstone unit.

The first macropalaeontologically dateable sediments of the Georgina epeiric shelf north of present latitude 22°S were deposited during the early Middle Cambrian, Late Ordian Zone of *Redlichia chinensis,* during the first major submergence of the Georgina Basin and surrounding basins. The Thorntonia Limestone and its correlatives, which form part of an extensive dolomite lithosome, are generally platy dolomite, passing upwards into more massive algal dolomite, often biohermal. The distribution of bedded Thorntonia Limestone is variable even within localised areas. Patches of massively bedded limestone and dolomite frequently alternate with patches of chert, silicified carbonate rubble and ferruginised silicified breccia. De Keyser and Cook (1972) proposed a supratidal environment for much of this Formation. In many places the Thorntonia Limestone is capped by a Chert Member from which the surface chert rubble is presumably derived. Recent work by Southgate and Henderson (see Henderson & Southgate 1978; Southgate & Henderson, in press), particularly in the Ardmore area, provides new evidence of an evaporitic depositional environment. In the vicinity of stop 1 (Fig. 4) in the Ardmore outlier,

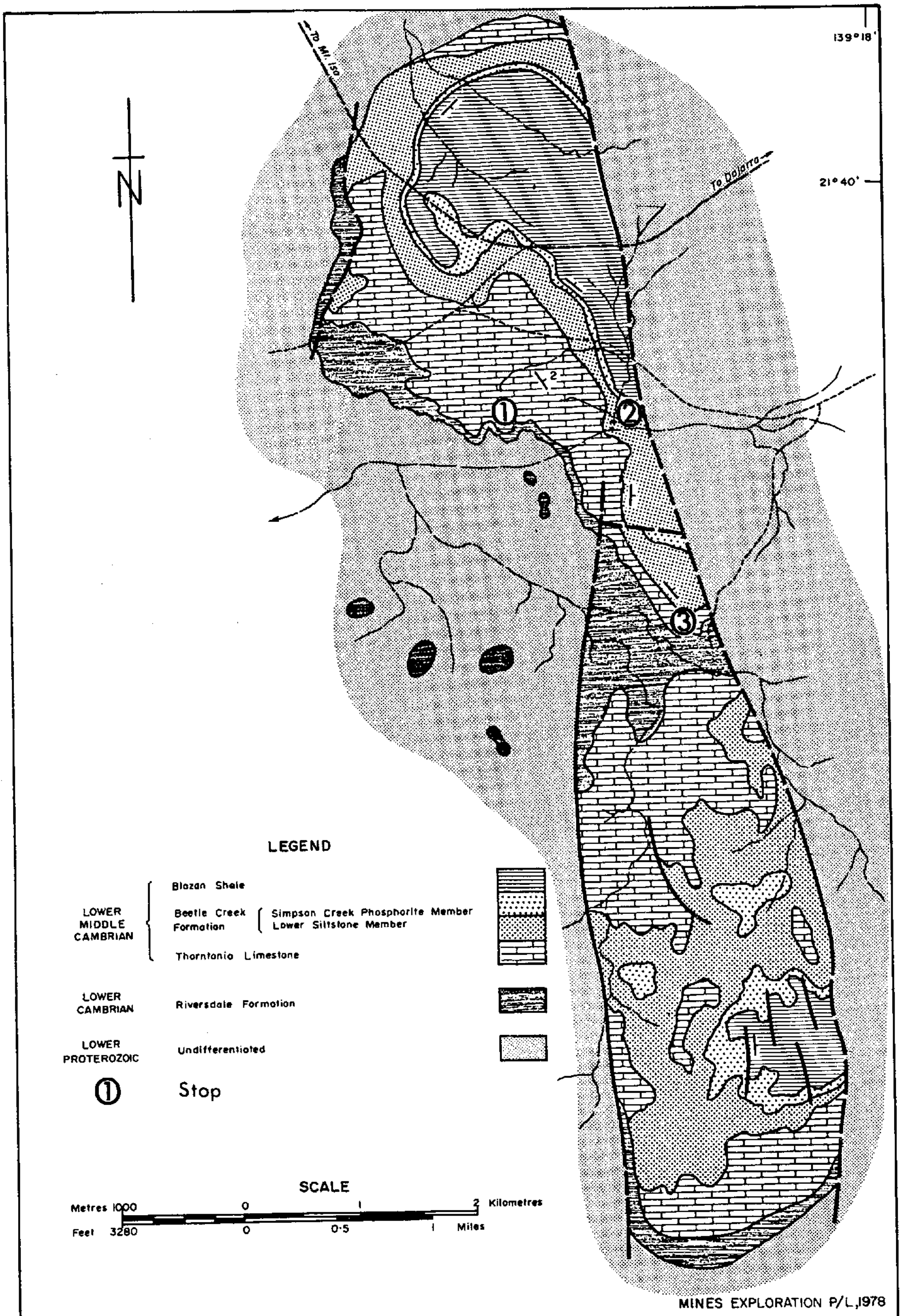


Fig.4 Geological plan, Ardmore outlier

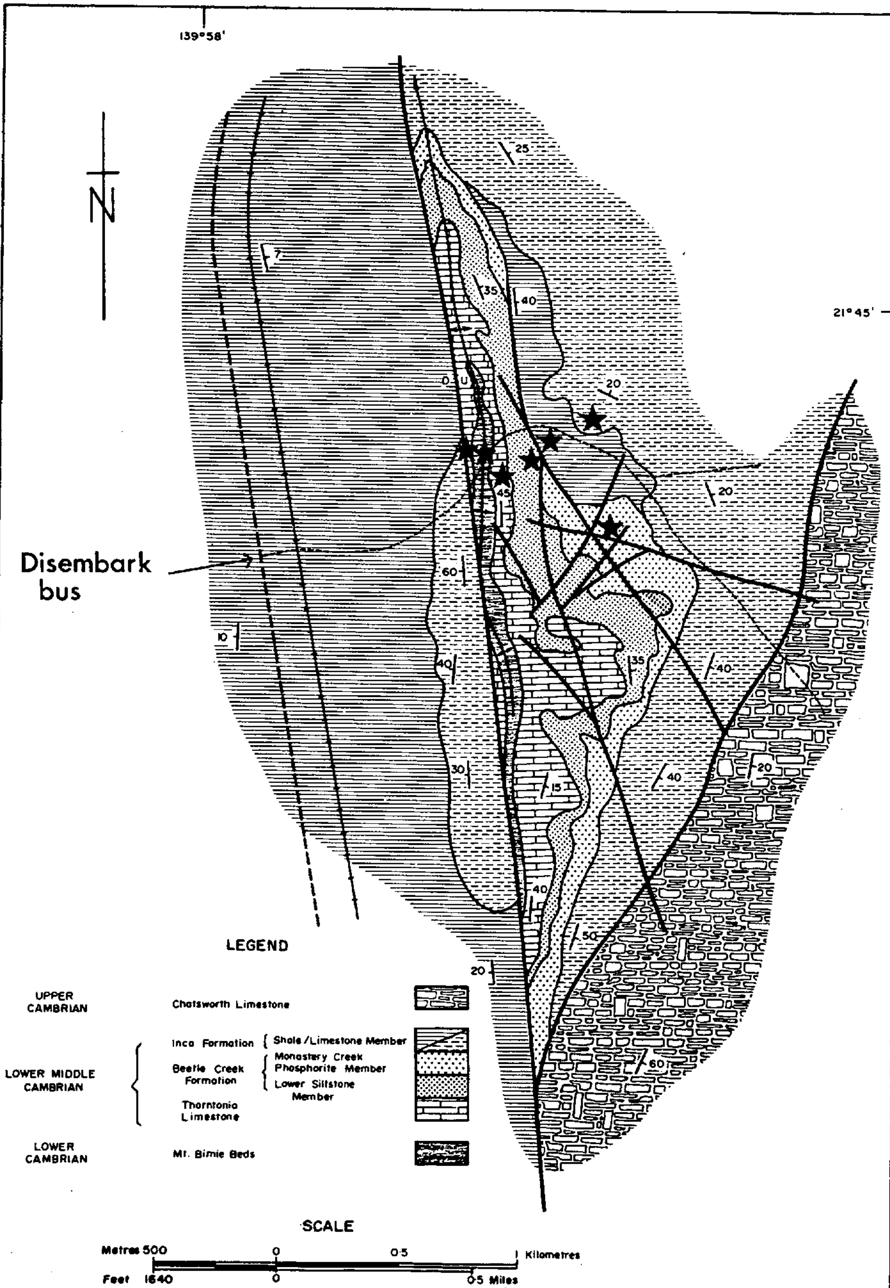


Fig.5 Geological plan, Rogers Ridge (Stop 4)

AUS 1/737

MINES EXPLORATION P/L, 1978

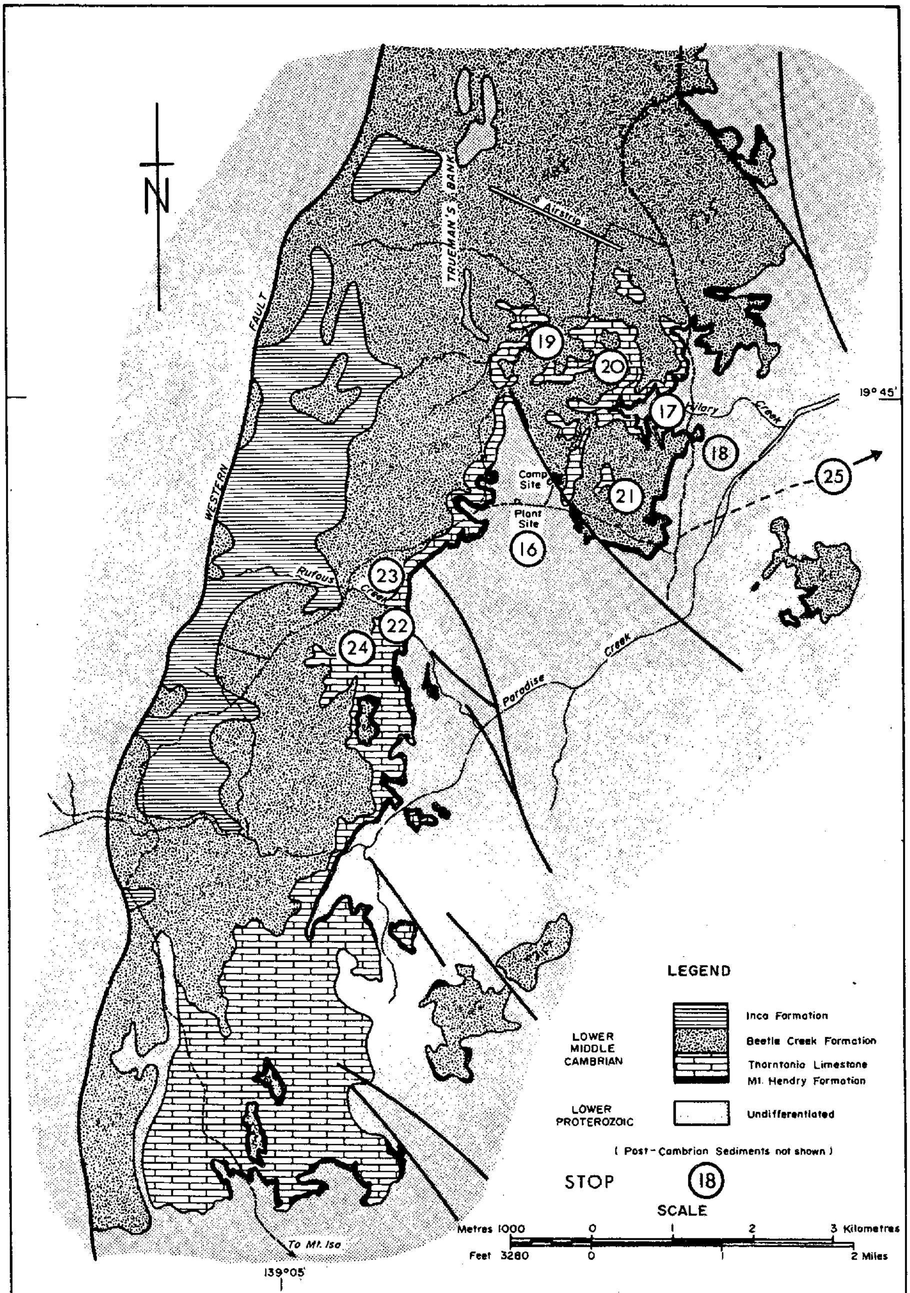


Fig.6 Interpretive Cambrian geology, Southern Lady Annie area, Northwestern Queensland

AUS 1/740

MINES EXPLORATION P/L, 1978

it is possible to recognise various types of chert, some of which are quite clearly after evaporites. Stromatolitic textures, and gypsum, anhydrite and halite pseudomorphs are all consistent with hypersalinity. Some of the evaporite minerals are demonstrated by Southgate and Henderson to have formed in standing pools; others appear to have formed within unconsolidated muds. There is abundant evidence of brecciation, probably associated with solution collapse. Prior to the deposition of the Lower Siltstone Member of the Beetle Creek Formation during the early Templetonian, the upper surface of the Thorntonia Limestone was subjected to a period of subaerial erosion. In some areas a karst topography can be recognised, and in others a ferruginised surface, enriched in base metal ions, occurs on the Thorntonia Limestone. The evaporite unit associated with the Chert Member of the Thorntonia Limestone appears to interdigiate with the Thorntonia Limestone in some areas, in others to overlie it. Possibly the evaporites developed in restricted pools on the eroded irregular Thorntonia Limestone surface during a latest Ordian regression, and may represent the conclusion of a transgressive/regressive cycle.

The Beetle Creek Formation and its correlatives the Border Waterhole Formation and the Burton and Wonarah Beds, make up a chert-siltstone-limestone-phosphorite lithosome. Generally it overlies the Thorntonia Limestone (including the Chert Member); more rarely, for instance at stop 3 (Fig. 4), it overlies the Riversdale Formation (or its equivalent) with a fairly marked disconformity. In some places, a Thorntonia Limestone-like carbonate may be laterally equivalent to the basal Beetle Creek Formation which typically consists of siliceous claystones, siltstone, and fine grained sandstone, chert, thin limestone, and phosphorite, deposited during the Templetonian Zones of *Xystridura templetonensis* and *Ptychagnostus gibbus.* Fleming (1974, 1977) regards the cherts as silicified carbonates, and the whole formation as representing a diagenetically altered quartz-carbonate lithosome. In the Duchess area, where the Beetle Creek Formation is divided into a basal Lower Silstone Member and an upper Monastery Creek Phosphorite Member (Russell 1967), the Lower Siltstone Member, which is typically a laminated weakly phosphatic, quartz-siltstone/shale containing articulated and/or disarticulated but undisturbed trilobite exuviae, appears to represent a low energy, shallow subtidal environment, and the deepest phase of the Beetle Creek transgression. The overlying chert-phosphorite-shale association of the Monastery Creek Phosphorite Member, comprising mainly pelletal siliceous and pelletal calcareous phosphorites, represents marked shoaling. The fauna, invariably disarticulated trilobite remains, infaunal bradoriid crustacea, inarticulate brachiopods, molluscs, and comminuted pelmatozoan debris, may have accumulated in skeletal sand shoals either close to a shoreline or on and around topographic highs. The dual division of the Beetle Creek Formation applies to the Duchess and Ardmore areas. At Lady Annie the dominant lithology is phosphatic and cherty siltstone, intercalated with friable coarse pelletal phosphorite and finer grained phosphorites (Rogers and Keevers 1976, p. 257). Bedded chert, silicified coquinite, siliceous siltstone and chert breccia also occur. There is evidence in the Lady Annie area that lithologies of Thorntonia Limestone type were locally deposited contemporaneously with the basal Beetle Creek Formation.

The overlying "silt-shale-chert lithosome" includes such units as the Inca Formation, Blazan Shale, Lancewood Shale and Roaring Siltstone. These units range into the late Middle Cambrian and intertongue laterally with a contemporaneous limestone lithosome which itself shows intertonguing relationships with other lithosomes. The intertonguing relationship is well developed in the Rogers Ridge area

(Fig. 5) where fine laminate cherts (Inca Formation) containing sponge spicules and agnostid trilobites, interdigitate with highly bituminous laminate limestones. The limestone lithosome which ranges into the Late Cambrian, includes the Chatsworth, Pomegranate, Selwyn Range, Devoncourt, Mungerebar, V-Creek, Currant Bush and Mail Change Limestones. There are a variety of sediment types, including grainstone, micrite, sandy limestone, oolitic limestone, dolomitic limestone, siliceous limestone and slightly phosphatic limestone. Interbedded with the limestones are calcareous mudstones and intraformational breccias. Evidence of shallow water origin is abundant. Southgate (pers. comm.) reports gypsum pseudomorphs in the Currant Bush and V-Creek Limestones, suggesting at times a supratidal environment for these units.

The Georgina Basin Phosphate Deposits

Prior to the discovery of the Georgina Basin deposits in 1966-1968 there were no known major phosphate deposits in Australia. As Australia was using in excess of 2 million tonnes of phosphate rock a year, the great majority of which was imported, the Federal Government began actively encouraging mining companies to prospect in the early 1960's. In 1965-1966 R.P. Sheldon pointed out the need to explore the correct type of phosphogenic province, and particularly basins which included black shale-cert-limestone assemblages. He further predicted that the Tasman Geosyncline in eastern Australia and the Georgina Basin of northwest Queensland contained potential phosphogenic sequences. A Bureau of Mineral Resources study of some of the oil wells which had penetrated Lower Palaeozoic sediments in the Georgina Basin had disclosed an unusually high phosphate content in the Middle Cambrian Thorntonia Limestone. In collaboration with officers of B.M.R., Mines Exploration Pty Ltd (MEPL), a subsidiary of BH South Ltd, made investigations of oil-well samples from the Georgina Basin, which showed that a phosphatic facies was present in two Middle Cambrian formations of regional significance, the Beetle Creek Formation and the Thorntonia Limestone. These were present in all of the wells tested, but usually at a depth far below that at which phosphate could be mined economically. Particular attention was directed to the south-eastern part of the Basin where in the Black Mountain No. 1 and The Brothers No. 1 oil-wells, phosphorites were found associated with black dolomitic shales and cherts in the Beetle Creek Formation. Having established that the phosphate occurred within this formation, MEPL undertook prospecting over a number of areas near Duchess and around the eastern margin of the Georgina Basin, where the Beetle Creek Formation and its equivalent, the Border Waterhole Formation, crop out. Prospecting south of Duchess in August 1966 was immediately successful, with phosphorites being found within three days of the commencement of prospecting. Other tenements were subsequently prospected by MEPL, resulting in the discovery of a further nine deposits (Fig. 7) including Ardmore, Quita Creek, Lady Annie, Lady Jane, Riversleigh, Mount Jennifer, Babbling Brook Hill, Phantom Hills, Mount O'Connor and Highland Plains.

At about the same time several other companies were also active in the area (Howard 1972). In November 1966, Continental Oil intersected phosphate in the Yelvertoft area which in early 1967 proved to represent a major portion of the Sherrin Creek deposit and a minor portion of the D Tree deposit. Scout drilling by IMC Development in October 1966 intersected low-grade phosphorite, and further

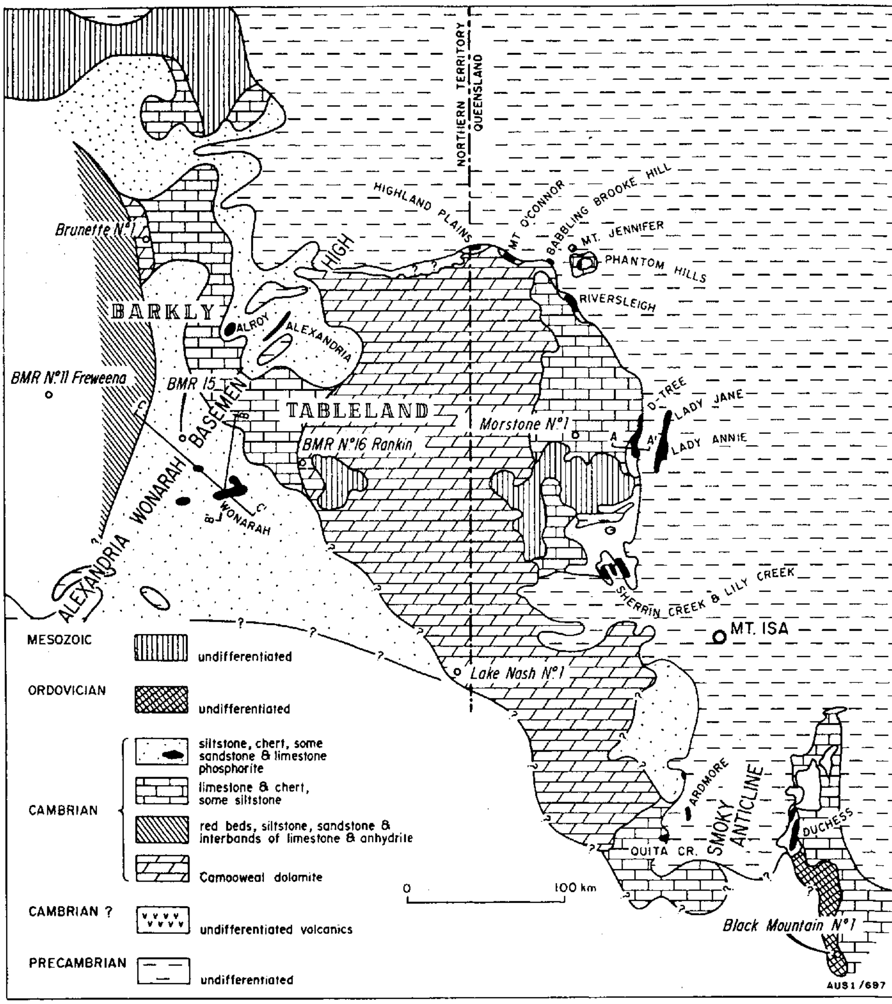


Fig.7 Location of major phosphate deposits in the Georgina Basin (after Howard, 1972)

drilling, begun in early 1967, proved the major portion of the D Tree deposit (Howard and Cooney 1976) and a minor portion of the Sherrin Creek deposit. The search for deposits by IMC was subsequently extended west into the geologically more remote areas adjacent to the Wonarah-Alexandria Basement High (Fig. 7). The location had many aspects in common with the location of known phosphate deposits adjacent to the Leichhardt-Kalkadoon Block. Poor outcrop necessitated using sub-surface information. Eleven abandoned water bores were located over a traverse distance of 160 km and logged with a down-hole scintillation probe. Of the eleven, seven had similar anomalous gamma-ray patterns. Drilling proved that these anomalies reflected phosphorite within a siltstone-chert–carbonate sequence. Two other deposits were found along the axis of the basement: the first was the Alexandria deposit which was found by scout drilling between two Precambrian inliers; and the second, Alroy, was found by a scout drilling program along the axis of one of the small inliers. The stated ore reserves for the various deposits are indicated in Table 3.

Table 3 Ore Reserves, Georgina Basin Phosphate Deposits

Name of deposit	Reserves: Measured Tonnes $(x10^6)$	Measured Grade $\%P_2O_5$	Indicated & inferred Tonnes $(x10^6)$	Indicated & inferred Grade $\%P_2O_5$	Lease Holder	Source of information
Duchess*) Ardmore)	504	18.3	914	16.9	BHS	1
Quita Creek					ICI-AFL	
Lady Annie) Lady Jane)	486	17.0			BHS	1
Sherrin Creek			233	16.0	IMC-ICI-AFL	3
Lily Creek			212	13.4	IMC-ICI-AFL	3
D Tree	250	18.6			IMC-ICI-AFL	
Riversleigh			11	14.4	BHS	2
Phantom Hills			46	16.0	BHS	2
Mt Jennifer			20	15.3	BHS	2
Babbling Brook Hill			38	16.8	BHS	2
Mt O'Connor			42	17.4	BHS	2
Highland Plains			84	13.4	BHS	2
Wonarah			900	15.7	ICI-AFL	3
Alexandria						
Alroy						

* BH South Limited reported that the Phosphate Hill zone contains 315 m tonnes of 18.3% P_2O_5, and within this zone there are 20 m tonnes of "direct shipping" rock with a grade in excess of 31% P_2O_5.
1 – Rogers and Keevers (1976).
2 – Queensland Govt Mining Jour., v. 78, No. 907 (1977).
3 – Howard (1972).

Duchess

To date, only the Duchess deposit has been mined. Operations by Queensland Phosphate Ltd commenced in 1976 and were suspended in 1978. In the main pit area of the deposit (T15-T18) there are ten distinctive lithological units in the Monastery Creek Phosphorite Member (Fig. 8). Unit 2, the highest grade ore, was until recently mined as direct shipping grade ore. The ten units are laterally continuous and can be used for correlation in the immediate area and for mining control (Fig. 9). The ore is dominantly pelletal with only minor laminae of "collophane mudstone". In the southern part of the deposit the sequences are not readily correlatable lithostratigraphically with those in the vicinity of Phosphate Hill, and company geologists divide the sequence at the V 9 Excavation into Units A-E. Of these, units E-D contain high grade direct shipping ore over a 7 m interval. Unit A represents a subsoil phosphatic calcrete overlying various units of the Monastery Creek Phosphorite Member. At V 9 collophane mudstone and chert are even less abundant than at the excavation to the north; the sequence is more heavily faulted; and on one excavation face, the phosphatic sequence is seen to pass abruptly into massive breccia which extends from top to bottom of the excavation, and is polygonal in plan. Large included angular blocks of the Inca Formation and Monastery Creek Phosphorite Member are up to several metres across. The contact with bedded phosphorite is very sharp. At one margin "terra rosa" type brecciation occurs. The breccia appears to be a collapse breccia, but there is disagreement on the precise collapse mechanism involved.

INCA FORMATION						
BEETLE CREEK FORMATION	MONASTERY CREEK PHOSPHORITE MEMBER	Unit 1	·27m	16 %	Sandy Phosphorite, Collophane Mudstones	Shale Marker
		Unit 2	2·32m	31·5 %	Indurated and Sandy Phosphorite	
		Unit 3	2·15m	14 %	Chert Phosphorite Silts and Shales	Chert Marker
		Unit 4	1·19m	29 %	Indurated and Sandy Phosphorite some Chert and Siliceous Phosphorite	
		Unit 5	1·45m	18 %	Chert Phosphorite Silts and Shales	
		Unit 6	1·47m	28 %	Phosphorite, Siliceous Phosphorite Phosphorite some Chert	Shale Marker
		Unit 7	0·38m	11 %	Siliceous and Phosphatic Siltstones	
		Unit 8	0·45m	27 %	Phosphorite and Chert	Collophane Marker
		Unit 9	0·36m	16 %	Phosphatic Siltstones	
		Unit 10	0·57m	23 %	Phosphorite, some Chert, minor Clastics	
	LOWER SILTSTONE MEMBER				Siliceous Siltstones	

Fig.8 Detailed stratigraphic section exposed in trenches, northern part of Phosphate Hill zone

AUS 1/738

MINES EXPLORATION P/L 1978

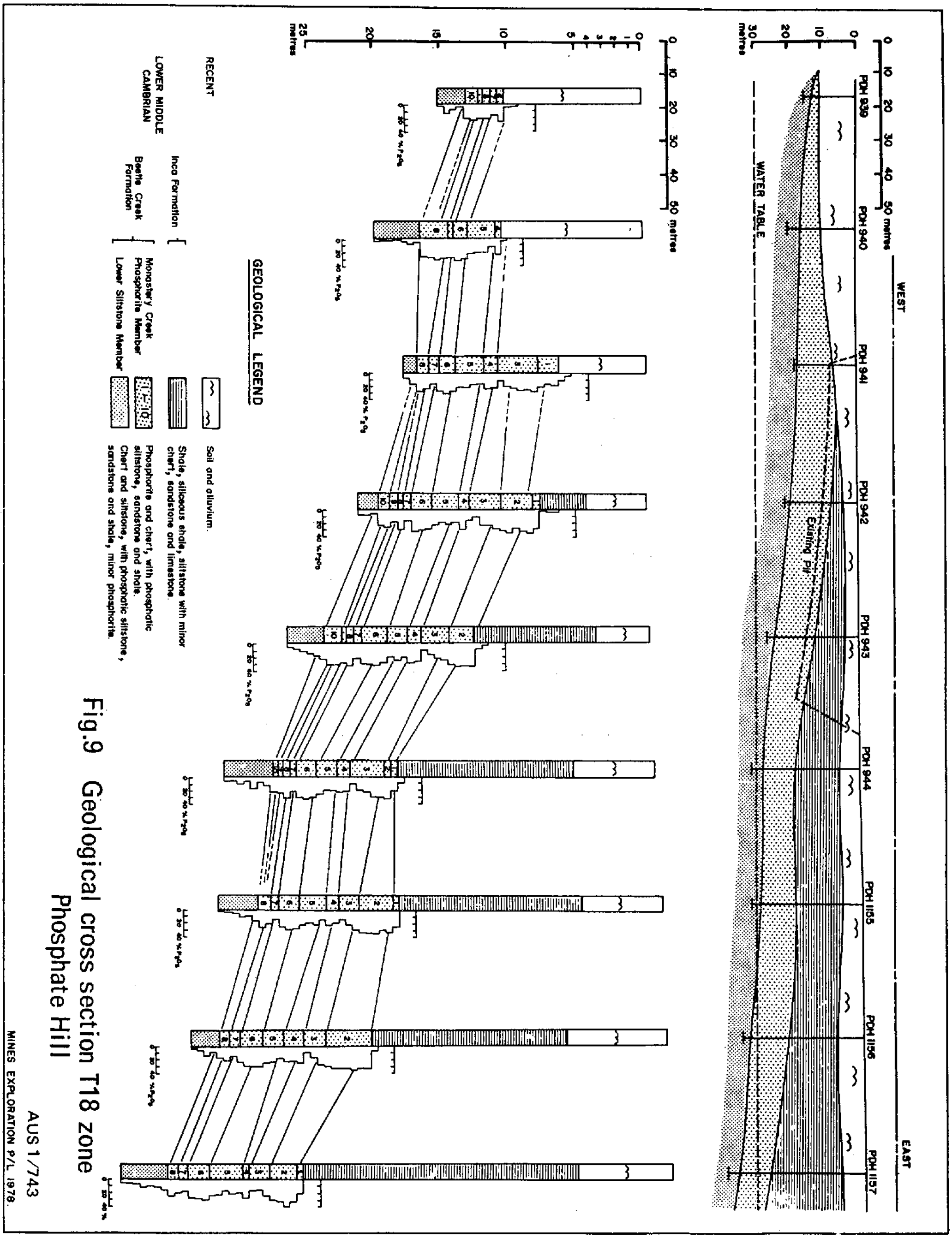


Fig.9 Geological cross section T18 zone Phosphate Hill

Ardmore

The main phosphate ore horizon in the Ardmore deposit (Fig. 4) is also predominantly pelletal with only a few thin bands of "collophane mudstone". Substantial reserves of ore are present in the Ardmore deposit but no mining operations have been undertaken to date. At locality 3 (Fig. 4) a thin pelletal phosphorite is present at the base of the Beetle Creek Formation. This is overlain by a thin high grade phosphorite of probable secondary origin termed a "phoscrete" (Cook 1972). The apparent association of this phoscrete with Tertiary silcretes and ferricretes support a Tertiary age for the phoscrete, however the possibility of it being of Cambrian age cannot be completely discounted.

Lady Annie

Both pelletal and non-pelletal phosphorites are present in the Lady Annie deposit, though the important ore is pelletal. A prominent topographic feature, Truemans Bank, divides the deposit into Eastern and Western Zones (Rogers and Keevers 1976). Non-pelletal phosphate is abundant in the Eastern Zone. In the vicinity of Replacement Hill (locality 19, Fig. 6), it is not possible to establish with any certainty whether some fine grained phosphorites are Tertiary phoscretes (their location on the top of the hill would support this), Cambrian phoscretes, weathered collophane mudstones, or replacement phosphorites. A particular feature of this locality is the occurrence of *Redlichia* sp. in collophane mudstone, implying an Ordian age, which would make these the oldest phosphates in the Georgina Basin. A puzzling feature of the Hillary Creek area (stop 20, Fig. 6) is an extremely irregular surface of Thorntonia Limestone overlain by white very fine grained partly brecciated phosphorite. This outcrop, illustrated by de Keyser and Cook (1972, plate 18, fig. 1), is interpreted as an infilled karst surface or as a carbonate replacement phenomenon. An equally puzzling exposure is present in the so-called "Microsphorite Trench" (stop 21, Fig. 6) where a fairly thick unit of partly brecciated fine grained non-pelletal phosphorite (variously called microsphorite, collophane mudstone, mudstone phosphorite or phospholutite) is well developed. Large grey irregular chert masses are a feature of the unit here, the origin of which is uncertain. There is abundant evidence of strong weathering, sub-aerial exposure, and erosion. However, the age of this weathering is again uncertain, with opinion ranging from it being Cambrian, i.e. a primary sediment, to representing the end product of more recent weathering of a pelletal unit (?Tertiary).

Truemans Bank appears to have been an important Cambrian topographic high which had a profound influence on the Lady Annie sediments. On the west side, in marked contrast to the east, the main ore (visible in the vicinity of localities 22, 23 and 24, Fig. 6) consists of several metres of high grade predominantly pelletal phosphorite exposed in creek beds, and particularly in excavations. Collophane mudstones are present only as thin laminae. Fossil debris, much now phosphatised, is common in these phosphorites. The sections show small scale faulting and some gentle broad folding, but overall, structural deformation is minor. A puzzling feature in some of these exposures is the breccias. In some places they appear to by syn-sedimentary, but most are probably later-stage features showing cross-cutting relationships with the bedding, and are perhaps related to collapse sink holes in the underlying Thorntonia Limestone.

References

Cavaney, R.J., 1975. Stratigraphic and structural controls to copper mineralisation in the Mt Isa-Lawn Hill district, north-west Queensland. *M.Sc. Thesis, James Cook Univ.* (unpubl.).

Cook, P.J., 1972. Petrology and geochemistry of the phosphate deposits of north-west Queensland, Australia. *Econ. Geol.*, 67: 1193-1213.

De Keyser, F., 1968. The Cambrian of the Burke River Outlier. *Bur. Miner. Resour. Aust. Geol. Geophys. Rec.* 1968/67 (unpubl.).

De Keyser, F., 1973. Review of the Middle Cambrian stratigraphy in the Queensland portion of the Georgina Basin. *Bur. Miner. Resour. Aust. Geol. Geophys. Bull.* 139: 13-27.

De Keyser, F. & Cook, P.J., 1972. Geology of the Middle Cambrian phosphorites and associated sediments of northwestern Queensland. *Bur. Miner. Resour. Geol. Geophys. Aust. Bull.,* 138: 79 pp.

Derrick, G.M., 1974. Stratigraphic and palaeogeographic evolution and revolution in the Mount Isa area. *Aust. Inst. Min. Metall., N.W. Qld Brch Regnl Mtg, 1977:* 177-187.

Fleming, P.J.G., 1974. Origin of some Cambrian bedded cherts, and other aspects of silicification of the Georgina Basin, Queensland. *Geol. Surv. Qld Publ.,* 358: 9 pp.

Fleming, P.J.G., 1977. Faunas, lithologies, and the origin of phosphorites in parts of the Middle Cambrian Beetle Creek Formation of northwest Queensland. *Geol. Surv. Qld Publ.,* 364: 21 pp.

Henderson, R.A., & Southgate, P.N. 1978. Middle Cambrian stratigraphy and sedimentology of the eastern Georgina Basin. *3rd Aust. geol. Conv. T'ville, Excursns Hndbk:* 85-110.

Howard, P.F. 1972. Exploration for phosphorite in Australia – a case history. *Econ. Geol.,* 67(8): 1180-1192.

Howard, P.F. & Cooney, A.M., 1976. D Tree phosphate deposit, Georgina Basin, Queensland. *In:* Knight, C.L. (Ed.), Economic Geology of Australia and Papua New Guinea, 4. Industrial minerals and rocks. *Aust. Inst. Min. Metall. Monogr. Ser.,* 8: 265-273.

McClay, K.R., & Carlile, D.G. 1978. Mid-Proterozoic sulphate evaporites in the Mt Isa Mine, Queensland, Australia. *Nature,* 274: 240-241.

Preiss, W.V., Walter, M.R., Coats, R.P. & Wells, A.T., 1978. Lithological correlations of the Adelaidean glaciogenic rocks in parts of the Amadeus, Ngalia and Georgina Basins. *BMR J. Aust. Geol. Geophys.,* 3: 48-53.

Reynolds, M.A. & Pritchard, P.W., 1964. The geology of the Glenormiston 1:250,000 Sheet area. *Bur. Miner. Resour. Geol. Geophys. Aust. Rec.,* 1964/28 (unpubl.).

Rogers, J.K. & Keevers, R.E., 1976. Lady Annie-Lady Jane phosphate deposits, Georgina Basin, Queensland. *In:* Knight, C.L. (Ed.), Economic Geology of Australia and Papua New Guinea, 4. Industrial minerals and rock. *Aust. Inst. Min. Metall., Monogr. Ser.,* 8: 251-265.

Russell, R.T., 1967. Discovery of major phosphate deposits in northwest Queensland. *Qld Govt Min. J.,* 68: 153-157.

Russell, R.T. & Trueman, N.A., 1971. The geology of the Duchess phosphate deposits, northwestern Queensland, Australia. *Econ. Geol.,* 66: 1186-1214.

Shergold, J.H., & Druce, E.C., (in press). The Upper Proterozoic and Lower Palaeozoic rocks of the Georgina Basin. *In* Henderson, R.A., & Stephenson, P.J. (Eds). *The geology of north-eastern Australia.* Proc. 3rd Aust. geol. Conv. Townsville.

Southgate, P.N., Henderson, R.A., & Hamilton, K.W., (in press). Sedimentary and replacement history of a bedded evaporite sequence pseudomorphed by chert. *J. sedim. Petrol.*

The Seminar

Introduction

The Seminar was directed towards understanding the geology of sedimentary phosphate deposits of Proterozoic and Cambrian age, particularly those of the Asian-Australian region; however, these deposits could not (and should not) be looked at in isolation. Consequently, deposits of similar age in Europe, Africa, and South America were also considered during the seminar. To place these deposits in a global perspective, emphasis was placed on the palaeogeography of the latest Proterozoic to Mid-Cambrian interval, and the relevance of lithospheric plate theory to models of phosphogenesis.

Geologically young phosphate deposits were also considered during the course of the Seminar because of their importance as analgoues to less well known ancient deposits, and contemporary phosphogenesis was necessarily considered, in order that, following the fundamental Huttonian tenet that 'the present is the key to the past', our knowledge of ancient phosphorites may be enhanced.

Papers given at the Seminar are published here in the form of abstracts or extended abstracts. Mostly these papers will be published in internationally recognised sources. Three papers, however, are published in full in an appendix to this volume. These include a global review of Precambrian and Cambrian phosphate occurrences compiled by A.J.G. Notholt, and a paper by P.A. Trudinger on the microbiological controls on phosphate accumulation. Since it was not intended to publish these papers elsewhere, and since they are of considerable interest and value to IGCP Project 156, we agreed to include them here. The third paper, on the role of dinoflagellates in phosphogenesis by D. Fauconnier and M. Slansky was intended to be published in a French journal. The editors have decided to take the opportunity to publish the paper in its English form thus ensuring a wider audience. We feel that these three papers will make valuable additions to the phosphate literature.

Seminar sessions commenced with papers on the spatial and temporal distribution of phosphorites and possible models of phosphogenesis. They were followed by detailed accounts of aspects of the geology of the phosphatic sediments of the Georgina Basin which gave the opportunity to bring some of the field observations made at the Workshop and theory together. Details were then presented, on a region by region basis, of phosphate deposits in the People's Republic of China, India, the Union of Soviet Socialist Republics, Europe, western Africa, and Brazil. Accounts of young phosphogenic systems in Florida and contemporary systems off Peru, and Chile in the east Pacific, on Chatham Rise in the west Pacific, and off Southwest Africa in the southern Atlantic were given, together with details of the geochemistry of contemporary systems. Discussion arising from all of these reports is published here.

We also include what are essentially interim reports of two special sessions. The first is on the problems involved in classifying phosphorites, the second of the development of a phosphate raw material data base. The reports in this volume will, we hope, stimulate discussion and provide the base from which to eventually develop viable systems for both these important areas.

Phosphogenic Models and the General Distribution of Phosphorites

Resources of Precambrian and Cambrian Sedimentary Phosphate Rock*
by *Arthur J.G. Notholt,* Institute of Geological Sciences, London

The extent of the known resources of Precambrian and Cambrian sedimentary phosphate rock is discussed. Some 92 occurrences of Precambrian or Cambrian sedimentary phosphate rock are recorded in the literature, of which those in Australia, Brazil, China, India, Korea, the USSR and Vietnam have been or are being worked on a commercial scale. Total estimated resources appear to amount to over 10,000 million tonnes of phosphate rock containing more than 4 per cent P_2O_5. However, only a very small proportion of this resource is likely to be commercially attractive at present.

At least one extensive Lower Palaeozoic (predominantly Cambrian) phosphate province appears to be present in the Asian-Australian region, extending from South Australia northwards to include the major deposits in the Georgina Basin of northern Queensland and adjacent parts of Northern Territory, and then to Vietnam and southern and central China. It may also be possible to establish links with those deposits of Cambrian age in the Mongolian People's Republic and neighbouring areas of the USSR, notably with the well-known Karatau deposits of southern Kazakhstan. The largest resource of phosphate rock of Cambrian age to have been found to date is in Australia (northwestern Queensland and the neighbouring parts of the Northern Territory).

Sedimentary phosphate rock of undoubted Precambrian age has, until comparatively recently, again been confined largely to Asia. Particularly noteworthy are the low-grade deposits found near Lake Baikal in the Buryat and Irkutsk regions, the phosphorites discovered much more recently in India in the Aravalli Group exposed in Rajasthan and Madhya Pradesh, and deposits found in China in the Toushanto suite in parts of the Hupeh and Hunan provinces. The identification, relatively recently, of phosphate-bearing sediments of Precambrian age in Africa (Morocco, Senegal and Upper Volta), and also in the USA and Brazil, indicates that further discoveries of the same age are very probable as systematic exploration proceeds. Several Precambrian phosphate provinces may eventually be delineated.

Phosphogenic Provinces of the Circum-Pacific Region
by *Richard P. Sheldon,* East-West Resource Systems Institute, Honolulu

The circum-Pacific region contains four major phosphogenic provinces. These include: 1) North American, and 2) South American marine phosphogenic pro-

* This paper is published in full in the Appendix.

vinces; 3) the Oceania insular province, all three of which have been actively forming up to the recent geologic past; and 4) the Australian-Asian Proterozoic-Lower Palaeozoic province, which is extinct. The oldest deposit of the South American marine phosphogenic province is the Peruvian deposit, of Jurassic age. Subsequent deposits include Colombian, Venezuelan and Peruvian deposits of Cretaceous age, Peruvian deposits of Miocene age, and seafloor deposits on the continental shelf of Peru. These deposits, excluding the seafloor deposits, aggregate to about 6 billion tonnes of phosphate rock. The North American marine phosphogenic province includes the Rocky Mountain deposits of Ordovician, Mississippian, and Permian age, the Alaskan Brooks Range deposits of Mississippian and Triassic age, the Mexican deposits of Jurassic, Miocene and Recent ages, the California deposit of Miocene age, and the present seafloor deposits on the continental shelf of southern Californiania and Baja California. These deposits, excluding the seafloor deposits, aggregate to about 13 billion tonnes of phosphate rock.

The Oceania equatorial insular province includes the late Tertiary-Quaternary deposits of Nauru and Ocean Islands in the South Pacific, and the Christmas Islands deposits of the Eastern Indian Ocean. These deposits aggregate to about 300 million tonnes of phosphate rock, less than half of which has been mined. The Australian-Asian province is made up of deposits of Cambrian age in the USSR, China, Vietnam, and Australia, and Precambrian age in India. Those deposits are widely spread and only grouped into a phosphogenic province as an hypothesis to test using palaeogeographic and palaeo-oceanographic plate-tectonic reconstructions that are quite tenuous. The deposits aggregate to a minimum of about 5 billion tonnes and probably are larger. It can be concluded that phosphate resources occurring throughout the circum-Pacific region exceed twenty-five billion tonnes of phosphate rock. In spite of this, mining of the phosphate rock at present is relatively small, and many countries of the region, including some of those with the most need for fertilizer, lack phosphate resources. However, exploration is not complete in much of the region, particularly southern Asia. Thus the opportunities of development of phosphate resources to meet the agricultural needs of the region are many.

The Spatial and Temporal Distribution of Phosphorites

by *Peter J. Cook* and *Michael W. McElhinny,* Australian National University, Canberra.

A new compilation of palaeolatitudes of phosphate deposits using world-wide palaeomagnetic data confirms that the majority formed at low latitudes. A number of Jurassic and possibly some Cambrian deposits formed at intermediate latitudes (30-50°). Phosphorites range in age from Early Proterozoic to Recent. There has been sporadic deposition of phosphate during this time, as continents drifted into low latitude locations. It is proposed that there is no direct genetic link between periods of volcanism, orogenesis, formation of evaporites, and episodes of phosphogenesis. All of these features are related through plate tectonics to particular phases in the rifting and separation of continents. In the case of diverging plates, volcanism and tectonism are an early stage feature, evaporites intermediate, and phosphorites late stage features. Models are developed to explain the sedimentary sequence which result in north-south and east-west seaways. No model is presently available for epeiric seas.

A temporal model is also proposed to explain the distribution of phosphorus in sediments in the last 3400 m.y. The association of phosphorus with iron and organic matter in the hydrosphere is particularly critical to the model. Even the temporal model is influenced to some extent by plate tectonics.

The sedimentary sequence of the Georgina Basin appears to fit with the proposed east-west spatial model. The Riversdale Formation and correlatives correspond to the continental pre-rift phase; the Colless Volcanics to the initiation of rifting. The Thorntonia Limestone (particularly the Chert Member) would correspond to the hypersaline incompletely-rifted phase. Finally, the Beetle Creek Formation would indicate the phase of complete plate separation and the formation of a major east-west seaway (perhaps along the orientation of the now north-south oriented Tasman Geosyncline) to the north. The Georgina Basin was a large shallow lobe off this seaway during the Middle Cambrian. It was this relatively narrow east-west seaway which provided the source for most of the phosphate which was ultimately trapped in the Georgina Basin, adjacent to basement highs.

Palaeogeography, Upwelling and Phosphorites

by *A.M. Ziegler, Judith Parrish* and *Roger Humphreville,* The University of Chicago

Large-scale coastal upwelling, due to Ekman Transport, occurs when water depths exceed 100 m, the wind is strong, consistent, and parallel to the coast, and the offshore direction is to the right of the wind in the northern hemisphere and to the left in the southern hemisphere. These conditions are met in three distinct geographic situations:—

1) Meridional Upwelling: north-south coasts between 10° and 40° latitude on the east sides of oceans in association with the eastern limbs of the subtropical highs (example – California Current).
2) Zonal Upwelling: east-west coasts of equator-centred continents at about 15° latitude in association with the easterly trade winds (e.g. – Caribbean Current).
3) Monsoonal Upwelling: diagonal east-facing coasts from 10° to 30° in association with monsoon circulation (e.g. – Somalia Current).

Palaeogeographic reconstructions are now accurate enough to test the notion that Phanerozoic phosphorites were deposited in association with predictable upwelling zones. Meridional upwelling would account for the phosphorites of the Mississippian Brazer Limestone (Utah), the Banff and Exshaw Formations (Alberta), and the Permian Phosphoria (Wyoming), Ishbel and Mowitch Formations (Alberta). Zonal upwelling would account for the Beetle Creek Formation (Queensland) and the Siberian Cambrian phosphorites; the Ordovician Trenton/Mayville (Tennessee) and Angullong (New South Wales) phosphorites; the Mississippian Alapeh Formation (Alaska); and finally, the Mesozoic Tethyan phosphorites of the northern margin of Gondwana. Occurrences of phosphorites formed in association with monsoonal circulation are as yet undetected. Palaeomagnetic orientations of Kazakhstania and China in the Cambrian are unknown, so that predictions of upwelling cannot yet be made for the phosphorite deposits of these continents. We conclude that a good case can be made for upwelling on theoretical grounds in areas where phosphorite has accumulated, particularly for those occurrences that are of "Phosphoria Type".

A Brine-leaching Mechanism of Phosphorite Genesis

by *R.A. Henderson, C. Cuff* and *P.N. Southgate,* James Cook University of North Queensland, Townsville

Many geologists regard upwelling waters as fundamental to phosphate genesis but such a circumstance is difficult to sustain for the extensive Middle Cambrian phosphorites of the Georgina Basin, northeastern Australia. The Georgina Basin is a platform terrain of truly cratonic nature, underlain by Precambrian crystalline basement, which extends for several hundred km beyond the basin margin in every direction. It follows that outer shelf environments in which upwelling might be expected to apply, are foreign to the sedimentary context of the Georgina Basin. Indeed lithographical data for the phosphorite and its enclosing stratigraphy is consistent with their deposition in a shallow water, inner shelf situation.

Georgina phosphorites are typically underlain by an interval of what was black, organic-rich shale prior to weathering. This in turn passes down to a leached, collapsed horizon formerly occupied by an evaporite of uncertain original thickness, now represented entirely by chert pseudomorphs. The nature of "collapse-related" deformation structures suggest that evaporite dissolution was an early diagenetic event which took place before the accretion of a substantial overburden and lithification of the overlying shale.

It is proposed that the black shales represent a disseminated phosphate source and that brines derived from dissolution of the evaporite, leached phosphate during their upward migration towards the seafloor. The efficiency of brines as a phosphate leaching agent has been assessed by a computer-based modelling technique (WATEC) using all pertinent, currently available phosphate solubility data. Concentrated brines, largely through the agency of Mg-ion pairing, show a dramatic increase in phosphate solubility relative to normal seawater. Seawater concentrated to a tenth of its volume has its phosphate solubility potential increased by two orders of magnitude.

We believe that phosphate concentrated and transported in this way was precipitated near the sediment/seawater interface where the brines must have experienced dilution and eventual oversaturation in phosphate. Mechanisms involving calcium carbonate replacement, probably under kinetic control, appear to have been important in nucleating apatite precipitation. Petrographic data suggest that most clasts of pelletal phosphorite varieties are replacements of calcium carbonate precursors. We believe the final concentrating process to have been mechanical. Submarine reworking of the sediment column is thought to have occured, leaving clean well sorted pelletal phosphorite, typical of the Georgina deposits, essentially as a lag accumulate.

The genetic model argued here for the Georgina Basin phosphorites may be of general application. A black shale-dolomite-chert association characterises many other deposits. Evaporites are also associated with some, but for most they have probably been removed by dissolution, as is the case for the Georgina Basin sequence.

The Role of Cyclic Sedimentation in the Formation of Phosphorite Deposits

by *E.A. Eganov,* Institute of Geology & Geophysics USSR Academcy of Sciences, Novosibirsk.

High-grade bedded phosphorites are confined to those parts of carbonate sequences which contain layers of clayey, cherty and silty-sandy rocks. They are, in addition, frequently confined to particular portions of the sequence. Studies of the distribution of carbonate cherty shaly and clastic beds from various sedimentary phosphate deposits show that these beds occur in a particular cyclical order. Cyclical phosphate-bearing sections were established some time ago for the Permian Western Phosphate Field in the USA. More recently, similar cycles were established for phosphorite deposits in northern Mongolia (Upper Precambrian, Hubsugul Basin) by I. Semeykin and others, and subsequently by the present author in Lower Cambrian phosphate-bearing sections in Karatau (Kazakhstan, USSR). Comparison of sequences in major phosphorite deposits in the Lower Cambrian of China, and Mesozoic and Paleogene deposits of North Africa and Asia Minor, reveal essentially the same cyclical nature of sedimentary sequences.

The phosphatic cycles usually reflect the alteration of transgressive and regressive tendencies in the development of a basin. Initially shallow sedimentation takes place, followed upward by more deep-sea sediments. These may be followed by a shoaling sequence and sometimes ending with scouring of the upper beds. The shallowest parts of a cycle are composed of dolomites and clastic rocks; deeper parts consist of cherty rocks (bedded cherts, cherty carbonates, etc.) and phosphorites represent still deeper environments. The deepest strata in a cycle are represented by siliceous shales, shales and laminated black limestones. Bedded phosphorites occur near the outer shelf edge. They are found in those formations which result from marine transgression onto peneplained coasts. Phosphorites form not at the beginning of a transgression, but at a time when the sea depth in the shelf zone reaches a sufficient depth. Further deepening creates the environment for deposition of siliceous and non-siliceous shales, and ultimately terminates the phosphogenic process. However, the formation of phosphorites may resume during shoaling. The process of phosphorite formation reaches its peak during major deepening cycles.

In Figure 10, the distribution of relative depths through the sequence of the phosphate-bearing units of the Karatau basin is shown. It is evident that there is a major transgressive cycle, and it is this cycle that is phosphate-bearing. Phosphates are present in cycles I-IV, but the most phosphogenic cycle is cycle II. The sequence of Middle Cambrian deposits in the Georgina Basin (Table 4).

When a basin only deepens once there is only one unit of phosphate rock deposited, but where deepening alternates with shoaling of equal or greater amplitude, two phosphorite members are formed, separated by a deeper water unit. Sections of some deposits (for instance, in Syria) display reversed cycles, that is regressive-transgressive cycles where two horizons of phosphorite are separated by a shallow-water non-phosphatic member.

The main (phosphate-bearing) sequence of a transgressive phase consists of three stages of development:

1) deposition of relatively coarse detritus in a shoaling coastal zone, or on the coastal plain in alluvial-lacustrine and supratidal environments;
2) deposition of phosphate-bearing carbonates, mostly dolomite and some cherty and clayey sediments, on a submerging shelf;
3) deeper marine pelagic sedimentation on the outer shelf or continental slope where siliceous, clayey and silty sediments or dark limestones form.

The presence of such a transgressive sequence of beds, or of a reversed (regressive) sequence, is a good prospecting guide for high grade phosphorite.

Table 4 Similarity of the sequence of lithological units in the Karatau and Georgina Basins.

Karatau Basin		Georgina Basin	
Shabakty Suite	Bugul subsuite	Upper calcareous unit	
	Gillan subsuite	Lower shaly unit, Inca Formation	
	Brown dolomite	(Perhaps the lowest part of Inca Fm.)	
	Fe-Mn horizon of dolomite		
	Upper phosphorite	Upper phosphorite	Beetle Creek Formation
	Shaly member	Lower Siltstone	
	Lower phosphorite	Lower phosphorite	
	Chert horizon	"Chert Member"	Thorntonia Limestone
	Lower dolomite	"Dolomite Member"	
Kyrshabakty Suite (red beds)		Mount Birnie Beds) Riversdale formation) Mt Hendry Formation)	

LEGEND (FIG. 10)

1 – Phosphorites (a – minor occurrences, b – economical);
2 – surfaces of erosion (major – thick, minor – thin);
3 – coarse elastic sediments;
4 – coarse clastic sediments which formed due to currents near sea-floor;
5 – sandy sediments;
6 – silty-clayey sediments;
7 – siliceous-clayey sediments;
8 – black carbonates;
9 – bedded cherts;
10 – secondary silicification and chert nodules;
11 – red beds and variegated material;
12 – glauconite thick circles indicate glauconite abundant; dashed circles indicates glauconite scattered;
13 – carbonate oncolites;
14 – wavy stromatolitic structures;
15 – patchy stromatolitic structures;
16 – columnar stromatolitic structures;
17 – flat-planar-wavy stromatolitic structures
18 – siliceous spicules;
19 – calcareous spicules;
20 – zone of fine grained phosphorites (microphosphorite);
21 – zone of oolitic-pelletal phosphorite;
22 – zone of bioclastic phosphorite.

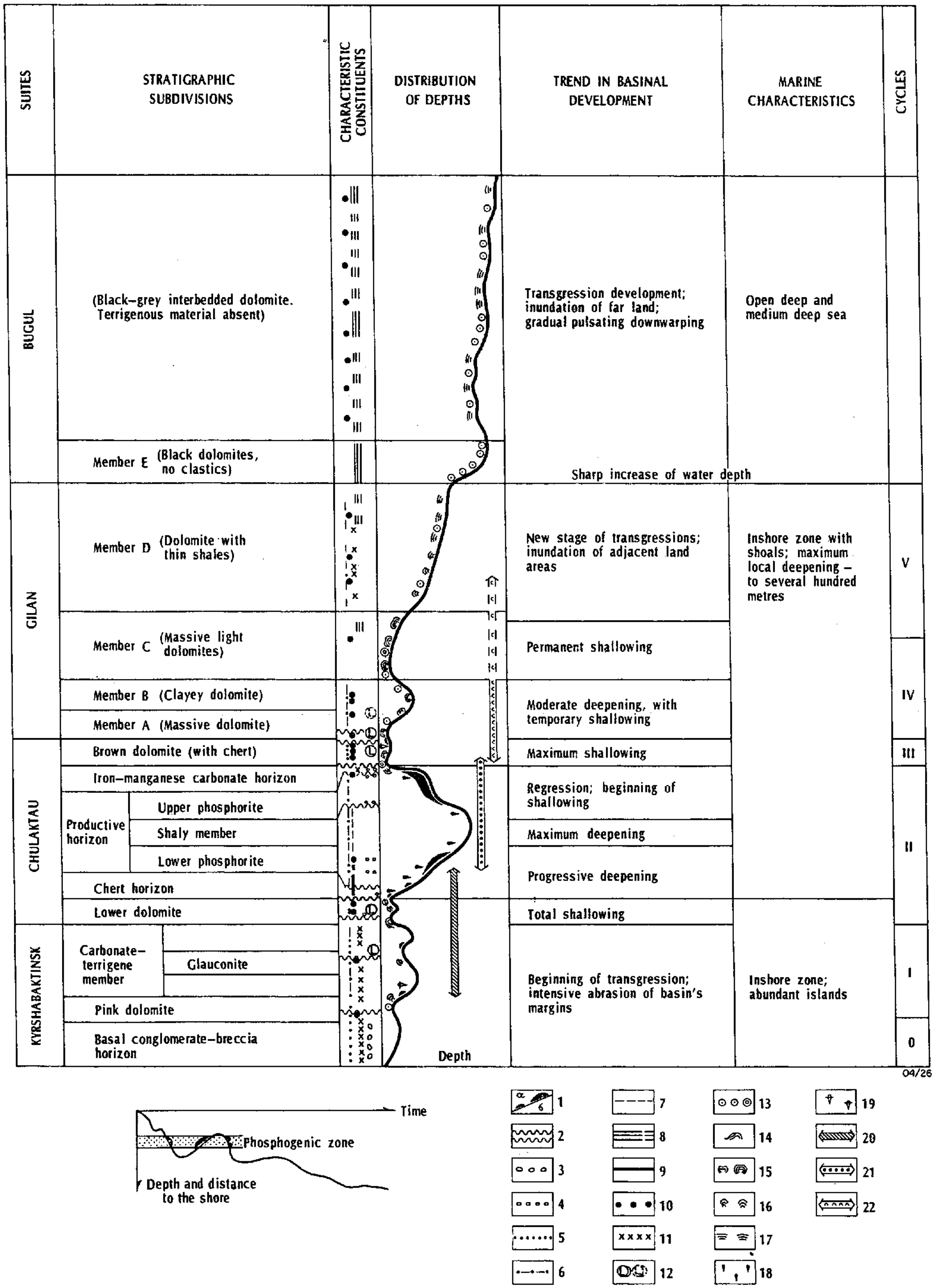


Fig.10 Rhythmic sedimentation in the Lower Cambrian Sequence of Karatau, Kazakhstan

Discussion

In response to a request by Notholt for corrections and additions to his preliminary tabulation of world deposits, newly discovered late Precambrian deposits in the Gurupi group in Para, Brazil, and the Precambrian Hirapur deposits in the Sagar district of India were mentioned. The exclusions of igneous deposits from this conference was questioned and justified by the initial aims of the IGCP project and the fact that igneous deposits contribute less than 20% of the world's phosphate production.

In response to the talk by Sheldon, the point was raised that many deposits seen on the present sea floor are not necessarily forming today and may, in fact, be as old as mid-Tertiary. The very high grade of the island deposits was questioned and explained as the result of complete replacement of clean limestone by phosphate-rich solutions derived from guano. Their age, as determined by uranium-series dating by H.H. Veeh, is greater than 800,000 yrs. The question of the earliest occurrence of upwelling organic-rich ocean water was raised but not resolved.

The analogies drawn by Cook and McElhinny between the temporal distribution and textural characteristics of phosphorite and iron formations were discussed. The high apatite content of banded iron formations associated with some base metal deposits in Australia was noted, as well as the enormous amount of P_2O_5 ($\sim10^{11}$ tonnes) contained at much lower concentration in, for instance, the Hamersley iron formations. The association of high P_2O_5 data from DSDP holes are in hand but their interpretation is not complete. The necessity of secondary mechanisms of sedimentary concentration of phosphatic materials produced by upwelling was of a correlation between petroleum occurrences and times of phosphorite formation. The inversion of sedimentary sequences proposed in the rifting model could be explained as forming in a converging rather than diverging situation.

The palaeogeographic reconstructions of Zeiger *et al.* discount the possibility of an expanding earth. The possibility of upwelling occurring on any shelf with water depth greater than 100 m was cited in answer to objections that upwelling would not explain the Georgina Basin deposits which were situated up to 500 km from the continental margin.

The problem of mass balances in the derivation of thick phosphorite over thin shales and the lack of evaporites associated with many deposits was raised in response to the hypothesis of Henderson *et al.* The required presence of organic-rich muds in this model suggests upwelling as at least a first stage process. The occurrence of unreplaced aragonitic shell material filled with phosphatic mud in some deposits does not support replacement of carbonate as a mechanism of phosphate precipitation but does not preclude mechanical mixing of previously precipitated phosphate. The problem of fluorine enrichment in phosphorites was discussed.

Eganov considered that the depth of formation of the phosphatic interval in Karatau is thought to be roughly 10 to 100m. Secondary effects are seen, but the major phosphate concentration is sedimentary. No evaporites are seen in the Karatau area, but red clastic sediments were deposited both below and above phosphorite horizons. Palaeontological information for the interpretation of depositional environments is very sparse. It was pointed out the lithologic similarity between Karatau and the Georgina Basin (despite the different ages), reflect similarities in tectonic control over gross sedimentation patterns.

Georgina Basin Phosphorites

Middle Cambrian Stratigraphy of the Georgina Basin

by *J.H. Shergold,* Bureau of Mineral Resources, Canberra.

The Georgina Basin includes Upper Proterozoic and Lower Palaeozoic strata, commencing with Vendian glaciogene sediments and concluding with possible Mid-Ordovician arenites. These rocks are divided into three tectonostratigraphic units, tectotopes, which are separated by major unconformities or disconformities. Tectotope 1, which includes glaciogene, terrigenous clastic and siliciclastic sediments passing upwards into carbonates, spans the Proterozoic (Vendian) to Early Cambrian (Atdabanian to early Lenan). Tectotope 2 commences with a volcanic episode in the later part of the Early Cambrian or earliest Middle Cambrian, and comprises predominantly carbonate sediments deposited throughout the Middle and Late Cambrian, and during the earliest Ordovician. Tectotope 3 commences with unconformity or disconformity during the early Arenig, and represents a dominantly siliciclastic phase of sedimentation whose record terminates in the Mid-Ordovician.

The Middle Cambrian sedimentary rocks of the Georgina Basin have conformable, disconformable or unconformable relationships with the basal volcanic rocks of tectotope 2, and earlier carbonate rocks of tectotope 1. The first dateable Middle Cambrian sequences are of late Ordian age, Zone of *Redlichia chinensis.* Where older Cambrian rocks are absent, the Ordian sequences commence with fluvial and grade through dolomite into biohermal carbonates (Thorntonia Limestone). A rapid regression during the latest Ordian caused the emergence of carbonate banks which suffered subaerial erosion, lateritization and karsting. Evaporites deposited in hypersaline pools on this surface, represent the terminal phase of the regression. During the earliest Templetonian, a second transgression deposited the Lower Siltstone Member of the Beetle Creek Formation. Shallowing upwards sequences were deposited during the later Templetonian, as indicated by the occurrence of phosphatic skeletal sands in the Monastery Creek Member of the Beetle Creek Formation. A third transgressive phase coincides with the deposition of the Inca Formation and its correlatives in the latest Templetonian. In post-Templetonian time there was gradual upward shallowing over the whole basin, and southwards progradation of regressive lithosomes continued into the early part of the Late Cambrian.

During the late Ordian, the palaeogeography is dominated by the development of carbonate banks, the largest of which (Camooweal Dolomite and associated formations) is some 350 km long and 150 km wide. At this time deeper water environments may exist over the site of the present Tennent Creek Block, as interpreted by the distribution of the Gum Ridge Formation. Carbonate bank mosaics (Camooweal Dolomite, Age Creek Formation, Thorntonia Limestone *sensu lato,* Currant Bush Limestone) continued to develop during the Templetonian, and these were cut by broad interbank seaways in which the Lower Siltstone Member of the Beetle Creek Formation and the Inca Shale were deposited. Whereas the carbonate banks have endemic faunas, the interbank deposits contain more cosmopolitan biota indicative of either deeper or cooler water. Since these latter deposits are punctuated by the Leichhardt-Kalkadoon Block and in places overlie it as erosional remnants, it is suggested that this structural block, like the

Tennant Creek Block, was submerged during the earlier part of the Middle Cambrian. Phosphate-rich waters were introduced from upwelling sources to the Cambrian north, and were trapped in restricted environemnts within the carbonate shoal network.

Middle Cambrian Hypersaline Environments Along the Eastern Margin of the Georgina Basin

by *P.N. Southgate*, James Cook University of North Queensland, Townsville.

Pseudomorphs after gypsum, anhydrite and halite have so far been found in four formations of Middle Cambrian age along the eastern margin of the Georgina Basin. These formations range in age from *Redlichia* through to *Ptychagnostus nathorsti* time and include the Thorntonia Limestone, Chert Member of the Thorntonia Limestone, Currant Bush and V-Creek Limestones as well as the Quita Formation. Pseudomorphs after gypsum have also been recognised in the early Upper Cambrian Mungerebar Limestone. Phosphate of *Ptychagnostus atavus* age found south of Thorntonia contains gypsum and anhydrite pseudomorphs as well as crystals of anhydrite. Nowhere have deep water basinal type evaporites been found. All occurrences thus far recognised are of intertidal and supratidal origin. The upper part of the Chert Member of the Thorntonia Limestone at Ardmore may be of very shallow subtidal origin.

The initial phase of hypersalinity along the basin's eastern margin is now represented by the Chert Member of the Thorntonia Limestone. Dated at Ardmore as Ordian by the presence of *Redlichia* sp. (Shergold, pers. comm.), this unit rests variously on top of a subaerially exposed surface of Thorntonia Limestone, or Riversdale Formation and equivalents, or basement rocks. Hypersaline conditions associated with the Chert Member probably extended into the base of the Lower Siltstone Member at Ardmore. Thus far, sulphate and halite casts have not been found in the main phosphate bearing horizons of the Beetle Creek Formation. However, south of Thorntonia, anhydrite as well as gypsum and anhydrite casts have been found in a phosphatic sequence at the base of the Currant Bush Limestone. In the Undilla area the Currant Bush Limestone consists of repetitious cyclic sequences of shallow restricted subtidal carbonates followed by hypersaline intertidal and supratidal conditions. A similar facies has so far been recognised at one locality in the overlying V-Creek Limestone.

As yet no evaporite mineral casts have been found in the Middle Cambrian carbonates of the Burke River Outlier, however this does not preclude their occurrence in this region. Evidence of hypersalinity has only recently been found in Middle Cambrian rocks of the Georgina Basin and as elsewhere, gypsum, anhydrite and halite pseudomorphs may have been overlooked by previous workers in the Burke River Outlier. The Camooweal Dolomite, a poorly outcropping unit in the central portion of the Georgina Basin is considered by de Keyser and Cook to have formed under hypersaline conditions. However no evaporite mineral pseudomorphs have yet been recognised from this dolomite.

The D Tree, Wonarah, and Nearby Phosphate Deposits, Georgina Basin

by *P.F. Howard,* Macquarie University, North Ryde

The early Middle Cambrian phosphate deposits which formed within the epicontinental-sea portion of the Georgina Basin show similar features. The D Tree and Sherrin Creek deposits are 15 to 18 km long and 1 to 3 km wide, Wonarah 30 km long and 5 to 8 km wide, while Alexandria is 25 km long and only 300 m wide. These elongate deposits show similar lateral changes in lithofacies from a near-shore phosphorite-siltstone-chert assemblage to an offshore phosphatic dolomite-limestone-chert assemblage. The deposits which variously contain or or two beds crop out only at D Tree. Here, high-grade phosphorite occurs as a diagenetic replacement of limestone and dolomite, immediately overlying the Chert Member of the Thorntonia Limestone. A second phosphorite bed is duplicated in the overlying Beetle Creek Formation as a regressive – transgressive cycle. The interbedded siltstones and cherts of the Beetle Creek Formation are weakly phosphatic except for the upper part, where the phosphatic section decreases in thickness and crosses lithologic boundaries away from the palaeoshore-line. The eustatic changes in sea level which are reflected by the regressive-transgressive cycle changed the sedimentary environment from one of restricted embayments and lagoons, to supratidal flats which were subaerially weathered and incised by stream channels. Fault scarps such as the West Thornton fault shed Precambrian detritus which was reworked into well defined conglomerate fans prior to the transgression of the Thorntonia Limestone and Beetle Creek Formation, and again at the close of Beetle Creek sedimentation as fans of sandstone. During cyclic pulses of the regressive-phase phosphorite bed, ferruginous, manganiferous and base metal detritus of the Precambrian hinterland was stripped and flushed across tidal flats and incorporated in the phosphorite as a terrigenous bed up to a metre thick.

The phosphorite consists primarily of mudstone phosphorite with interbeds of phosphatised coquina and phosphatised pelletal fossil debris, which attain thicknesses of up to a metre. Additionally, phosphatised shell debris occurs in the mudstone phosphorite as a mosaic of broken shells. The principal dilutants which comprise an average of 60 per cent of the rock include kaolinite, illite and minor sand-sized chert fragments. Interbands of chert are recognised as silicified coquinas and carbonate sands. The coquinas are interpreted to have been carbonate banks which were moved about by tidal scour in shallow water embayments, and abraided to skeletal carbonate sands and mudstones during high energy conditions. The interrelationship of the sediments indicate that the phosphatisation and silification took place as an early diagenetic effect, possibly at the sediment-water interface. Further, the interrelationships of the phosphorite types suggest that all of them were formed by diagenetic phosphatisation and that no primary precipitate of carbonate apatite occurred.

Phosphate Occurrences in the Area South and West of Mount Isa

by *D. Hackett,* ICI (Australia), Mount Isa

During 1975 and 1976 the eastern side of the Georgina Basin was tested by drill traverses normal to the outcrop on the edge of the basin. Drill holes intermittently intersected phosphatic material of interesting grades. Most of the traverse lines intersected phosphatic material in the Beetle Creek Formation within a sedimentary assemblage of siltstone, chert, and phosphorite, suggestive of a ?shelf facies. Overall, P_2O_5 values ranged from 0.5-3%. The few significant phosphate occurrences located were subsequently shown to have formed in locations suggestive of a restricted circulation environment. In all cases, these locations appear to have been protected from normal marine activity by Proterozoic highs on the sea floor.

Only the Quita Creek area justified more detailed work, and drilling down to 500 metre-spacing indicated that the deposit formed behind calcareous off-shore banks extending southwest from Proterozoic topographic highs. Compared to the known phosphorite deposits, Quita Creek is small and of only moderate grade. A second type of phosphorite forms within embayments or basins within the carbonate banks. These phosphorites tend to be high in iron, and compared with the main deposit have an Fe_2O_3/Al_2O_3 ratio greater than 1, while the main deposit ratio is less than 1. The significance of this is not clear. The conclusion from the program was that phosphorites are deposited in environments of restricted circulation.

Cambrian Lithofacies and Biofacies Patterns in Western United States – a Model for the Georgina Basin

by *A.R. Palmer*, State University of New York, Stony Brook

During most of Cambrian time, North America was surrounded by three concentric lithofacies belts: an inner belt of sands and silts, often glauconitic; a more peripheral belt of shallow water carbonates characterised by an abundance of oolitic, oncolitic and echinodermal grainstones and packstones, trilobite wackestones and packstones, algal stromatolites, and burrowed lime mudstone; and an outer marginal belt of siliceous, thin and platy bedded limestones, fine clastics and some cherts. The seaward edge of the carbonate belt was the outer edge of the epicontinental sea.

The trilobite faunas show a concentric as well as temporal zonation. The inner detrital belt and inner part of the carbonate belt have typically endemic faunas with low diversity. The outer edge of the carbonate belt had a high diversity mixture of endemic and probably pelagic trilobites. In the Middle Cambrian, these probable pelagic trilobites include eodiscids, agnostids and oryctocephalids. The outer siliceous belt in Middle and Late Cambrian time is characterised by agnostids and hexactinellid sponges.

Analysis of depositional environments shows the carbonate belt to contain lithofacies typical of the shallowest environments (exclusive of the innermost shelf clastics), and the outer siliceous belt to represent the deeper outer part of the shelf, which had unrestricted access to Pacific water masses. This distribution of lithofacies and biofacies, with similar palaeogeographic implications, characterises the northern and eastern parts of the Cambrian of the Siberian Platform and parts of the Cambrian of eastern China. There is strong evidence that the Beetle Creek (Duchess-style) and Inca Formations, with faunas typical of the outer siliceous belt or outermost margins of the carbonate belt, represent sedimentary packages that accumulated in an environment having unrestricted access to the Pacific Ocean, and that these were deeper water sediments than coeval lime mudstones of Devoncourt type, or interior-bank Cammoweal Dolomite.

Discussion

Discussion on the paper by Shergold centred around the palaeogeography of the Georgina Basin. Shergold considered that an extensive epeiric shelf possibly extended from the Wiso Basin in the west, to the position of Brisbane in the east. Phosphatic waters were introduced into a system of carbonate banks via broad interbank channels. The phosphate accumulated in restricted carbonate bank environments which have endemic faunas. The faunas of the interbank environments are more cosmopolitan reflecting deeper and/or cooler waters. It was suggested that the Leichhardt-Kalkadoon Block was not an emergent high during Middle Cambrian time since remnants of Beetle Creek Formation occur on top of it; however, some members of the audience disagreed with this, pointing to the disposition of phosphate deposits around the present basement high, in support of a Cambrian basement high. Shergold thinks this can only be resolved when the sub-Georgina Basin topography is better understood.

In his paper, Southgate pointed to the widespread evidence of hypersalinity. In the Currant Bush Limestone, phosphate pellets and gypsum pseudomorphs occur together. These phosphate pellets do not seem to have been reworked from the Beetle Creek Formation, but appear to have formed by *in situ* chemical growth. The relative lack of halite in the sequence is a consequence of its high degree of solubility. The cyclicity of the pseudomorphs and their morphology provide good evidence that they formed in sabkha cycles.

Howard considered that the present basement highs were indeed Cambrian basement highs and that the phosphate deposits are restricted to the vicinity of those basement highs. The Cambrian equator was located just south of the D Tree – Lady Annie deposits.

The paper by Hackett provoked the response that there are many similarities between the Georgina and the Florida deposits. One of the features of the Quita Creek area is the very abrupt change from high grade ore (20% P_2O_5) to very poorly phosphatic sediments.

The paper by Palmer on the North American Cambrian pointed to the facies similarities with the Georgina Basin. The lack of phosphate in the Cambrian of the USA (apart from a minor occurrence in western Nevada) is attributed to the high rate of sedimentation. Although no major evaporites are known from the Cambrian of the USA, some salt casts are known. There appears to have been a world-wide eustatic sea-level rise at about *Ptychagnostus gibbus* time, possibly related to a time of sea-floor spreading and mid ocean-ridge development.

In a general discussion on the water depth at the time of deposition of the phosphate deposits, Cook proposed a model in which the initial deposition of phosphate occurred on or adjacent to basement highs during a transgressive phase and then was reworked and trapped on the flanks of the basement high during the subsequent regression. Palmer commented that any such regression was not a global event but can have only been in response to local tectonic activity. Howard pointed out that the D Tree deposits formed during a regressive cycle. Trueman considered tht in the Phosphate Hill area, the top of the phosphatic sequence shows evidence of deposition under very shallow oxygenated conditions but with no evidence of reworking. He disagreed with the comparison of the Georgina deposits and those of Florida because of great lateral continuity with many of the Georgina deposits. The presence of ?tuffaceous cherts in the phosphatic sequence at Duchess was mentioned. However, S.R. Riggs felt that the well known central Florida district is not typical of all the Florida deposits and that in many deposits of the southeast United States there are striking similarities with the Georgina Basin. M. Slanksy pointed out that in the Tunisian deposits the PO_4/SO_4 ratio has been shown to be a measure of the salinity prevailing at the time of deposition. The sulphate content of the Georgina Basin phosphorites appears to be higher than usual, indicating a relatively high salinity at the time of precipitation of the collophane.

Phosphorites of Southeast Asia

The Phosphate Deposits of China

by *Yeh Lien-chun,* Geological Institute, Academia Sinica, Peking

The phosphate deposits of China are discussed with respect to regularities in their distribution in time and space, and in their physical and chemical environment of formation.

(i) Regularities in time. Sedimentary mineral deposits are intimately related to the evolution of the earth's crust; e.g. epeirogenic, eustatic, or orogenic movement, magmatic activities, palaeoclimate, and the origin and extinction of organisms. Every metallogenic epoch has its own metallogenic cycle and metallogenic sequences. All these regularities are clearly shown by the Chinese phosphate deposits. Every type of phosphate deposit is found in the basal part of transgressive series. The Cambrian is one of the important phosphogenic epochs in China.

(ii) Regularities in space. This falls in two categories – (a) Palaeogeographically, phosphorite deposits form under paralic conditions of restricted or semi-restricted shallow marine basins. They may be formed adjacent to palaeo-topographic highs, or positive elements, or growth structures, and the phosphate-bearing basins may be either "antecedent" or "syndepositional". (b) The types of phosphorite deposits are inherently governed by the difference in lithologic associations. Most of the commercial Chinese deposits were formed in platform environments. Nevertheless, deposits which were formed in a "mobile platform" (like the upper Yangtze platform) are quite different from those which were formed on a "rigid platform" (like the North China platform). Deposits formed during an epeirogenic episode are also quite different from those formed during a eustatic episode. The depicted global phosphogenic zones of different geologic periods might coincide with these rules in one way or another.

(iii) Regularities in their mode and history of formation. As proved by the textural and structural habits of the ore rocks, commercial phosphorite deposits are apt to be deposited in two basic steps. The first step is the chemical and biochemical deposition of original phosphate material either through the bottom oceanic water or through the pore waters within the bottom mud. Of course, the process may be direct chemical precipitation, or sort of halmyrolysis. Following this chemical stage, there is always a physical process of reworking. It is only in this later period that a commercial deposit can ever be formed.

The Conditions of Formation of the Lower Cambrian Phosphorites and the Regularities of their Distribution, Yunnan Province, China

by *Wang Chung-wu,* Yunnan Provincial Geological Survey, Kunming

The major phosphorites in Yunnan were formed in the Early Cambrian and are located in the lowest part of a transgressive series. Because of the good quality of ores and their huge reserves, these phosphorites are one of the most important phosphorus resources available in China.

The phosphatic sequence represents a suite of fine clastic with chemically or biochemically-deposited sediments and associated phosphorites, carbonates and siliceous rocks. The phosphatic horizons occur in stratified or stratoid forms, generally of 1-5 layers. The ores are mainly banded; less commonly they are oolitic, brecciated and nodular. There is also some massive ore. The ores can be grouped into siliceous phosphorite, carbonate-type phosphorite, calcilutite-phosphorite, and nodular clastic phosphorite, among which the carbonate-phosphorite has the highest and the siliceous phosphorite has the next highest P_2O_5 content. There is an apparent increase of P_2O_5 content in various types of ores after they have undergone oxidation, especially in the carbonate-type phosphorites where the absolute increase of P_2O_5 amounts to about 7%.

Various phosphorites are associated with certain types of rocks, and in accordance with the characteristics of the lithologic association, three facies are recognized: the siliceous-phosphorite facies, the carbonate-phosphorite facies, and the nodular clastic phosphorite facies. These three facies are all approximately parallel to the ancient coastline and are distributed in the form of belts. From the land area seaward, we have the nodular clastic phosphorite facies, the carbonate-phosphorite facies, and the siliceous phosphorite facies respectively. Such a regularity of distribution of phosphorites is related to depositional differentiation with various physical and chemical conditions in different locations within shallow marine basins. The water depth and the adjacent topography influence the grade of phosphate ore. The phosphorites of eastern Yunnan were deposited in a semi-enclosed embayment with a low rate of sedimentation, only minor clastics, and a hot arid climate.

The Occurrence of Cambrian and Related Sediments in Malaysia

by *Foo Khong-yee,* Geological Survey of Malaysia, Ipoh

The "Machinchang Formation", the oldest known fossiliferous formation in Malaysia, is of Cambrian age and forms the basal part of a conformable sequence of Lower Palaeozoic strata in the type area of Pulau Langkawi. The formation comprises essentially shallow-water clastics of probable deltaic origin, which can be subdivided into three units, viz., a basal unit of interbedded subgreywacke and micaceous argillite, a middle unit of thickly bedded sandstone and grit, and a top unit of "passage beds" consisting of interbedded sandstone, shale and limestone. A sparse fauna of orthid brachiopods and saukiid trilobites found in the upper part of the formation indicates a Late Cambrian age.

Correlative clastics, which are unfossiliferous and called the "Jerai Formation", outcrop to the southeast in central Kedah. These sediments are more variously metamorphosed, generally to greenschist facies, and consist of an upper unit of metaquartzite with occasional grit and quartz porphyry, overlying a lower unit of quartz mica schist and phyllite. The two formations show lithological and homotaxial similarities. Both formations are intruded by granite, and in the rocks of the Jerai Formation there is associated mineralisation (tin, tantalum-niobium and iron).

Discussion

Much of the discussion centred around the location of the numerous Chinese phosphorites and the way in which these deposits relate to Cambrian sediments elsewhere in Asia. However, the relative lack of palaeomagnetic information for this area makes continental reconstruction difficult. Questions concerning the phosphate nodules of the Yunnan deposits revealed that they are on average approximately 1 cm in diameter. Many are clearly diagenetic; some show concentric banding; most are relatively structureless internally; some may be reworked. The nodules are found most commonly in thick carbonaceous shale sequences, which are probably laterally equivalent to the higher grade pelletal-shelly phosphorites.

At Pulau Langkawi the basal Palaeozoic sequence is of latest Cambrian age, and equivalents of the phosphatic sequence of China are missing. If they are present in central Kedah, they have been metamorphosed.

Phosphorites of the Indian Subcontinent

Study of Primary Layer Properties in the Precambrian Phosphorite Depositional Basins of India

by *D.M. Banerjee,* University of Delhi

Study of primary layer properties in the phosphorite bearing beds, the overlying lithological units and their relationship with the palaeoshoreline in three major phosphorite occurrences in India, indicate persistent shallow-water sedimentation. Beginning with a clastic conglomerate having large-scale cross-bedding and mega-ripple structures the sequences pass into a pelitic-carbonate mudflat environment. The phosphate unit shows excellent preservation of columnar, laminar and domal stromatolites of Early to Middle Riphean affinity. In the Jhabua area late Riphean stromatolites indicate a younger age for the phosphorite. The phosphorite occurrence is primarily restricted to stromatolite columns, although fragmentation of stromatolitic columns and the reworking of fragments has produced some inter-columnar distribution of phosphatic material. Many of these have assumed a pelletal habit due to the activity of tidal currents. Primary sedimentary structures include skip casts, bounce casts, starved ripples, current ripples, small scale ripple cross-bedding and algal bedding, characteristic of modern tidal-intertidal settings. The beds overlying the phosphatic unit show a gradual deepening of the basin with sub-tidal oncolites, and finally pass into a deeper shelf deposit showing all the characteristics of a proximal turbidite. In the Precambrian Gangolihat Dolomite of the Himalaya, phosphorite is associated with stromatolites and magnesite, with evidence of sub-aerial exposure and possible evaporitic facies intervening between the carbonate and phosphate units. It can reasonably be concluded that the Precambrian phosphorites of India formed in a tidal-intertidal environment, associated with stromatolite growths within a carbonate facies. Secondary dolomitisation and phosphatisation often obliterates the primary characteristics, but in some areas, there are sufficient clues to make it possible to interpret their origin.

Status of Phosphorite Investigation in Uttar Pradesh, India, and Approach for Future Work

by *A. Pant, B. Dayal, S.C. Jain* and *T.K. Chakravarty,* Geological Survey of India, Lucknow

Uttar Pradesh, a northern state of the Indian Union, can be divided into three distinct geomorphic divisions: the northern part occupied by the Himalayan belt; a strip in the south comprising the extension of the Peninsular shield area; and the intervening portion forming the great Plain of Ganga-Yamuna which is occupied by a thick cover of alluvium. Phosphorites have been found both in the Himalayan region in the north and the Peninsular area of the south. The physiographic, structural and stratigraphic setting of the two regions is very different. Phosphorite occurs in the Himalayan belt in (i) the Tal Formation (Jurassic?) of the Mussoorie Syncline, (ii) the Garhwal Group (Silurian?) in the "Window Zone" and (iii) the Kuling Shale, of Late Permian age, Spiti Shales of Late Jurassic age, and the Cretaceous sediments overlying the Giumal Sandstone in the Tethyan belt of the trans-Himalayan region. In the shield area of southern Uttar Pradesh, phosphorites reported from the Lower Vindhyan rocks, may belong to the oldest part of the Palaeozoic or earlier, while the phosphorites of the Bijawar rocks are believed to be of Proterozoic age. Of the above occurrences, the Mussoorie phosphorite deposit has been explored and is now being exploited. The recently discovered Lalitpur deposit of Uttar Pradesh, occurring in the Bijawar sequence may have some economic potential. The phosphorite deposits of Mussoorie and south Lalitpur therefore, require special mention.

Mussoorie deposits: Phosphorite occurs in the Krol-Tal Syncline which trends in an approximately NW-SE direction and occupies an area of about 180 sq km. The phosphatic unit generally overlies black chert and associated shales (base of the Lower Tal Formation) which in turn overlie the Krol Formation (carbonate sequence). At places, the chert unit is very thin or absent and the phosphorite bed is found to directly overlie the rocks of the Krol Formation. In some sections there is a transition zone between the Upper Krol Formation and the Chert Member. The phosphatic unit varies in thickness from a few cm to about 10 m, and the chert unit attains a thickness of about 100 m. It has been observed that the phosphatic unit is generally better developed, both in thickness and grade, where the chert unit is thin or absent. This may perhaps be due to the relative rate of sedimentation. The phosphorite is of sedimentary bedded type – lenticular in places, grey to brownish black in colour, granular in texture, brittle and friable. It occurs in four distinct varieties, namely platy and laminated, granular, lenticular, and nodular. The dominant phosphate mineral is collophane with some fibrous francolite and dahllite. Dolomite and calcite constitute the main gangue minerals. Pyrite, quartz and clay occur in minor amounts. Barite, feldspar, limonite, biotite, green amphibole and tourmaline occur in trace amounts. Most of the samples vary in U_3O_8 from 0.005% to 0.03%, though a few show up to 0.11%. A total of about 18 million tonnes of rock phosphate reserves with a P_2O_5 content varying from 5 to 30% and averaging

20% were proved, of which about 8.2 million tonnes are under probable and 9.3 million tonnes are under possible categories.

Lalitpur depost: During the course of recent systematic mapping, several lensoid bodies of phosphorite have been located over a strike lenth of about 15 km in the Bijawar Group of rocks in the south Lalitpur district of Uttar Pradesh. The phosphorite occurs in a sequence of phosphatic shale and dolomitic limestone with occasional conglomerate beds towards base, followed by brecciated massive quartzite with phosphorite, dolomitic limestone and then basic volcanics. Although the shale and dolomitic limestone of the basal unit contains thin beds of phosphorite, generally occurring within the shale, the main phosphorite horizon is associated with pink to white brecciated, massive quartzite. The phosphorite horizons occurring as lensoid bodies have a stratigraphic control and the deposit appears to be of a sedimentary-residual type. It varies in thickness from about 5 to 35 m. Apart from a number of small lensoid bodies, six individual lenses have been found extending for distances of 50 to 250 m along strike. The P_2O_5 content ranges from 5% to 25%, averaging about 20%.

In weathered and leached zone, the phosphate content has been enriched to about 30% P_2O_5. It is likely that the grade may decrease downdip. The zone of brecciated, massive quartzite, containing phosphorite, may perhaps represent the weathered zone of part of a composite carbonate unit, as beds of dolomitic limestone are found to occur both below and above the phosphorite horizon. The brecciated nature of the so-called massive quartzite unit may have resulted from volume reduction by the removal of the soluble components of the limestone (the calcium and magnesium carbonates), causing the collapse of quartzite and enrichment of phosphate which were left as a residuum. In addition, some joints and fractures are infilled by pinkish to buff coloured phosphatic veins occurring in an anastomosing pattern in the enriched zone. Botryoidal structures are also quite common in the high-grade varieties, with the botyroidal walls layered with phosphatic material. So far no definite stromatolites have been identified associated with the phosphorite, but some of the botryoidal layerings may perhaps be algal in origin. Under the microscope, the dominant phosphorite mineral in the botryoidal variety, is dahllite. It occurs in a fibrous, subradiating form in the laminae of the botryoids. The massive variety has a microcrystalline texture and contains collophane. It is isotropic to weakly anisotropic and ranges from yellowish grey to dark grey in colour.

Based on all the available information, the following areas have been identified for phosphorite investigation in Uttar Pradesh:

(i) Bijawar Group of rocks of southern Uttar Pradesh.
(ii) Lower Vindhyan rocks of southern Uttar Pradesh.
(iii) Garhwar Group of rocks of the Himalayan belt.
(iv) The entire sequence of the Tethyan belt from the Permian to the Cretaceous.
(v) The Krol-Tal Synclines of Nainital and Garhwal.

Palaeozoic Phosphorites, Rajasthan, India

by *G.P. Deshmukh*, Geological Survey of India, Jaipur

Birmania Phosphorite Deposit. Jaisalmer District: Sedimentary phosphorite is associated with unfossiliferous Palaeozoic rocks known as the Birmania Formation. The area lies in the heart of the Indian territory of the Thar Desert and is exposed over an area of about 50 sq km. The rocks have been correlated with the Dhanapa and Gotal Formations of the Bilara Group, forming the middle calcareous suite of rocks of the Marwar Super Group. They overlie the Malani suite of igneous rocks which have been dated at about 505 million years.

The stratigraphic succession in the area comprises:–

Jurassic	Lathi Formation:	conglomerate, sandstone and grit
	Birmania Formation: (915-3050 m thick)	shale, limestone, quartzite and phosphorite
Palaeozoic	–––––Fault–––––	
	Basal Randha Formation: (214 m thick)	maroon shales and quartzitic sandstones

The phosphorite horizon can broadly be divided into three groups: an upper group comprising shale, sandstone, limestone, dolomitic and cherty carbonaceous shale; a middle group comprising cherty phosphatic limestone, shale and siltstone; a lower group comprising sandstone underlain by siltstone, ferruginous sandstone, and varigated shales. An analysis of the phosphorite is given in Table 5.

Phosphorites occur associated with a thinly banded calcareous sandstone and banded limestone varying in thickness from 0.56 to 9 m immediately overlying a quartzitic sandstone. A calcareous shaly sandstone forms the most prominent phosphatic rock, with alternating layers of white to bluish grey argillaceous sandstone and black chert. The phosphorite occurs as irregular grains and pellets up to one mm in diameter. It is associated with arenaceous layers interbanded with minor calcareous arenaceous shale. The bluish sheen of the cherty bands greatly facilitates the identification of the phosphorite. The thickness of the individual bands varies from a few mm to about 30 cm.

In thin section the phosphorite is seen as an aggregate of calcite, quartz, and collophane associated with very fine quartz. Green amphibole, epidote and garnet are present as accessories. Collophane is present as pale, yellowish to brown coloured grains and pellets. It is occasionally lath-shaped and forms 30% to 40% of the rock. Calcite constitutes up to 35% of the rock and is observed as anhedral to subhedral crystals occupying the intergranular spaces of quartz and collophane. Chert is a minor constitutent, while quartz occurs as scattered detrital grains. The rocks are weakly radioactive.

Table 5 Composition of three samples of Birmanian phosphate ore.

	FCI		TVA
Moisture (at 105°C)	1.05	0.49	3.50
P_2O_5	27.35	11.17	27.70
CaO	45.50	38.66	32.50
SiO_2 + insolubles	4.92	27.09	9.60
MgO	0.08	0.05	
R_2O_3	1.69	11.56	14.00
F	4.35	2.12	2.30
Cl (as NaCl)	0.95	0.95	nd
SO_2	1.15	0.05	nd
CO_2	11.63	8.17	nd
P_2O_5 (citrate soluble)	nd	nd	4.70
L.O.I.	26.07	11.76	10.00

The Birmania Formation is exposed over an area of 4 km by 1 km, but geophysical work by the Oil and Natural Gas Commission indicates that the rocks extend beyond the present outcrop area. A marine transgression extending over much of western Rajasthan took place during the Palaeozoic, and sediments comprising the Randha and Birmania Formations were deposited. The Malania suite of igneous rocks exposed to the south of Randha and Kohra formed the source area for the Randha Formation. Cross-bedded Randha Formation sandstones and shales were deposited under shallow water conditions. The sediments overlying the Randha Formation are essentially calcareous, and comprise shale, cherty phosphatic limestone, minor sandstone, dolomite, and siltstone. The deposition of the sediments probably took place in the zone between the shallow water platform and deep water geosyncline. The presence of carbonaceous shales towards the top of the phosphorites indicate restricted anaerobic conditions for some period. After the deposition of the Birmania there was a period of non-deposition, as the overlying sediments (Lathi Formation) are of Jurassic age.

The phosphate deposits of the Birmania area were intensively prospected by pitting and trenching during 1966. A probable reserve of 4.89 m tonnes averaging 10.15% P_2O_5 was proved. Later, in 1969-70, 1054 m of drilling was carried out in the Birmania block which proved a strike length of 2.2 km. The drill indicated reserves totalling 3.49 m tonnes averaging 12.9% P_2O_5.

Fatehgarh Phosphorite Deposit, Bermer and Jaisalmer Districts: The phosphatic horizon in the Fatehgarh Phosphorite Deposit of western Rajasthan is associated with fossiliferous calcareous and ferruginous fine to medium grained sandstone and sub-bentonitic clay of Creto-Eocene age. The carbonate of the fossil shells shows various stages of replacement by collophane. Phosphate is also seen in the mud and matrix at some places. In thin-section the phosphorites are seen to consist chiefly of fine to coarse sub-angular to round quartz, with collophane, phosphatic mud and fossil shells, spines, spicules, and fish dental plates in various stages of replacement. Collophane is present as small dark grey irregular grains (rarely oolitic) with abundant scattered ferruginous material. The bigger pellets (3 mm) are sub-spherical to spherical and are extensively replaced and veined by carbonate. In many cases the pellets are pseudomorphs after shell material. The interstitial areas between the ooids is filled with calcareous or ferruginous matter. Some ooids show colour zoning and have a core of dark grey collophane. Phosphatic mud is white to yellowish white and contains ooids, disseminated carbonate material, grains of quartz, and bone fragments, the latter being seen in most sections. In most sections the quartz and the matrix constitute more than 70% of the rock. The accessories are zircon, tourmaline and glauconite.

The phosphatic beds are overlain by 30 to 40 m of ferruginous sandstones and siltstones with plant impressions. These are in turn overlain by Eocene bentonitic clays over 500 m thick. A one to six metre section of ferruginous sandstone unconformably overlying the Lathi Conglomerate is generally phosphatic in the Fatehgarh scarp. In other areas the unit has a thickness of generally less than one metre. Fossils include the gastropods *Lunatica, Billemia, Acteon, Bulliopsia, Hydrobia, Lymnaea, Turritella,* and *Trochus.* Lamellibranchs, echinoid spines, fish dental plates, ostracods, and stem and seed impressions of angiospermic plants also occur. Cross-bedding is common. The presence of feldspar in sandstones of the Lathi Formation and the overall immaturity of the sediments points to moderate relief in the source area. The sediments are mostly deltaic and of a cyclical nature.

The concentration of phosphate was probably achieved through the following processes:

1. An increase in the phosphate ion by upwelling currents and also influx of water rich in dissolved phosphate from the rivers.
2. A part of the phosphate was probably derived from the decay of the soft parts of dead organisms on the sea bottom.
3. The dispersed phosphate in the sediments was concentrated in the form of pellets, ovules, ooids etc., concentration being increased by washing out of the finer admixtures by wave action. Later concentration (or in some cases impoverishment) resulted from diagenesis.

The economic viability of the deposit was examined by putting 6 trenches over a distance of 1.3 km. The P_2O_5 percentage varies from 1.9 to 7.9 and the iron 21.9 to 50.0. Loss on ignition varies from 7.8 to 23.4%. Potential reserves of about 12 m tonnes of very low grade phosphatic rock with high percentage iron has been estimated from the Fatehgarh block taking an average thickness of 2 m, and a downdip extension of 100 m.

Precambrian Phosphorite of Rajasthan, India: A Case History
by *V.N. Sant*, Mineral Exploration Corporation Limited, Nagpur

Systematic ground scanning of prospective areas, selected on the basis of modern concepts of phosphogenesis, resulted in the discovery of workable phosphorite deposits in the Precambrian Aravalli rocks of the Udaipur area, Rajasthan, India, in 1967. The Aravalli phosphogenic province is now known to extend over a length of more than 250 km.

The Aravalli rocks unconformably rest over the Archaean 'Banded Gneissic Complex', and comprise: (a) basal conglomerate, arkose, red quartzite with minor schist; (b) middle carbonaceous phyllite, dolomitic marble, jasperoid quartzite, quartzite, greywacke-phyllite sequences; and (c) an upper orthoquartzite, phyllite sequence. The three sequences respectively indicate nearshore littoral, unstable shelf, and somewhat deeper depositional environments. Phosphorite beds occur within the middle sequence, which also shows a typical upwelling suite of rocks – chert, black shale and phosphorite. The phosphorite beds occur in the lower and upper part of the middle sequence of the Aravalli group of rocks. Of these, the lower part contains the most promising phosphorite deposits. The Aravallis trend in a general north-northwest to north direction with generally steep westerly dips. They have been deformed at fairly shallow depths during the Aravalli orogeny, with later superimposition of post-Delhi deformation. The grade of regional metamorphism is lower greenschist to upper amphibolite facies. While the absolute age data gives a pre-Riphean (2500-2000 my.) age to the Aravalli group of rocks, the stromatolitic forms indicate Middle to Late Riphean age. Although the Aravalli phosphorite facies is similar to that recorded from many parts of the world in rocks of many different ages, the association of phosphate with stromatolitic algal structures is unique in these rocks. The phosphatic stromatolites are associated either with the dolomitic marble, brecciated jasperoidal granular quartzite or sandy phyllite. The beds vary in strike length from a few meters to over 17,000 m and range in thickness from a few centimetres to 40 m. The phosphatic stromatolites are usually dark bluish grey in colour, though locally, pink-white, reddish-brown colourations are seen.

The phosphorite occurs in three forms: (a) *columnar stromatolitic phosphorite* comprising beds of phosphatic columnar (locally oncolitic) stromatolites associated with dolomitic marble; (b) *fragmental (reworked) stromatolitic phosphorite*, associated with brecciated jasperoid granular quartzite (locally phyllitic), consisting of angular to subangular fragments of phosphatic stromatolite in a graunular jasperoid matrix; and (c) *bedded phosphorite* consisting of minute collophane laminations, usually associated with dolomitic marble and at places with jasperitic quartzite. While the fragmental phosphorites are formed as a result of contemporaneous rolling and rewashing/reworking of phosphatic stromatolites by tidal waves in shallow waters, the bedded phosphorites either represent phosphatised or phosphatic algal mats, or redeposition of phosphate gel (?) derived from the phosphatic algal colonies. It has also been established that while the grade of phosphorite associated with dolomitic marble is low to medium (8-22% P_2O_5), that associated with jasperoidal quartzite, is medium to high (18-39% P_2O_5).

There is no evidence to show that the phosphorite beds have been formed as a result of direct precipitation of phosphate from sea water. On the other hand, the algae seem to have played a decisive role in 'fixing' the phosphate within their columnar structures. The phosphate appears to have derived from upwelling deep oceanic sea water, but there is no clear evidence to indicate that the phosphate has partly or wholly replaced pre-existing algal structures. Stromatolites are essentially biogenic sedimentary structures formed by blue-green algae and bacteria, generally in shallow waters, possibly in protected tidal/intertidal flats or in lagoons of low tidal regions. In this respect the disposition of the phosphatic stromatolite horizon in the Jhamarkotra area of Rajasthan is significant. The broad synformal structure represented by the phosphorite and associated rocks may indicate an original basin topography and development of the phosphatic stromatolitic algal colony in restricted marginal waters of an embayment.

Though many workers have put forward hypotheses on the origin of stromatolitic phosphorite, a number of features have still to be resolved including:

1. Exclusive association of phosphatic material with the stromatolitic structures.
2 Occurrence of completely phosphatic and partially phosphatic or even very weakly phosphatic stromatolites in the same biostrome.
3. Occurrence of a completely phosphatic stromatolite biostrome a few metres above a non-phosphatic biostrome.
4. Marked absence of phosphorite in the inter-columnar space between the stromatolitic structures, except for a few small angular to sub-angular phosphatic fragments.
5. Occurrence of biohermal phosphatic stromatolites (associated with dolomitic marble) and fragmentary phosphatic stromatolites (angular to subangular fragments) in granular jasperoidal quartzite along almost the same stratigraphic horizon.

The Characteristics of the Jhamarkotra Phosphorite Deposit in Udaipur District, Rajasthan, India

by *R. Choudhuri*, Rajasthan State Mines and Minerals Ltd, Udaipur

The occurrence of stromatolitic phosphorites makes the Jhamarkotra phosphorite deposit one of the few of its kind in the world. The deposit was discovered by the State Directorate of Mines & Geology, Rajasthan, in 1968. Though a relatively small deposit, Jhamarkotra constitutes the only deposit of economic significance in India. It has proven resources of 53 m.tonnes (about 17 m tonnes of high grade (+30% P_2O_5) and the remainder low to medium grade [12-29% P_2O_5]); this deposit accounts for almost half of the total known phosphate reserve of India. With a production of 0.5 m tonnes per annum of ROM, Jhamarkotra currently contributes more than 80% of the indigenous phosphatic ore production.

A persistent phosphorite bed with a thickness of 5-25 m, outcrops over a strike length of 16 km. The phosphorite occurs between dolomitic/siliceous limestone units of the Aravalli Formation. On the basis of a radiometric age determination of 2060 m.y. on pegmatite at Govalia, north of Udaipur, which is coincident with the first phase of folding and an inferred late synkinatic relationship of the Aravalli sediments, the age of the phosphorite-bearing Aravallis can be placed at around 2000 million years (A.B. Roy, pers. comm.). The entire sedimentary sequence of the Jhamarkotra area has undergone polyphase folding and the Jhamarkotra phosphorite bed can broadly be visualised as a gently north dipping but strongly crumpled sheet.

The main phosphorite is in general characterised by a typical bluish bloom and a conspicuous association with stromatolites. The phosphate ore shows three broadly variable modes of occurrence: (1) columnar-stromatolite set in a dominantly carbonate matrix; (2) brecciated fragmental/reworked stromatolite; and (3) laminated/foliated stromatolite. While the fragmental zones are usually characterised by the high grade ore, the other two types are usually of poor to medium grade. The phosphatic stromatolite columns shows evidence of penecontemporaneous deformation. Petrographic studies point to the fact that most of the phosphatic material is confined within the stromatolites while the matrix shows almost negligible phosphate concentrations. This is confirmed by electron microprobe studies, which show a sharp contact between the walls of the phosphatic stromatolitic columns and the carbonate matrix. The constituent phosphatic grains are strongly recrystallised and coarse (10-50μ and above). This coarse grain size in a sedimentary phosphorite is attributed here to contact effects produced by the emplacement of the granites of Udaisagar Group corresponding to greenschist facies metamorphism. Petrographic, X-ray, infra-red and D.T.A. studies show that the phosphatic constituents belonging to the Jharmakotra deposit as well as adjoining occurrences such as Maton, Kanpur, Dakon Koltra and Nemach Mata, are of the carbonate-fluorapatite type. Structural substitution of CO_2 is almost negligible. In this respect, the apatite resembles that of the Khibhine Complex of the Kola Peninsula. Dolomite constitutes the dominant recrystallised gangue, although caclite is not uncommon. Spherulitic chalcedony constitutes the silicate gangue and usually occurs as infilling material between the fragmental phosphate clasts. The role of stromatolites in entrapping the phosphatic constitutents has been remarkably uniform. Analyses of a large number of randomly chosen and selectively scooped out fractions from the unweathered stromatolites show a P_2O_5 distribution in the relatively narrow range of 27-30%. Consequently, it has been possible to indicate the tentative grade of the stromatolitic phosphorite from the abundance of stromatolites and by the space occupied by the stromatolitic column per unit area.

The extrapolation of bore hole data on a longitudinal section clearly brings out the grade distribution pattern of the Jhamarkotra deposit. The frequency distribution of P_2O_5, as obtained from the analysis of core log when projected in histograms, brings out a bimodal distribution of phosphate. The grade distribution in Jhamarkotra is characterised by the relatively high percentage of silica (3-12%) in high-grade ore (+30% P_2O_5) and the high percentage of MgO (6-12%) in low-grade ore (15-20%). The transition from high to low grade ore is sharp. This grade distribution pattern may be a consequence of variable parameters such as the relative abundance of stromatolites on topographic highs, coupled with higher *in situ* phosphate localisation, differential weathering and leaching of the carbonate matrix, structural disturbance (in some cases low grade columnar stromatolites occupy the crestal area of the fold, while the brecciated/fragmental stromatolitic zone with high P_2O_5 percentage occupies the core), or a combination of these variables.

An Appraisal of Precambrian Phosphorites of Jhabua, M.P., India

by *H.H. Khan,* Geological Survey of India, Bhopal

The Jhabua phosphorite deposits were discovered during 1973, and since then the Geological Survey of India has carried out a detailed exploration programme in the area. Geologically, the area forms the southern extension of the main Aravalli belt of Rajasthan, in the western parts of Madhya Pradesh. The rajasthan phosphorite deposit is found 320 km north of this occurrence. The Aravalli group of rocks comprises folded and metamorphosed Precambrian rocks including dolomitic limestones, quartzites and quartz veins. All known phosphorite bodies in the area are associated with a dolomitic limestone carbonate unit which extends for about 12 km from north to south, between Amlamal and Rambhapur villages, and has a surface width varying between 100 and 800 m. The metasediments in the area have been regionally folded into comparatively open anticlines and tight synclines, and the phosphate-bearing dolomitic limestone forms a part of a doubly plunging fold in the regional synclinal structure, with its culmination near the central part of the belt.

Two distinct phosphate horizons have been noted in the area. The oldest horizon is interbedded with the dolomitic limestones, while the younger horizon overlies the dolomitic limestones and is interbedded with brown cherts. The phosphorites in both these horizons occur as discontinuous lenticular bodies, individually varying in width from 2 to 250 m and in length from 10 to 100 m. The thickness varies from 1 to about 60 m. The younger phosphorite horizon forms the main phosphate deposits in the area while the older one is much less extensive and is of comparatively low grade. Both these horizons are closely associated with stromatolitic structures. In places there is an interesting association of manganiferous rock formations of the same age as the phosphate deposits.

In the older horizon the phosphorites are mainly of the carbonate type. This horizon broadly resembles the Jhamarkotra phosphorite deposit of Rajasthan in the way in which the phosphorite is concentrated only in the body framework of stromatolites in that particular area. As such, wherever the concentration of stromatolites is high, the grade is also high. Where there are mainly massive bodies, the grade varies from 5 to 34% P_2O_5, the average being 15%. The average SiO_2 content is about 10%; R_2O_3 varies between 1.5 and 2.5%; and fluorine is on the average about 2%. This horizon has not been extensively explored as yet.

The younger horizon which clearly overlies the dolomitic limestones, is mainly a cherty phosphorite and is also associated with stromatolites. In this horizon, the phosphate is not concentrated in the framework of the stromatolites but in the interspaces between individual stromatolite columns. In addition, it is seen that at many places in this unit the phosphorites are devoid of any stromatolitic structures, and as such the deposition of phosphorites in this horizon does not seem to be directly related to the stromatolitic structures. The grade of this unit ranges between 25 and 36% P_2O_5, averaging to about 30%. The phosphorites are both massive and bedded and also in part brecciated. The colour ranges from white, cream, blue, grey and brown. The SiO_2 percentages vary between 8 and 30%, averaging 18% to 30% grade rock; R_2O_3 ranges between 2 and 4%, while fluorine varies between 1.5 and 3.5%.

Exploratory work aimed at proving the overall potential of this phosphorite horizon still continues and so far only 4.5 km along the northern strike length has been assessed. The rest of the area has yet to be investigated in detail. Although the stromatolites have not so far been fully classified, different forms of stromatolites which have been noted in the area are broadly classified as *Colonella, Collenia symmetrica, Bicalia, Minjaria, Tungussia, Conophyton, Stratifera, Kussiella,* and oncolites. Mining of these deposits has been underway by the M.P. State Mining Corporation since 1975.

New Data on the Mussoorie Phosphorites Lower Himalaya

by *A.M. Patwardhan*, Panjab University, Chandigarh

Fossils belonging to the Order Moravamminida, Family Moravamminidae, Subfamily Palaeobereselliinae have been discovered from the phosphorite deposits occurring around Mussoorie in the Lower Himalaya. Forms discovered are analogous but not identical to the Genus *Palaeoberesella* Mamet & Raus, 1974 which has a restricted Permian age. The moravamminids are regarded as characteristic fossils of the Upper Palaeozoic (Permian-Carboniferous) and so far are unknown from any horizon younger than Permian.

The discovery casts doubt on the conventional correlation with the Tal Formation (Jurassic to Cretaceous) of the Himalaya, a correlation not based on any fossil evidence, but depending entirely on lithological similarity and a crude resemblance in the superpositional order. As such, this correlation is said to have been proposed with "only that much certainty as is possible in correlating between rocks of isolated basins".

In view of the presence of micro-organisms, stromatolitic structures, and a ubiquitous association with carbonaceous matter, a biochemical mode of origin for these phosphorites is envisaged. Microscopic and megascopic examination of the stromatolitic structures found with these phosphorites, reveal concordant alternating phosphate-carbonate-pyrite laminae, which provide evidence in support of an initial primary deposition of phosphorite layers through a process of accretion by algae or other organisms. The stromatolites formed under quiesscent reducing conditions. There may have been intermittent periods of turbulence as evidenced by phosphorite layers comprised mostly of oncolites, intraclastic fragments of chert, shale and limestone, and grains and pellets of phosphate. The moravamminids do not occur in either the stromatolitic phosphorite or in the pelletal variety. They are usually found in fine grained phosphorite which is broadly laminated with fine layers of carbonaceous shaly material. It is surprising that morphologically the stromatolitic types found in the phosphorites are very much analogous to the types known from carbonate sediments of the Himalaya which are presumed to be of

Precambrian age without the evidence of any other fossils. The moravamminids have an established Tethyan affinity and therefore their occurrence in phosphorites belonging to a normal sequence of the Lower Himalaya has a special significance. As the phosphorites are interbedded within a sequence of black shale, chert and limestone, conventionally regarded as the upwelling suite of rocks, it will be worthwhile to re-examine the accepted southern boundary of the Tethyan belt in the Himalayan region and the areas of upwelling on the northern fringe of Gondwanaland during Late Palaeozoic time.

Hazarah Phosphate Deposits – Pakistan
by *N.A. Bhatti,* Geological Survey of Pakistan, Lahore

The Hazarah phosphate deposits are located in the northern region of Pakistan at the foot of the western Himalaysa, within Longitudes 73 to 74°E and Latitudes 34 to 35°N.

Phosphorite occurs associated with dolomite mainly in the upper 100 m of the Abbotabad Formation. This formation overlies the red beds of the Kakul Formation in the west, and lies unconformably above the metamorphic slaty siltstone of the Tanol Formation in the east. The Abbotabad Formation is unconformably overlain by the ferruginous glauconitic siltstones of the Galdanian Formation which are apparently succeeded conformably by limestones of Jurassic age. The phosphate bearing Abbottabad Formation is believed to be of Cambrian age on the basis of fossil evidence.

Phosphorites extend stratigraphically above and below the Abbottabad Formation, into the overlying Galdanian Formation and the underlying Tanol Formation. Within this interval, the phosphate rock varies in dimension from lesses a few millimetres thick to thick zones which extend for up to four kilometres along strike. The phosphorites vary in composition and appearance but are dominantly dark grey and distinctly pelletal, and grade to dolomite and chert. Pellets are mainly composed of collophane and are mostly about 5 mm across. Some pellets are entirely composed of dahllite, but a few have dahllite only along their marginal bands. Deposition of phosphate took place in a complex system of restricted basins with east and west shore lines, and open sea in the north. It is possible that the Hazarah deposits are a southern extension of the Chinese and Russian deposits of the same age.

Discussion

In the discussion which followed, the importance of the Proterozoic stromatolitic phosphorites of Rajasthan and Madhya Pradesh was emphasized. In western Rajasthan, the Birmania deposits are associated with north-south-trending fault blocks, but the western extension of these blocks and of any potential phosphate deposits into Pakistan has not yet been delineated. No genetic relationship has been established between the bentonite beds found in the overlying strata, which are probably of Early Eocene age, or with oil occurring in the Oligocene rocks further to the south.

With reference to the Proterozoic Jhamarkotra phosphate deposits, sections indicate that they occur to depths of up to 60 m. Another feature is the orientation of the stromatolites almost at right angles to the bedding. At Jhamarkotra and elsewhere, phosphate was almost always taken up in the stromatolites, although in places some reworking and recementation had also taken place. Traces of lead, zinc copper and uranium have been recorded from the stromatolitic phosphates in the Aravalli Group and further work might reveal some genetic association with similarly mineralized areas nearby.

Of interest was the contention that the Mussoorie phosphorites in the Lower Himalaya are of Late Palaeozoic, probably Permian, age. In particular, if a Permian age is accepted, it raises problems regarding the age of the glacial 'boulder beds' in the succeeding strata, at least one of which has been regarded as a well-defined mappable unit of Late Carboniferous age.

Discussion of the paper on the Pakistan deposits centred around the basis of the age of the Hazarah deposit which was originally classified as Permo-Triassic. It is now considered to be Early Cambrian on the basis of the presence of hyolithids (*Circotheca* and *Linevitus*) and *Chancelloria*.

Phosphorites of the USSR

Upper Precambrian and Lower Palaeozoic Phosphate Deposits in the USSR and the Mongolian Peoples Republic

by *A.L. Yanshin*, Institute of Geology and Geophysics, Novosibirsk.

The best known Lower Cambrian phosphorites of the USSR are those of the Karatau Basin, in the southern Kazakhstan Republic. The Karatau Mountains represent the northwestern portion of the extensive Tien Shan Mountains. This mountain system comprises folded Precambrian and Lower Cambrian rocks, intruded by Caledonide granites. The phosphorites were discovered in 1936 and their age established as Early Cambrian on the basis of the trilobite faunas. The phosphatic interval, which is 50 to 100 m thick, lies conformably on argillaceous sediments of the Vendian Kara Formation, and is overlain by a thick carbonate sequence (the Tamdo Formation) of Late Cambrian to Early Ordovician age.

The Maly Karatau phosphatic sequence comprises the following:

	Top	
5	10-25m	Cherty interval with some bedded phosphorites; P_2O_5 content 3-6%.
4	5-20m	Main ore horizon comprising black and dark grey fine-grained pelletal phosphorites; P_2O_5 content ranges from 23-32%.
3	1-5m	Mn-Fe rich dolomitic horizon with thin interbeds of chert and phosphorite; P_2O_5 content averages 9%.
2	up to 2m	Cherty dolomite averaging 1% P_2O_5 with a few thin bands of phosphorite.
1		Pebbly sandstones at the base overlain by light grey and massive to laminate dolomite.

The sequence has been strongly folded and overthrust, with beds generally dipping at 30-45° to the northwest over an area 250 km long by 60 km wide. Consequently, the main ore horizon is accessible to open-cut mining methods – in places along a distance of 20 km. In the northwest of the region the phosphate ore is overlain by Mesozoic sediments. Reserves are estimated by Bushinskii at 1×10^{12} tonnes of ore, equivalent to about 1.1×10^{11} tonnes of phosphate. There are two types of phosphorite in the Karatau Basin – pelletal (with a grain diameter of about 0.1mm), and oolitic. There are in addition, conglomerates composed of phosphate pebbles, and breccias composed by phosphate clasts. Erganov (pers. comm.) considers that these coarse phosphorites are not detrital but result from diagenetic dolomitization of pre-existing phosphorites.

Palaeogeographic analysis leads to the conclusion that during the time of phosphogenesis, the Karatau Basin was a marine strait 100-150 km wide. In the present southwestern part of the basin, the Kokdjon phosphate deposit ranges from 2-20m in thickness and averages 30% P_2O_5. In the southeast, where the water depth was greater, the main ore is 20-40 m thick, the average grade is lower (25% P_2O_5), and there are interbedded dolomites, siliceous, and argillaceous sediments. In the weathered zone the grade of the ore increases in all deposits due to the removal of carbonates and sulphur. In places there has been weathering and dissolution of apatite, followed by reprecipitation, to form white thin-bedded and brecciated, secondary phosphorite, enriched in manganese leached from overlying units.

A second important phosphate deposit of Early Cambrian and Late Precambrian age is in the Hubsugul Basin, which extends for 220 km north-south by 80 km east-west. It is of the Mongolian People's Republic, west of Lake Hubsugul, and extends into the USSR. Thick units of dolomite with bands of chert nodules contain two distinct phosphatic members each containing several units of black pelletal phosphorite. The presence of the trilobite *Olenellus* in the upper unit, suggests the same age as the Maly Karatau phosphorites. The upper phosphatic unit is generally about 2 m thick and has a P_2O_5 content of about 16%. The second phosphatic unit which occurs 250-300 m below the upper unit, contains no Cambrian fossils and in the interfingering dolomites there are stromatolites of Precambrian (probably of Yudomian or Vendian age). The lower unit is of particular interest as it contains five major phosphorite horizons ranging from 3-71 m thick. The interbedded units comprise phosphatized limestone, dolomite, and chert. In addition the phosphorites have a dolomitic or siliceous cement. Massive microsphoritic and brecciated phosphorites are common. The P_2O_5 content generally ranges from 18-25%, but in places approaches 31% P_2O_5. As in the Maly Karatau, all the units have undergone Caledonide folding. Reserves (down to 200 m depth) of 1×10^9 tonnes of ore have been established but only a limited amount of exploration has been undertaken to date and it is likely that the total reserves will exceed those of the Karatau region.

In addition to the Karatau and Hubsugul Basins, there are numerous other phosphate occurrences. North of Karatau there are thin beds of pelletal and nodular phosphorite in the Lower and Middle Cambrian. East of Karatau, the Middle Cambrian consists of grey limestone averaging 3.5% P_2O_5; but in places containing thin layers and lenses of pelletal phosphorite containing 27-32% P_2O_5. In the northern Tien Shan mountains, there are black shales of Middle Cambrian age which have high phosphorous and vanadium contents, and thin beds of high-grade pelletal phosphorite continue southeastwards into the People's Republic of China.

In the mountainous Altai-Sayan region of Siberia, there are carbonates of late Precambrian and Early Cambrian age, which in places contain 7-8% P_2O_5, and locally up to 15% P_2O_5 within the weathered zone. In places, irregularities in the karst surface (developed on top of the Cambrian carbonates during a Mesozoic weathering cycle) are filled with fine-grained white and yellowish collophane, similar in appearance to the phoscretes of the Georgina Basin. The total reserves of karst phosphorite are relatively small and do not exceed a few million tonnes.

Further east, along the northwestern bank of Lake Baikal, there are phosphate deposits of Late Riphean age which extend for more than 200 km. The sequence consists of siliceous limestone and dolomite 50-150 m thick, with thin interbeds of siliceous oolitic phosphorite containing 11-16% P_2O_5. Younger phosphorites of Late Precambrian and Early Cambrian age, containing up to 27% P_2O_5, occur in the Far East, including the Shantar Islands in the Sea of Okhotsk.

Thus, the area of the Late Precambrian and Cambrian phosphate deposits and occurrences extends from the Maly Karatau area of Kazakhstan to the Sea of Okhotsk, a distance of 7000 km.

Many parallels appear to exist between the phosphorites of the USSR and those of Australia. The pelletal and breccia types are found in both areas, and Mesozoic and Tertiary weathering has played a most important role in upgrading the deposits. The Australian phosphorites are much lighter in colour than those of Asia, but this may be attributed to the tropical climate of northern Australia which has produced deep weathering. In both Asia and Australia, phosphorites are accompanied by dolomite limestone and calcareous shale, but detrital sediments are generally absent from both areas.

The origin of the Precambrian and Cambrian phosphorites in northern Asia is still very problematical and several hypotheses have been put forward. It is hoped that Project 156 will be able to help resolve this and other problems.

Calcium Phosphates from Ancient Geosynclinal Basins

by *Yu. N. Zanin,* Institute of Geology and Geophysics, Novosibirsk

It is an old observation that the CO_2 content of phosphorites decreases with increasing age; however, there are many exceptions. For example, the Ordovician phosphorites from the eastern European platform contain more CO_2 than Neogene (Miocene) phosphorites from Sakhalin Island; Palaeogene phosphorites from western Africa contain the same amount of CO_2 as the Cambrian phosphorites of Australia; and the Neogene phosphorites of Africa have the same CO_2 content as the Mesozoic ones of the eastern European platform (Table 6).

Analysis of samples shows that, as a rule, low content of CO_2, Na_2O and H_2O+ are found in calcium phosphates from phosphorites overlain by sedimentary series at least several kilometres thick (buried to the zone of catagenesis and affected by high temperatures and pressures). These phosphorites include those of the Karatau, Hubsugul, and Georgina Basins, and the Phosphoria Formation. Perhaps similar conclusions may be drawn for phosphorites which have been buried to depths which extend into the zone of temperatures of up to 300°C and pressures of up to 2500-3000 bars. These temperatures and pressures do not cause any noticable change in phosphorite composition in the short term and only by subjecting them to these temperatures and pressures for hundreds of millions of years are the above mentioned effects produced. So, in the catagenetic environment, a long period of time is necessary to account for the compositional change in phosphorites. It has been established by Kzivoputskaya that catagenesis promotes the development of the fine crystalline structure of apatite, which decreases the degree of microdistortion. Vachrameev has similarly established (using nuclear magnetic resonance) that hydroxyl ions and structurally-bound water are present. The decrease of H_2O in the apatite is considered to result mainly from the loss of this structurally-bound water. Finally, it is noted that catagenesis affects not only composition but also the solubility of calcium phosphates.

Table 6 Chemical Composition of some Phosphorites

Deposit, basin, area	Age	Number of samples	Constituents, % P_2O_5	CaO	Na_2O	F	CO_2	H_2O^+	CO_2: P_2O_5	Na_2O: P_2O_5	H_2O^+: P_2O_5	Reference
1. Phosphorites unaffected by catagenesis												
		Concretional										
East European platform	J_3-Cr	10	30.34	47.59	1.35	2.86	5.44	4.39	0.18	0.044	0.14	Author's data
	"	11	30,59	48.01	–	3.27	5.94	–	0.19	–	–	Smirnov 1972
						Granular						
North Carolina	Ng	2	29.81	47,89	1.23	3.32	4.38	3.95	0.13	0.041	0.13	Rooney & Kerr 1967
	"	1	31.50	48.02	1.45	2,60	5.32	5.23	0.17	0.048	0.18	Author's data
	"	1	30.56	47.50	0.96	3.76	4.90	–	0,16	0.031	–	McClellan & Lehr 1969
		2	30.70	48.90	–	3.60	5.30	–	0.17	–	–	Smith & Lehr 1966
Florida	Ng	2	33.80	50.77	0.62	4.00	3.45	–	0.12	0.019	–	McClellan & Lehr 1969
	"	2	34.00	50.61	1,02	2,90	3.45	3.34	0.10	0.030	0.10	Author's data
	"	11	33.90	48.00	–	3.70	2.50	–	0.07	–	–	Cathcart 1963
	"	5	33.00	49.60	–	4.00	3.80	–	0.12	–	–	Smith & Lehr 1966
West Africa:												
Senegal	Pg	2	37.92	52.72	–	3,51	1,60	–	0.04	–	–	British Sulphur Corp 1961
		1	37.46	52.42	0.17	3.83	1,65	–	0.04	0.005	–	McClellan & Lehr 1969
Togo	Pg	1	37.29	51.71	0.12	3,32	1,27	–	0.03	0.003	–	British Sulphur Corp 1961
East European platform						Shelly						
Maardu	θ_1	3	34.02	48.99	0.95	2.68	3.33	2.64	0.10	0,028	0,08	Author's data
Kingisepp	"	5	37.23	51.60	1.04	2.59	4.14	2,53	0.11	0.027	0,07	Author's data
2. Phosphorites affected by catagenesis												
		Microgranular										
Karatau Basin (Aksai and Ganatas deposits	ϵ_1	5	35.17	49,94	0.76	2.90	2.00	1.12	0,06	0.021	0.032	Author's data
Udsko-Selemdqinsk interfluve	ϵ	2	28.60	40.42	0.33	3.40	0.84	0,26	0.03	0.011	0.01	Author's data
Hubsugul Basin	ϵ_1	2	40.20	52,85	–	3.60	0.76	–	0,02	–	–	Ilyin 1973
Phosphoria Formation	P	60	30.50	44.00	0,60	3.10	2.20	1,60	0,07	0.020	0,05	Gulbrandsen 1966
North-West Queensland	ϵ_2	10	36.26	49.48	0.24	3.4	1.27	0,77	0.04	0.007	0.02	Cook 1972
		4	37.70	52.00	0.36	–	1.11	1.02	0.03	0.010	0.03	Russell & Trueman 1971
China (concretional and microangular phosphorites)	ϵ_1	10	34,73	48,38	0,64	2,7	1.74	0.24	0.05	0,018	0.006	Bushinsky 1966
Antarctica (slightly met)	Pz	3	26,90	39.50	0,04	2.49	0.48	–	0.02	0.0015	–	Cathcart & Schmidt 1977
						Concretional						
Turukhansk Upland	R	3	30.30	39.81	0.55	2.40	0.75	–	0.025	0.017	–	Ivanovskaja (unpubl.)
Sakhalin island	Ng	5	31.93	42.37	–	2,30	1,12		0,040	–	–	Brodskaya 1959

The Hubsugul Phosphorite-bearing Basin

by *N.S. Zaitsev*[1], Geological Institute of the USSR Academy of Sciences, Moscow

The Hubsugul phosphorite-bearing basin lies to the west of Lake Hubsugul in a mountainous area in the northern part of the Mongolian People's Republic. Phosphorites were discovered about 1960. Geological studies of the territory carried out subsequently have led to the recognition of a phosphorite-bearing basin about 25,000 sq kms in area, stretching from north to south for over 150 km, and from west to east for approximately 100 km. Although the area has been incompletely studied, several groups of large deposits and a number of occurrences have been discovered. The phosphorite-bearing sediments of the basin were deposited during the latest Precambrian to earliest Cambrian. They are associated with a thick (over 3 km) series of mainly siliceous-carbonate rocks, deposited under geosynclinal trough conditions, which transgress over older Precambrian sediments. The basin has a complicated synclinal structure. Some deposits and occurrences are localised in its western and eastern parts. Phosphorites of the eastern belt which are potentially the most important, pinch out towards the central part of the basin.

The phosphorites occur in a series of carbonate-siliceous rocks which include some basic volcanics and terrigenous rocks. As a rule, phosphorites form two members in this series; the lower is the major one. Petrographically, both carbonate and siliceous variieties can be distinguished among these phosphorites. Texturally, they comprise pelitomorphic, granular, brecciated, and massive varieties. The P_2O_5 content averages 20-22% in deposits on the eastern margin of the basin. The palaeogeographic and palaeotectonic conditions for the formation of the phosphorite-bearing series have been extensively studied. It has been established that the sedimentation of siliceous-carbonate rhythmically-laminated phosphorite-bearing rocks occurred in the marginal part of a large geosynclinal basin during Vendian-Early Cambrian time. A relatively narrow (200-300 km) trough, bordered to the east and west by large uplifted blocks composed of older Proterozoic-Archean rocks, was separated from the geosyncline in the Hubsugul region. In the north and south the trough was connected with the open Vendian-Cambrian sea. Predominantly volcanogenic-terrigenous sediments accumulated in areas adjacent to the phosphorite basin. Impoverishment of the phosphorite-bearing series takes place in this direction, i.e. north and south of the Hubsugal Basin. Enormous masses of submarine basic and intermediate effusive rocks are widely distributed in adjacent and more remote parts of the Vendian Cambrian basin which could have served as a source of phosphorous and silica for the Hubsugul phosphorite-bearing series. On the whole, the bedded phosphorites of the Hubsugul Basin are attributed to the Proterozoic-Cambrian geochemical epoch of phosphorite accumulation, which was recognized in 1965 by A.L. Yanshin as of major importance to much of Asia. Phosphorites of the Georgina Basin in Australia and those of Karatau in Kazakhstan appear to have been formed in the same geochemical epoch.

Discussion

Discussion on Yanshin's paper centred around 3 points: 1) The nature of the depositional basins at Karatau and Hubsugul, i.e. depth of phosphorite deposition – topographic controls – and geometry of the basins. The Karatau Basin is believed

[1] The writer was unable to be present at the Seminar.

to have been an open strait because of the presence of sands at both the northeastern and southwestern ends of the basin. There was no major topographic control; the phosphorites were believed to be epicontinental deposits with water depths reaching about 200 m. 2) The economic parameters of the phosphorites, i.e. reserve calculations and grade distribution. It was explained that the 10 billion tonne reserve figure for the Karatau Basin represents the total potential phosphate available in the basin. The middle bed of the deposit contains the richest ore with 32% P_2O_5 The adjacent beds average 9% P_2O_5. 3) The origin of the phosphate grains. Professor Yanshin believed that the formation of Cambrian phosphates cannot be explained by upwelling, because life was not abundant enough at that time. Rather he believes it was formed as a chemical sediment of amorphous collophane.

In response to the question of whether Dr Zanin had examined both primary and secondary apatites, Zanin explained that all the apatites analysed were unweathered continental phosphates that had undergone the first stage of diagenesis. It was pointed out that the work was done on powdered material and that no one to date knows the precise structural formula of the sedimentary apatites because of their extremely fine-grained nature. The comment was made that work on the organic fraction of the Georgina Basin phosphorites indicated that they had not been affected by catagenesis as Dr Zanin postulates. The organic fraction of the Georgina Basin demonstrates for instance a greater similarity to the younger deposits of the eastern United States, than Karatau or the Phosphoria. Dr Zanin replied that the Georgina Basin material had not been studied from a catagenic viewpoint; if this were to be done, then similarities may become more apparent.

Phosphorites of Europe, Africa, and South America

Proterozoic and Cambrian Phosphorites in Europe

by *A.J.G. Notholt,* Institute of Geological Sciences, London

Sedimentary phosphate rock is widely distributed in Europe, occurring mainly as phosphate nodules and concretions marking unconformities or diastemic surfaces and as formations of Upper Cretaceous phosphatic chalk (in France and the United Kingdom), or phosphatic limestone (in southern Italy), the latter being primarily of Miocene age. A relatively large number of deposits were worked during the 19th century, but because of their limited extent and thickness none is of commericial interest at present. However, a small tonnage of low-grade phosphatic chalk continues to be produced annually from the Paris Basin. Of significance also, in recent years, has been the recovery of apatite in Sweden as a by-product of iron ore mining. Apatite production is likely to increase but, in spite of this, Europe will most probably continue to be virtually dependent upon imports of phosphate rock for use in the manufacture of phosphate fertilizers and phosphate chemicals.

The presence of sedimentary phosphate rock of Cambrian and Proterozoic age in Europe has been known for many years, the first occurrences having been described from the United Kingdom in 1875 and 1904 respectively. Other occurrences have been described from Norway, Sweden, Denmark, Poland, Czechoslovakia and, fairly recently, in eastern Finland. Most of the occurrences are in the form of thin, reworked nodule beds, with the notable exception of the new discoveries made in the Cambrian strata of northern and southern France. Further discoveries in Europe are likely if systematic phosphate exploration is undertaken. A sedimentary phosphate province of at least Cambrian age may exist.

Mention should be made also of the various alkaline igneous-carbonatite complexes which have been extensively investigated in recent years in Norway and Finland. Phosphate mineralisation is also known to occur in the Loch Borralan igneous complex in the North West Highlands of Scotland. The most advanced project is centred on the Siilinjarvi carbonatite in central Finland, where commercial production was scheduled to begin during the latter half of 1978.

West African Infracambrian Phosphorites
by *M. Slansky*, Bureau de Recherches géologiques et Minières, Orléans

Phosphorites are located on the western (east Senegal) and the eastern (west of River Niger area) sides of the West African craton. The area west of the river has the most important phosphate deposits. These are distributed between the Republics of Niger, Haute Volta and Benin. The phosphatic sequence is considered to have an Infracambrian age (about 650 m.y.). The sequence generally commences with a tillite, which is followed by limestone, pelites, and chert associated with phosphorites. The main phosphorite is commonly several metres thick and has a P_2O_5 content between 20 and 25%. In a drillhole at Tapoa, the main ore is 60 m thick. The ore is generally pelletal (phosphorite), and is finer-grained in Haute Volta (Kodjari) than in Niger or Benin, where it is mixed with more terrigenous material. In east Senegal the phosphate is less regular and has stromatolitic textures.

Phosphorite Deposits, Bambui Group, near Patos de Minas, Minas Gerais, Brazil
by *J.B. Carthcart*, U.S. Geological Survey, Denver

The Bambui Group of late Precambrian or early Cambrian age is present over a large part of the Brazilian state of Minas Gerais and adjacent parts of Gorias to the west and Bahia to the north. The Rio Sao Francisco effectively divides the group into a western facies composed of fine-grained clastics and carbonate, and an eastern facies composed of coarser clastics – sandstone, some shales and conglomerates, and only minor carbonate. The Bambui Group is divided into three formations – the Paranoa Formation at the base, the Paraopeba Formation in the middle, and the Ires Marias Formation at the top. The group is overlain by flat-lying Cretaceous sandstones, and is underlain by Precambrian metamorphic and intrusive igneous rocks.

Phosphoritic deposits are found in the Indaia member of the Paraopeba Formation, at the base of a series of yellow, red and green siltstones. The phosphorite is laminated, isoclinally folded, and is composed of black, elongate apatite pellets and quartz grains, cemented by quartz and muscovite. Abundant narrow quartz veinlets cut through the rock at right angles to the elongation direction of the pellets. The phosphorite is up to 80 m thick and contains 5 to 30% P_2O_5. The deposit is elongate to the northwest, and the central part of the deposit, which is the thickest and richest part, is bounded by faults. Reserves total almost 500 million tonnes with an average grade of 11% P_2O_5. Additional resources are known to be present at Ponte Caida to the southwest and at Coromandel to the west. These resources may be at least equal to those at Patos de Minas.

Discussion

Recent discoveries of Cretaceous-Eocene phosphorites in Greece, and Yugoslavia, were mentioned during the discussion. The exploration of European carbonatites and nephelene syenites for phosphate is now feasible because of advances in mineral processing technology. These advances permit the exploration today of deposits containing only 5% P_2O_5 (Brazil, USSR).

The Infracambrian age of the Niger-Volta deposits was questioned. A radiometric date greater than 640 m.y. is based on a shale that overlies the phosphorite. While some shale dates are subject to criticism, this date is accepted by people familiar with the deposit. The structure of the Bambui deposit was discussed at length. The phosphate-bearing portion of the Bambui is folded between two unfolded limestones and is interpreted as slumping between two competent beds. The Bambui deposit is stratigraphically equivalent to the slightly phosphatic sediments known near Abaete, Brazil.

Young Phosphogenic Systems

Phosphorite Sedimentation in Florida, a Model Phosphogenic System

by *Stanley R. Riggs,* East Carolina University, Greenville

Phosphatic sediments occur in many parts of the geologic column and form in many environments on the seafloor in response to "normal" conditions and processes of sedimentation. However, that portion of the Miocene which contains the extensive phosphorites and associated anomalous sediments of the Hawthorn Group represents a very "abnormal" period of sedimentation. This phosphogenic system was characterised by a specific tectonic setting, structural framework, and an "abnormal" set of environmental conditions; the consequence of which was one of the most extensive and important phosphate deposits in the world.

The structural framework which controlled the formation and deposition of the phosphorites of the Florida Miocene was a series of arches or topographic highs associated with the major Ocala Upland and Sanford High. Extensive coastal, shallow near-shore shelf, and platform enviornments occurred around the highs and were the sites of major phosphorite sedimentation – the *phosphate machines* and associated *entrapment basins.* The peripheral phosphogenic belt is situated around the Ocala Upland and was dominated by microsphorite-intraclast sedimentation. The outer phosphogenic belt occurs down the depositional slope from the Ocala and in the offshore areas around the Sanford High: this area was characterised by pelletal phosphorite sedimentation. Phosphorite precipitation took place as the cold, chemically supercharged and possibly somewhat toxic upwelling waters moved across the shallow platforms and into the coastal environments. The biologically stressed shallow-water environments received the bacterially precipitated microcrystalline phosphorite mud, or *microsphorite,* as well as the other biologically produced phosphate grains. This orthochemical microsphorite mud, includes dolomite mud, and fine terrigenous sediment. This was affected by the local environmental energy conditions and biological processes. The muds were populated by a benthic community, characterised by high environmental tolerances and a low diversity index, which ingested and excreted the muds as faecal pellets. Under low energy conditions the muds settled out, became indurated, and were subsequently broken up by biological and physical processes, to produce intraclasts. Very locally, under high energy conditions some of the mud was aggregated to produce pseudoolites. The resulting phosphorite allochems (phosphorite gravel, sand and silt) were then transported as clastic particles along and off the shoals by periodic high energy conditions. They were diluted by the associated terrigenous and carbonate sediment systems and were deposited and accumulated in the adjacent entrapment basins and on the flanks of the structural highs. Thus, wherever the phosphorous sources were adequate, the physical current suitable, the geochemical systems appropriate, and the shallow marine environments had the proper geometry, then the "phosphate machine" produced and supplied clastic phosphorites to the associated "entrapment basins". The ultimate magnitude of phosphorite deposition was then dependent upon the size of the structural system, the duration of the phosphogenic system through geologic time, and the volume and rate of terrigenous or carbonate diluent sedimentation. Subsequent fluvial erosion and subaerial weathering severely modified the updip portions of the Hawthorn phosphorites following emergence.

Microbiological Controls on Phosphate Accumulation

by *P.A. Trudinger**, Baas Becking Geobiological Group, Canberra

Speculations on the possible roles of organisms in the formation of phosphate deposits have lead to the formulation of three main hypotheses: 1) biological reduction of phosphate to soluble hypophosphites followed by oxidation to the latter in aerobic environments with the formation of apatite; 2) modification of the CO_2-bicarbonate-carbonate equilibrium, which in turn controls phosphate deposition; 3) accumulation of phosphate by phytoplankton followed by incorporation of the plankton into sediments and the release and fixation of phosphate.

Only the last of these three hypotheses appears to be consistent with current evidence. It is particularly relevant to regions of coastal upwelling where high nutrient levels result in increased productivity and where the levels of phosphate appear to be insufficient to allow chemical precipitation of calcium phosphates. Calculations show that the microflora in upwelling environments could supply sufficient phosphate to form large phosphorite deposits in a geologically reasonable time.

The possible role of Dinoflagellates in Phosphate Sedimentation

by *D. Fauconnier* and *M. Slansky*†, Bureau de Recherches géologiques et Minières, Orléans.

The relatively high content of phosphorous in the mineral fraction of dinoflaggelates, and the particular abundance of this oceanic plankton close to modern or recent phosphatic nodule deposits, led to research into the possible links between this phytoplankton and phosphate sedimentation. Albian-Cenomanian phosphatic sequences of the Paris Basin and a Palaeocene sequence of the Gafsa Basin, Tunisia,

* This paper is given in full in the Appendix.

† Published in full in the Appendix. This paper is published in French in BRGM Bull. 4(3), 1978.

have been studied with this object in mind. Data obtained show in both cases an association of phosphate with sediments rich in dinoflagellates, with periodic disequilibrium in relative abundance of species, as in "red tides". This association appears valid at the scale of the sequence but is not generally true in detail because during diagenesis, apatite neoformations seem to grow, at least in part, out of dinoflagellate cysts. It seems also that these cysts may contribute to silicate neoformations such as glauconite or montmorillonite.

Submarine Phosphorite Deposits on Chatham Rise, East of New Zealand

by *David J. Cullen,* New Zealand Oceanographic Institute, Wellington North.

Phosphorite occurs on Chatham Rise as a nodular deposit interspersed with an unconsolidated foraminiferal ooze matrix, and resting on a basement of Oligocene chert-bearing chalk. The nodules consist of phosphatised limestones mainly of Early and early Middle Miocene age, and are typically coated with greenish black glaunconite. The latter is equated with granular glauconite on Chatham Rise that has been radiometrically dated as 5.6 ± 1 m.y. Phosphatisation and nodule formation are therefore assigned to Middle – Late Miocene times. The phosphorite extends patchily for some 480 km along the crest of the Rise at depths usually less than 400 m, with major concentrations in the broad saddle between Reserve and Matheson Banks, in the vicinity of the 180° meridian. The phosphorite deposits are being investigated by a combination of bottom photography, box and piston coring, and 3.5 kHz profiling, with a view to determining their economic potential. So far, local concentrations of phosphorite up to 75-80 kg/m^2 have been established for the topmost 0.25 m of sediment, with a provisional average figure in the order of 17 kg/m^2 over large areas. The phosphorite particles range in diameter from 2-150 mm, with maximum frequencies in the 2-4 mm and 16-32 mm size grades. Their P_2O_5 contents vary from about 16 to 25%, the higher values occurring in the Chatham Rise phosphorites. The maximum uranium value for an individual sample is 512 ppm U_3O_8, and 27 random samples average 220-230 ppm U_3O_8. Rare-earth element analyses show an overall depletion in cerium and europium.

Environment of Deposition of Marine Phosphate Deposts off Peru and Chile

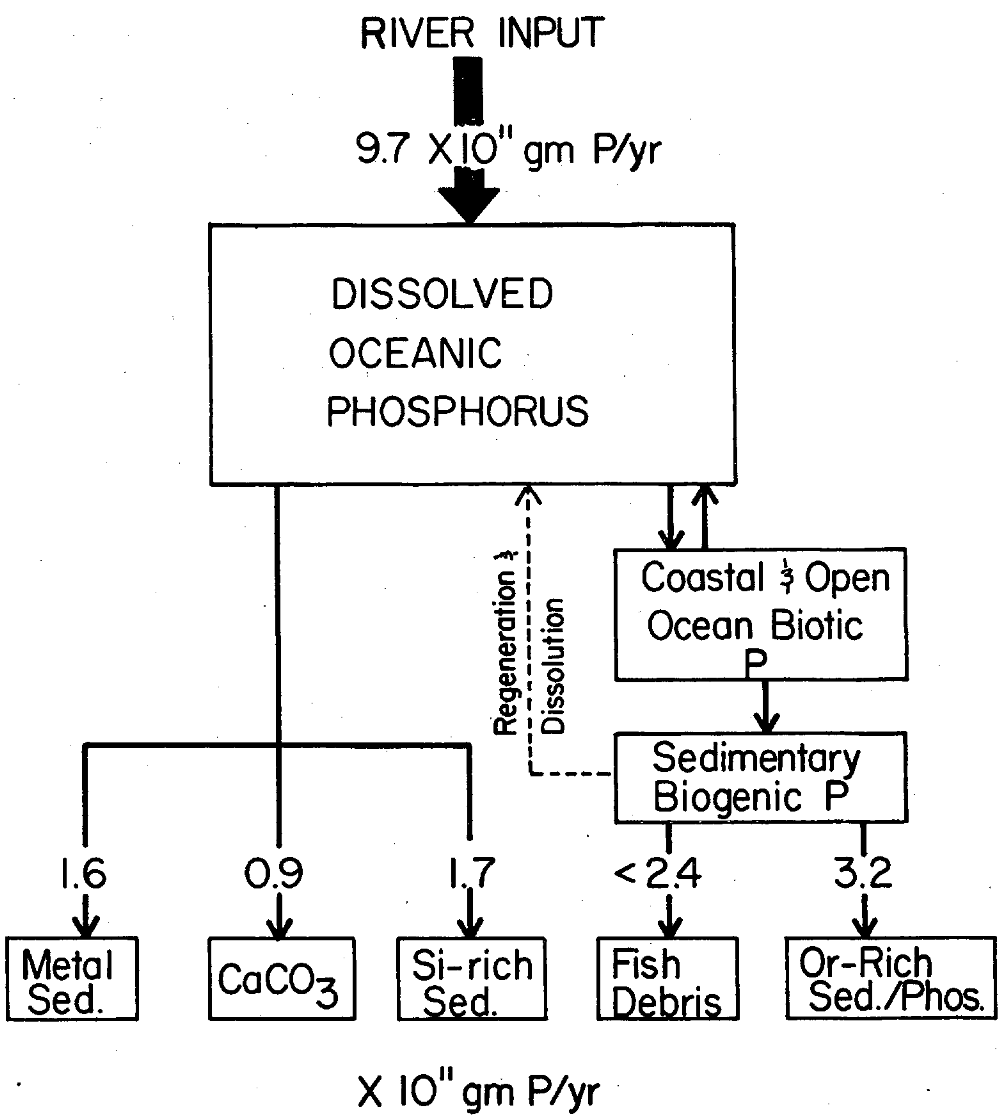
by *W.C. Burnett* and *T.G. Oas,* Department of Oceanography,
Florida State University, Tallahassee

Modern authigenic phosphorite deposits occur along the upper continental margins of Peru and Chile. This region is one of only two areas of the world where the contemporary formation of phosphorite has been documented by radiometric dating. The phosphorite occurs mainly as nodules associated with laminated, organic-rich diatomaceous ooze, a reflection of the extremely high organic productivity of the area. The distribution of phosphorite nodules with youthful uranium-series ages parallels the regions of minimum dissolved oxygen and maximum dissolved phosphate in the bottom waters off Peru. Further to the south, off Chile, the uranium-series ages become progressively older and there is no longer any apparent correlation between the distribution of the phosphate deposits and prevailing oceanographic conditions. Apparently, the conditions favourable for forma-

Fig. 11 Suggested geochemical balance for the cycle of dissolved phosphate in modern oceans.

Assuming steady-state conditions, sum of all outputs must equal the riverine flux of phosphorous to the oceans. All fluxes are in terms of 10^{11} grams dissolved phosphorous per year. River input calculated by multiplying the "buffered" estuarine concentration of P in estuaries (Liss 1976) by average river discharge. Rate of P uptake by metalliferous sediments taken from Froelich *et al.* (1978). Amounts of P incorporated into carbonate and siliceous sediments per year calculated by multiplying average clay-free concentration of each sediment type by their respective accumulation rates. The P accumulation in the form of fish debris (bones, teeth, etc.), is from Lowenstam (1974). This is an upper-limit number since dissolution of fish debris was not taken into account. The average annual flux of P into organic-rich sediments and phosphorites is simply the river input minus the summation of the other reported sinks.

Note that the box marked "Sedimentary Biogenic P" represents all the P fixed in the biochemical cycle that is deposited as sediment. The smaller boxes marked "fish debris" and "organic-rich sediments/phosphorites" on the other hand, represent the amount of P which is *preserved* in these sinks. The combined effects of dissolution and regeneration make these sinks some intermined amount less than that originally deposited in the sediments.



tion of phosphorite have migrated towards the north during the past few tens of thousands of years. Because of low dissolved phosphate levels, few nucleation sites, and the presence of interfering ions, it is doubtful that marine apatite precipitates directly out of bottom waters flowing over the continental margin of Peru. It is suggested, however, that inorganic precipitation of carbonate fluorapatite within sediment pore waters, with subsequent reworking into indurated nodular deposits is the most likely mechanism for the origin of these deposits. High phosphate concentrations (approximately two orders of magnitude above saturation), availability of suitable nucleation sites, high pH, and low concentrations of interfering ions, are the factors which apparently control the incipient formation of marine apatite within the anoxic sediments currently being deposited off Peru.

In an attempt to evaluate the role sedimentary phosphorites play in controlling the marine budget of phosphorous, a geochemical balance for P in the modern ocean has been constructed (Fig. 11). Our estimate of the annual flux of P to organic-rich sediments and phosphorites indicates that approximately 30% of the river-derived P may be deposited in upwelling areas. Without additional information concerning net accumulation rates of organic P in coastal sediments, growth rates of phosphorites, regenerative loss of phosphate, and amounts of P fixed by productivity in upwelling regions, it is impossible to evaluate more explicitly the extent to which phosphorites act as a sink of phosphorous in the oceans. If phosphorites do act as a significant output of P from the oceans, then it is logical to ask: what happens to the P which is normally incorporated into phosphorites during periods of non-deposition of phosphatic sediments? It has been suggested that phosphorite formation in the past has not been continuous but episodic and perhaps has been tied to other large-scale changing phenomena. If this is the case, then either the oceans have periods when they accumulate dissolved P or the other P "sinks" play a proportionately greater role during times of non-deposition of phosphorites. Kolodny has pointed out, for example, that periods of greater productivity, and hence phosphorite formation, could be associated with periods of slower sea-floor spreading, when metalliferous sediments were produced at a slower rate than at present. Rather than accept the point of view of phosphate accumulation in sea water, we favor the hypothesis that alternate sinks pick up "excess' P not incorporated into organic-rich sediments and phosphorites during periods when these form only in small amounts.

South West African Offshore Phosphorites

by *J.M. Bremner*, Geological Survey of South Africa, Rondebosch

Phosphorite deposits on the Agulhas Bank and the west coast of South Africa are predominantly of the replacement-type, having formed by phosphate substituting for carbonate in pre-existing calcareous sediments. North of the Orange River, phosphorites of Neogene age appear to be the result of direct inorganic precipitation of apatite from sea water, and those of Quaternary age, to slow authigenic growth of carbonate fluorapatite in the interstitial fluids of nearshore diatomaceous sediments.

Four different phosphorite types occur on the South West African continental shelf (Fig. 12). The oldest of these are pelletal phosphorite (pP) and glauconitised pelletal phosphorite (gpP) which formed penecontemporaneously during the Late

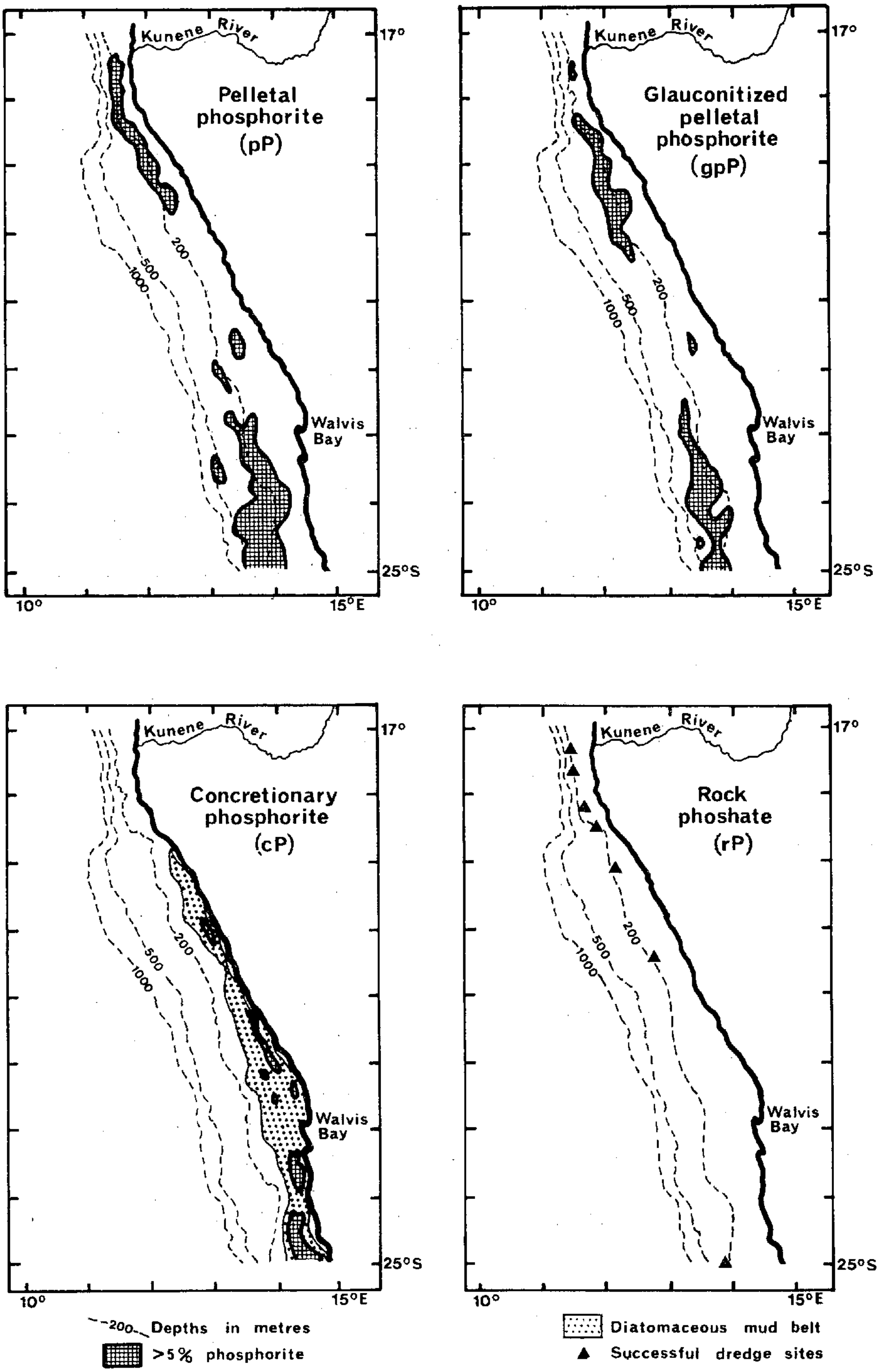


Fig.12 The distribution of phosphorite types on the southwest African continental shelf AUS 1/741

Miocene, and are found today in two mineralized provinces on the mid shelf. The particles are fine sand-size, spherical, and occur intimately mixed with unconsolidated relict sediments. The third phosphorite type is rock phosphate (rP). It occurs only in minor quantities and is typically found as small infillings in bored limestones. A tentative Pliocene age has been assigned to it by analogy with similar material confidently dated from south of the Orange River. The fourth phosphorite type on the South West African continental shelf is concretionary phosphorite (cP) which has been dated by uranium-series methods as Quaternary in age. It is found predominantly along the landward flank of the diatomaceous mud belt and occurs in a great variety of different sizes and forms. Dark brown concretions are generally older and more lithified than pale yellowish examples and frequently they contain fish debris, such as scales and small vertebrae.

Geochemically the pP are distinguishable by high concentrations of S and C_{org}. Most of the S is situated in pyrite which in 20% of the pellets is distributed along discontinuous rings. The gpP contain abnormally high concentrations of Fe, and when the rims exhibit significant glauconitisation, K is also present in abundance. Mature cP nodules consist almost entirely of Ca and P but they also contain higher concentrations of Mg and CO_3 than either of the two pelletal varieties. Regarding the trace element geochemistry of these phosphorite types, Y, Cu, Ni, Ti, Cr, V, Rb, Mn and Zr occur most abundantly in the gpP, and then in the pP; Sr, Ba and Zn are most concentrated in the cP; and Co and Nb are present in concentrations below the detectable limits of the analytical method.

A model envisaged for pP and gpP formation involves the development of estuarine lagoons along the coast resulting from increased rainfall in the hinterland. Cold, upwelled, nutrient-rich water drawn into the lagoons through estuarine circulation was heated by solar radiation, and became admixed with river water which imported terrigenous clay material and iron ions. The Ca/Mg ration of the lagoon waters was raised through cation exchange with the suspended clay material, and bacteria actively assisted in the apatite re-precipitation process. Close to the river mouth, the lagoon waters possessed a relatively low pH and high Eh and proto-gpP mud precipitated directly from the water column in the intertidal zone. Further away from the river mouth, the waters possessed a relatively high pH and low Eh which initiated precipitation of proto-pP mud. Sub-aerial exposure of these mud layers resulted in desiccation and the development of mud cracks, and periodic entry of storm-generated waves then fragmented the material into discrete particles.

The model envisaged for present-day cP formation involves the existence of a suspended barrier of illite mica with a high proportion of free iron immediately above the sediment-water interface on the landward flank of the diatomaceous mud belt. This barrier is brought about by the high phosphate absorption capacity of illite, and serves to prevent regeneration of phosphate from the muds to the overlying water. The interstitial fluids consequently become grossly oversaturated with respect to orthophosphate ions. However, the Ca/Mg ratio of the diatomaceous muds is too low, and the temperature of upwelled waters on the open shelf is too cold for direct participation to occur. Instead, a slow process of authigenic growth of carbonate fluorapatite crystallites takes place. This is brought about by seeding of the interstitial fluids with phosphatic solids such as fish scales.

Modern Environments of Phosphorite Formation and the Geochemical Balance of Phosphorous in the Ocean

by *H. Herbert Veeh,* Flinders University of South Australia, Bedford Park

Modern environments of phosphorite formation have the following characteristics in common:

1 high organic productivity, caused by intense upwelling associated with eastern boundary currents ;

2 oxygen deficient water (<1 ml O_2/L) in the immediate vicinity of the sea floor ;

3 a matrix of organic-rich sediment in relatively shallow water (<500 m);

4 a location with 30° latitude north or south of the present equator.

No contemporary marine phosphorites, as defined by uranium-series disequilibrium dating, have so far been found in areas where any of these conditions are not met. It appears that high organic productivity is required in order to maintain an adequate supply of organic matter and hence phosphorous to the sea floor, while a low oxygen content combined with shallow depth of water would prevent complete destruction of the organic matter prior to its burial in the sediment, where apatite then forms by heterogeneous nucleation on suitable sites. Since apatite generally becomes less soluble with increasing temperatures, the formation of phosphorites is more likely to take place at low latitudes.

Geochemical balance calculations suggest that dissolved phosphorous is removed from the ocean predominantly by metalliferous sediments, ferromanganese nodules, biogenic carbonates and organic-rich sediments including fish debris and phosphorites. The relative importance of these phosphorous sinks at a given time depends on many factors, of which eustatic sea level appears to play a significant role. At the present time, organic-rich sediments together with associated phosphorites in areas of upwelling are not a major phosphorous sink, and phosphorous removal must be dominated by other sinks. During times of maximum invasion of continents by shallow seas, relatively more carbonate is trapped on the continents, raising the carbonate compensation depth in the ocean and hence transferring a potential phosphorous sink from the deep sea into shallow water. At the same time, owing to the expansion and intensification of the oxygen minimum layer, a larger proportion of organic matter survives destruction, making more phosphorous available for the formation of apatite. The association of major phosphorite deposits with transgressions in the geologic record would be consistent with this model.

Discussion

Several comparisons were made between Florida and the Georgina Basin deposits, and the similarities between the respective deposits were noted. In both cases, it appears that the mudstones are low in organic carbon contents, presumably because of more oxygenated conditions during the formation of the former. This interpretation is consistent with shallow water features observed in the mudstones of the Florida deposit. The possibility of a biological origin for offshore pelletal phoshorites was discussed. Of particular interest in this connection is the observation, made elsewhere, that certain molluscs living under stressed conditions secrete phosphatic kidney stones.

Following the talk by Trudinger, the difficulty of explaining the association of ancient phosphorite deposits with stromatolites in terms of modern biologic processes was noted. The question was raised whether the periodicity of major phosphorite deposits in the geological record would require periodic increases in the phosphate content of the ocean, and whether this would violate the steady-state assumption of current ocean models. Slanksy showed that the phosphorous content, normalised to silica, was much greater in dinoglagellates than in diatoms, and proposed that the chert-phosphorite association noted in many deposits could be explained in terms of deposition by diatoms and dinoflagellates, respectively.

Comments were made on similarities between the petrography of modern phosphorites from the sea floor of Peru-Chile and the deposits in Florida and the Georgina Basin. An example was cited from the Baltic Sea, where anaerobic regeneration of phosphate from the sediment is a common phenomenon. This raised the question of how phosphate remained fixed in the laminated, anaerobic sediments on the upper continental slope of Peru. The different behaviour of phosphate in these two environments would suggest that phosphate is held in the sediments off Peru by diagenetic apatite which apparently does not form in the sediments of the Baltic Sea. Various aspects of the geochemical balance of phosphorous were examined, including the possibility of hydrothermal input of phosphorous along active mid-oceanic ridges for which there are at present insufficient data. Of special interest was the possible expansion of the oxygen minimum in the ocean during major transgressions and its possible effect on the phosphorous budget in a steady state model of the ocean.

The question was raised why no phosphatic hydrogels, described by previous workers, were reported in the study of the southwest African phosphorites. Apparently these hydrogels, which occur as very soft layers near the surface within diatomaceous muds on the inner shelf, are easily destroyed by the sampling procedure (grab samples) employed. It was proposed that hydrogels form by adsorption of phosphate onto illite, and hence the illite acts as a trap for dissolved phosphate after its release from organic matter within the diatomaceous muds.

The occurrence of pelletal phosphorite of Miocene age in deep (200 m) water outside the main belt of diatomacous mud was noted. Since in the model presented, these phosphorite pellets are of relatively shallow water origin, either a temporary Miocene lowering of sea level, or tectonic subsidence of the outer shelf must have taken place in this area.

Classification of Phosphorites

Proposals for Nomenclature and Classification of Sedimentary Phosphate Rocks

by *M. Slansky*, Bureau de Recherches géologiques et Minières, Orléans

The "Glossary of Geology" (American Geological Institute 1974) uses the words "Phosphorite" and "Phosphatite" as follows:

"*Phosphorite:* A sedimentary rock composed principally of phosphate minerals (Ca, Al, Fe. . . . phosphate minerals)".

"*Phosphatite:* A sedimentary phosphatic rock composed principally of the mineral apatite in its various forms".

When a sedimentary rock contains 50% phosphate minerals, its grade may generally vary from about 15% to about 22% P_2O_5, according to the minerals present. I propose to take the limit between phosphorites (or phosphatites), and phosphatic rocks (such as phosphatic clay, phosphatic sandstone, phosphatic limestone) at 18% P_2O_5.

Nomenclature and classification of phosphatites ($P_2O_5 > 18\%$)
The system proposed here is essentially descriptive, mainly adapted, with some simplification, from the Folk carbonate nomenclatural system. The size of phosphatic particles is a key factor. Folk considers these particles only when their diameter is above 10 microns, and they play a leading part in the name of the rock as soon as they account for more than 10% of it (Table 7).

Case 1: the phosphatite contains less than 10% phosphatic grains ($<10\mu m$)
Several names can be suggested: asphanitic phosphatite, microsphorite, collophane mudstone. I propose "collophanite". This collophanite may be laminated, stromalitic, concretionary. If the rock contains more than 20% non-phosphatic material, it may be arenitic siliceous collophanite, a pebbly (or shelly) calcareous collophanite, a flinty collophanite . . . With only a small percentage of extraneous material: collophanite with 5% quartz grains, with any chert nodules, with scattered glauconitic grains etc.

Case 2: the phosphatite contains more than 10% phosphatic grains
The size of the most frequent grains is:

$< 63\ \mu m$ =	phosphalutite
$> 63\mu m$ and < 2 mm =	phospharenite
> 2 mm =	phospharudite

If the most frequent grains are distributed nearly equally between 2 categories = phospharenolutite, phospharudite. Among phospharudites may be distinguished "granular phospharudite" (2-4mm), "pebbly phospharudite" (4-64mm), "cobbly phospharudite" (64-256mm), or, eventually "nodular phospharudite". The nature of most frequent phosphatic particles (bioclasts, lithoclasts, ooliths, pellets, bones . . .) may be included in the name of the phosphatite:

- lithophospharenite, lithosphospharudite
- oophospharenite
- pelphospharenite, pelphosphalutite
- biophospharenite, biopelphospharenite
- pebbly bone phospharudite

If the phosphatite contains a significant amount of collophanite or of phosphatic grains of a size other than the most frequent ones, an adjective may may be added: collophanitic pelphospharenite, arenite phosphalutite, pebbly lithophospharenite etc.

Non-phosphatic material occurs as a gangue in which we may distinguish an endogangue located inside phosphatic grains and an exogangue, outside.

Endogangue may be considered in a detailed phosphate classification. In that case it is necessary to indicate its nature and its relative quantity of phosphate grains (scarce, frequent, abundant . . .):

- pelphospharite with scarce quartz endogangue
- nodular biophospharudite with abundant glauconitic and endogangue
- lithophospharenite with frequent pyritic and organic endogangue

Table 7 Phosphorites
(sedimentary rocks with more than 18% P_2O_5)

Phosphatites = Ca phosphorites					A1, Fe phosphorites	
< 10% Phosphate particles = collophanite						
> 10% Phosphate particles						
Phosphatic Material				Exogangue		
Minor Components or size of rudites	Nature of phosphate grains	Phosphatite	Size of phosphate grains	Percentage in rock	Mineral composition and size	Cement or matrix
Granular	Bio (Bone)		lutite	0%	Cryptocrystalline chalcedony	
					micrite, dolomicrite	Cement
Pebbly	Intra	Phospha-	arenite	10%	Sparite	
Cobbly	Litho		rudite	20%	–	
Arenitic	Oo			.	–	
	Pel			.		
Lutitic Collophanitic					Clayey, glauconitic quartz siltite quartzanenite arkose biocalcarenite	Matrix

percentage and nature of exogangue may be added here

Exogangue, if present, is another key factor in the nomenclatural scheme. It is called "cement" when apparently chemically precipitated and "matrix" in all other cases, even when coarser than phosphatic particles. Cement and matrix are characterized by their mineral composition and the size of the crystals and grains. Relative quantity of cement and matrix in the rock are important too, and it is necessary to give an estimate of corresponding percentage.

Examples:

- biopelphospharenite with less than 10% cement
- pelphospholutite with 10% microcrystalline cement
- biophospharenite with 30% dolomicrite cement (or matrix)
- biophospharenite with 20% sparite cement
- pelphospharenolutite with 20% clay matrix
- biophospharenite with 10% quartzsiltite matrix
- lithophospharudite with 30% glauconitic and clayey quartzarenite
- nodular lithophospharenorudite with 40% quartz-feldspathic areno-rudite matrix

Texture may be added to the name of the phosphatite. The Dunham terminology (grainstone, packstone, wackestone) seems generally suitable.

A Petrographic Classification of Sedimentary Phosphorites
by *Stanley R. Riggs,* East Carolina University, Greenville

A working classification has evolved from extensive stratigraphic, sedimentologic and petrographic work on the phosphorite sections throughout the southeastern United States. The phosphorite classification is most important since the different types of particles directly affects the economics of any deposit. The classification supplies the basic information upon which the model for the origin and deposition of phosphorites is built.

Four basic types of macroscopic phosphorites have been recognised within the Florida stratigraphic section. Orthochemical and allochemical phosphorite are primary marine sediments formed within the environments of deposition. The authigenic microcrystalline phosphorite mud (microsphorite), which precipitates *in situ* either biochemically or physico-chemically, is orthochemical phosphorite. If the microsphorite mud is subsequently modified into discrete clastic molecules, then it is considered to be allochemical phosphorite. The muds may be torn up by biological or physical processes to produce the intraclastic allochems, or ingested and excreted by organisms to form pelletal phosphorites: if there is sufficient energy, the muds may also aggregate around a nucleus grain to form oolites or pseudo-oolites. A fourth type of allochemical grain is the fossil skeletal material which rains into the sediment system. The bulk of the phosphate macro-grains deposited during the Miocene phosphogenic system consisted of these orthochemical and allochemical phosphorites. Subsequent processes modified some of the primary phosphorites to produce the two other varieties of macroscopic grains. Any phosphorite which is later reworked into a younger sediment system is called lithochemical phosphorite. Subaerial weathering processes chemically and mineralogically change the phosphorite to produce the metachemical grains.

Macroscopically, most of the phosphate macrograins are true aggregates, composed of a complex mixture of various mineralogical and biological components. The primary component is the cryptograined carbonate fluorapatite matrix, with various types and amounts of disseminated cryptograined colouring matter. Also there is a multitude of micrograined included material which represents a mixture of everything that was in the environment at the time of precipitation of the orthochemical mud. The inclusions consist primarily of bacteria-like rods and rod aggregates, micro-organism fossil hash, dolomite rhombs, and terrigenous sand and clay. Consequently, each phosphate micrograin is a complex sedimentary rock; the chemical composition and physical characteristics of which are totally dependent upon the specific types of inclusions and their abundances.

Discussion

Initial comment was in the form of disagreement with the term collophanite for the very fine grained phosphorites. McClellan thought that phosphanite would be a better term since collophane is a mineral, not a rock descriptor. Sheldon suggested that within the proposal the term phospholutite covered the 10μ material and that the term collophanite be abandoned. Yanshin thought that the proposal was very detailed but has some shortcomings, particularly the 18% P_2O_5 break. This boundary would exclude many phosphate deposits in the USSR that were being mined – including ore deposits where an upper bed at 18% P_2O_5 would be included in phosphorite, and a lower bed at <18% but largely undistinguishable from it would be excluded. It was pointed out that a committee of USSR geologists was meeting to finalise phosphate rock nomenclature, and that the decisions from this committee would be presented to the next Project meeting. Slansky said he preferred the 18% cut-off because at this level the rock contained 50% or more of apatite, at which level the rock could be called a phosphorite. Below this level phosphate was not the dominant constituent. A general discussion followed on the subject of using an analysis of rock as a basis for defining a phosphorite. Riggs said the idea that >10% of apatite grains would constitute a phosphorite was based on extensive grain counts which suggested that there was a distinct break in the rock types which contain greater than and less than 10% apatite grains. Sheldon then stated that some of the terms used i.e. arenite, rudite and lutite had a widely accepted usage for clastic rocks and he thought that the use of these terms for phosphatic rocks could be misleading. Slansky said he thought that this usage was only descriptive of size and was not a statement on the origin of the rock. V.N. Sant then re-introduced the problems of conflict between the use of phosphorite for a mineable rock of varying grades and the cut-off descriptor proposed of 18%. He was followed by Howard on the difficulties of distinguishing between the phosphorite and non-phosphorite both being ore within the same pit. Slanksy's opinion was that the terms should be restricted to geology and not mining. If the term phosphate ore or phosphate rock was applied to mineable phosphatic material this should distinguish between the geological and the mining terms. Zanin also spoke on the distinctions between the geological ore terms and said that this would be left to the USSR committee to decide. He also brought in the problem of phosphorites made up of composite grains. In cases such as these, there were difficulties in a primary definition. Sheldon thought that the answer to this was to use the predominant grain size as the main description. He followed this up with the introduction of fields within a ternary phosphate-silicate-carbonate diagram to define the various descriptive terms. Cook agreed that the ternary diagram was a good basis for subdivisions of the range of phosphatic rocks but thought that some of the proposed divisions would exclude major mining fields, e.g. Florida would be excluded from the phosphorite field. He also thought that, practically, people would not use terms like phosphatite and that it was necessary to be confined by previous glossaries. Bremner suggested that some distinction should be made between phosphorites in consolidated and unconsolidated sediments. S.R. Riggs felt that since phosphatic rocks were always anomalous they should not be treated as normal rocks and that the descriptions should be specific to phosphate rocks. Descriptions should be based on the natural systems with phosphatic rocks and the distinction should be based on the percentage of types of phosphate grains.

Slansky, however, thought that for field use the approximate and easily obtained P_2O_5 percentage was more useable. Sheldon commented that phosphate rock was only one of a large family of sedimentary rocks and that the rules governing the terminology of one should be compatible with the rest. The Riggs system would be unworkable in the field. Cook suggested that the term phosphate rock should be used initially, with a breakdown to the use of particular terms as necessary. Choudhuri thought that all phosphate rocks with grades above the economic cut-off should be termed phosphorite. Sheldon was willing to exclude Florida rock phosphate from phosphorites and suggested the IGCP Project collect the various nomenclature proposals from Slansky, the USSR, Riggs, himself and McKelvey and others for discussion. Notholt spoke on attempts to devise a nomenclature to satisfy both the academic and economic geologists. Terms like phosphate rock and phosphorite were deeply entrenched and not easy to change. He favoured an accurate petrographic system. Riggs then recommended that the various nomenclatural systems be circulated in the project Newsletter next year and that the ideas arising from these be discussed at the next Project meeting. While he disliked classifications he thought that they were useful for understanding and communication. The meeting generally agreed to this recommendation.

Phosphate Data Storage

An International Phosphate Resources Data Base

by *R.P. Sheldon,* East West Resources Systems Institute, Honolulu

The delegates to the conference considered the preliminary format of the International Phosphate Resources Data Base (IPRDB) that had been developed the previous April by a group of geologists at Honolulu. That group included members from Australia, Great Britain, France, India, and United States, and was sponsored by the Resource Systems Institute of the East-West Center in Honolulu, the U.S. Geological Survey, and IGCP Projects 156 and 98. The PRRDB format was presented by R.P. Sheldon to the group and that, along with the general philosophy, the user group and the plans for development of IPRDB were discussed.

The purpose of the International Phosphate Resource Data Base will be to:

1 collect and organise geologic knowledge of phosphate deposits in order to allow better scientific analyses of phosphate deposits. These analyses would deal with a) the extent of phosphogenic provinces in space and time, b) mod-

els of deposition of phosphate, c) epochs of phosphate deposition, and d) relationship between palaeo-oceanographic (plate tectonic) history and phosphate deposition;

2 allow the assessment of our knowledge of phosphate geology in order to direct future research;

3 collect and organise the data on phosphate that, combined with regional geologic information, are basic to the appraisal of undiscovered phosphate resources in unexplored or underexplored parts of the globe. This includes analogues analysis to estimate size distributions of undiscovered deposits;

4 enable the development of computerised exploration strategies based on the various depositional models developed in item 1 above; and

5 with a combination of items 3 and 4, develop possible phosphate exploration programs in developing countries.

The prime users of the data base will be geologists undertaking 1) research on phosphate deposits, including both basic research and resource assessment, and 2) the prospecting stage of exploration. Secondary users will be engineers and mineral scientists concerned with the development stage of exploration and exploitation. Economists and national planners will be indirect users in that they will be concerned with phosphate availability estimates generated from the data base. It is unlikely that they would be direct users.

The type of objective data that will be stored in the data base would include:

1 the name of the phosphate occurrence and the category of occurrence (palaeogeologic province, structural province, formation outcrop, etc.);
2 geographic data (country, state, district);
3 deposit type (igneous, sedimentary);
4 chemistry (elemental analyses; organic fraction, etc.);
5 petrography (%components, grain types, size cement, etc.);
6 mineralogy (mineral type, cell parameters, mineral grain chemistry, empirical formula);
7 typical rock stratigraphic sections;
8 relationships with associated strata;
9 palaeontology; and
10 sedimentary structures.

Interpretative data to be stored in the data base would include:

1 age (geochronologic; biochronologic);
2 degree of metamorphism;
3 depositional processes (weathering, mechanical reworking, etc.);
4 depositional environment (shelf, supratidal flat, etc.);
5 palaeogeography;
6 stage of basin development;
7 plate tectonic setting; and
8 regional structural setting.

In addition to essentially geologic data, the data base could store resources assessment data including:

1 thickness and grade of phosphate beds in a typical section;
2 identified resources;
3 hypothetical resources;
4 speculative resources;
5 quality of the ore;

6 reserves;
7 production;
8 information on mines; and
9 by-products of phosphate production.

Additionally, references would also be provided in the data base (author(s) and date); complete references would then be obtained from a separate compatible data base.

The final format will be prepared by R.P. Sheldon for distribution to members of Project 156, who will undertake a pilot project, which will develop data sets for a relatively few phosphate occurrences with a relatively wide range of characteristics. At that point, after appropriate modifications, the complete data base will be ready for full development. Strong support was expressed by delegates for the IPRDB.

Further information may be obtained from Richard P. Sheldon, East-West Resource Systems Institute, 1777 East-West Road, Honolulu HI 96848, USA.

Conclusions from the Field Workshop and Seminar

The scientists who attended the Queensland Field Workshop and Conference represented many different disciplines within the science of geology, ranging through palaeontology, geochemistry, stratigraphy, sedimentology, marine geology, mineralogy and economic geology. These scientists, of wide international and interdisciplinary scope, approached the Queensland phosphate deposits with differing perspectives, and their impressions and interpretations of the rocks could have been expected to differ widely. In view of this, the degree of similarity of views on the deposits and their origin, was scientifically gratifying, and provided not only a measure of scientific progress for phosphate geology, but also a foundation for identifying some important problems for future study. Conclusions of the workshop and seminar are divided into three groups: (i) the Georgina Basin phosphorites, representing a synthesis of opinion as a result of field observation and subsequent discussion; (ii) general points of agreement on phosphogenesis; (iii) points to be resolved which are in dispute, require clarification, or further research.

Georgina Basin Phosphorites

The Cambrian Period appears to have been a time of exceptionally abundant phosphatic sediments.

The Middle Cambrian phosphorites of the Georgina Basin were deposited in shallow marine environments associated with carbonate bank sedimentation on a marine epeiric shelf, of which a fragment only is now preserved in northern Australia.

This shelf was located in low palaeolatitudes on the southern side of a major east-west seaway. Deeper, cooler oceanic waters welled up along the northern margin of this shelf to supply the source of phosphorous eventually deposited on the Georgina shelf.

Phosphorite deposition accompanied a relative rise in sea level along this shelf, resulting in transgression across it.

A particular set of palaeogeographic and palaeocurrent conditions resulted in a relatively shallow chemical and sedimentological trap for the accumulation of phosphate.

Phosphogenesis: Points in Agreement

Arising from the Georgina Basin example and the synthesis of deposits elsewhere in the world, it is possible to agree on some generalities:

(i) there is an apparent periodicity in phosphogenesis on a global scale, i.e. there have been preferred times for the formation of sedimentary phosphate deposits;
(ii) upwelling of oceanic waters (such as takes place on continental margins) is the source of much of the phosphorous in the shallow marine environment;
(iii) a trapping mechanism is necessary for the accumulation of large quantities of phosphorite (such as those of the Cambrian). This entrapment must relate to regional basinal topography (basement structure control) and palaeogeography, i.e. the distribution of shoal areas and embayments.

Phosphogenesis: Points for Resolution

(i) The constancy of phosphorous concentration in sea water during geological time is not known. If it varies, is the variation cyclical or irregular?
(ii) Many think phosphate has been deposited in relatively shallow coastal waters, but little agreement exists regarding the precise depositional environment. Some consider that deposition occurred in water as shallow as the intertidal-supratidal zone, and others that it was deposited in sub-tidal water. Some feel the environment was open shelf, but others that it was relatively restricted.
(iii) The mechanism of precipitation of the phosphate is imperfectly understood and many disagreements exist. Some think that phosphate grains are formed diagenetically either by the interstitial precipitation of collophane or the phosphatisation of pre-existing calcareous or terrigenous grains, either by locally-derived pore waters, or by phosphorous-rich brines. Others consider that the collophane is precipitated directly at the sediment-water interface. The role of organisms in the precipitation of phosphate is thought by most to be important, but the mechanisms are not understood.
(iv) The repetitive sedimentation of beds of phosphorite in a sedimentary sequence is clearly observed but poorly understood. The reasons for its lithological association with dolomite, chert, black shale and other rock types are not explained to the satisfaction of all geologists.
(v) Because of the lack of fresh samples from many deposits, the behaviour of phosphate-bearing formations during processes of diagenesis and weathering are not fully understood. The origin of the fine-grained phosphorites (variously termed "microsphorite", "phospholutite", etc.) is particularly controversial. The nature and origin of "phoscrete" is similarly regarded as being a difficult question to resolve.

Recommendations for further research

(i) The formation of phosphorites in the modern ocean, requires detailed sedimentologic and geochemical study if comprehensive depositional models are to be constructed for the interpretation of, and exploration for, ancient deposits.
(ii) Studies of the diagenetic and weathering processes affecting phosphate rock need additional research efforts.
(iii) Detailed stratigraphical mineralogical, petrological geochemical (organic,

inorganic and isotopic) studies of a wide range of phosphate deposits need to be undertaken to establish the origin and evolution of phosphate deposition in time.

(iv) The phosphorous cycle is imperfectly understood, because of a lack of much of the required basic geochemical information. There is a very real need to understand the behaviour of phosphorous in the present-day lithosphere and hydrosphere so that we can better understand its behaviour in the past.

Appendix I: Complete Papers

Resources of Precambrian and Cambrian Sedimentary Phosphate Rock

by *A.J.G. Notholt,* Institute of Geological Sciences, London, U.K.

Abstract

Some 92 occurrences of Precambrian or Cambrian sedimentary phosphate rock are recorded in the literature, of which those in Australia, Brazil, China, India, Korea, the USSR and Vietnam have been or are being worked on a commercial scale. Total estimated resources appear to be large; however, only a very small proportion of this resource is commercially attractive at present. At least one extensive Lower Palaeozoic (predominantly Cambrian) phosphate province appears to be present in the Asian-Australian region, extending from Australia through Vietnam and southern and central China, the Mongolian People's Republic and neighbouring areas of the USSR, and southern Kazakhstan. The largest resource of phosphate rock of Cambrian age to have been found outside Asia to date is in Australia (northwestern Queensland and the neighbouring parts of the Northern Territory. Sedimentary phosphate rock of undoubted Precambrian age has, until comparatively recently, again been confined largely to Asia. However, the identification, relatively recently, of phosphate-bearing sediments of Precambrian age in Africa, the USA and Brazil, indicates that further discoveries of the same age are very probable as systematic exploration proceeds.

Introduction

The purpose of the present, preliminary contribution is to indicate the extent of the known resources of Precambrian and Cambrian sedimentary phosphate rock by means of a world outline map (Fig. 13) and a select bibliography to occurrences and deposits. It is hoped that both will serve as a useful basis for further research. In the preparation of the bibliography, the assistance of Mr K. Hartley, Mineral Index, I.G.S., is gratefully acknowledged.

The presence of sedimentary phosphate rock of Cambrian and Precambrian age has been known for many years, the first occurrences having been described from the United Kingdom in 1875 and 1904 respectively. Most of the occurrences, however, are located in the Asian-Australian region, where at least one, extensive Lower Palaeozoic (predominantly Cambrian) phosphate province appears to be present, extending from South Australia northwards to include the major deposits in the Georgina Basin of northern Queensland and adjacent parts of the Northern Territory and probably continuing as far as Vietnam and southern and central China. Correlation between individual deposits is incomplete, however. It may eventually prove possible to establish closer links with those of comparable age in the Mongolian People's Republic and neighbouring areas of the USSR, notably

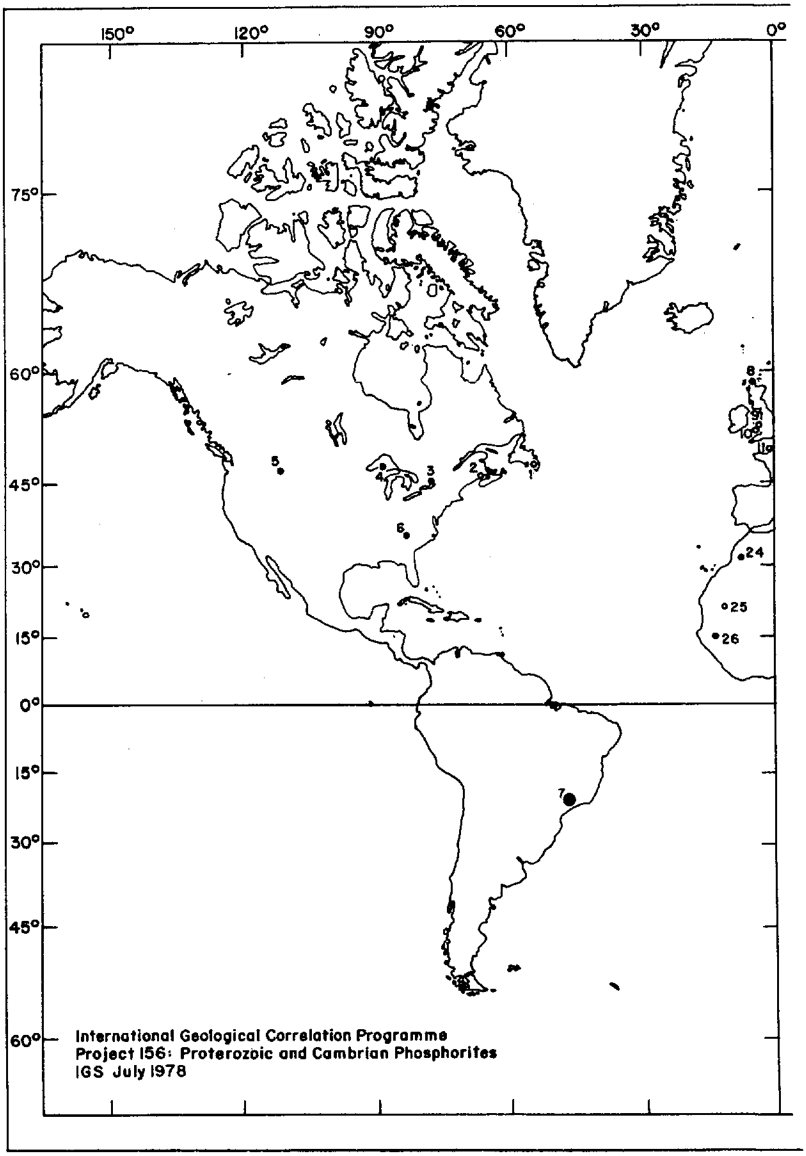


Fig.13 World distribution of Precambrian and Cambrian sedimentary phosphate rock

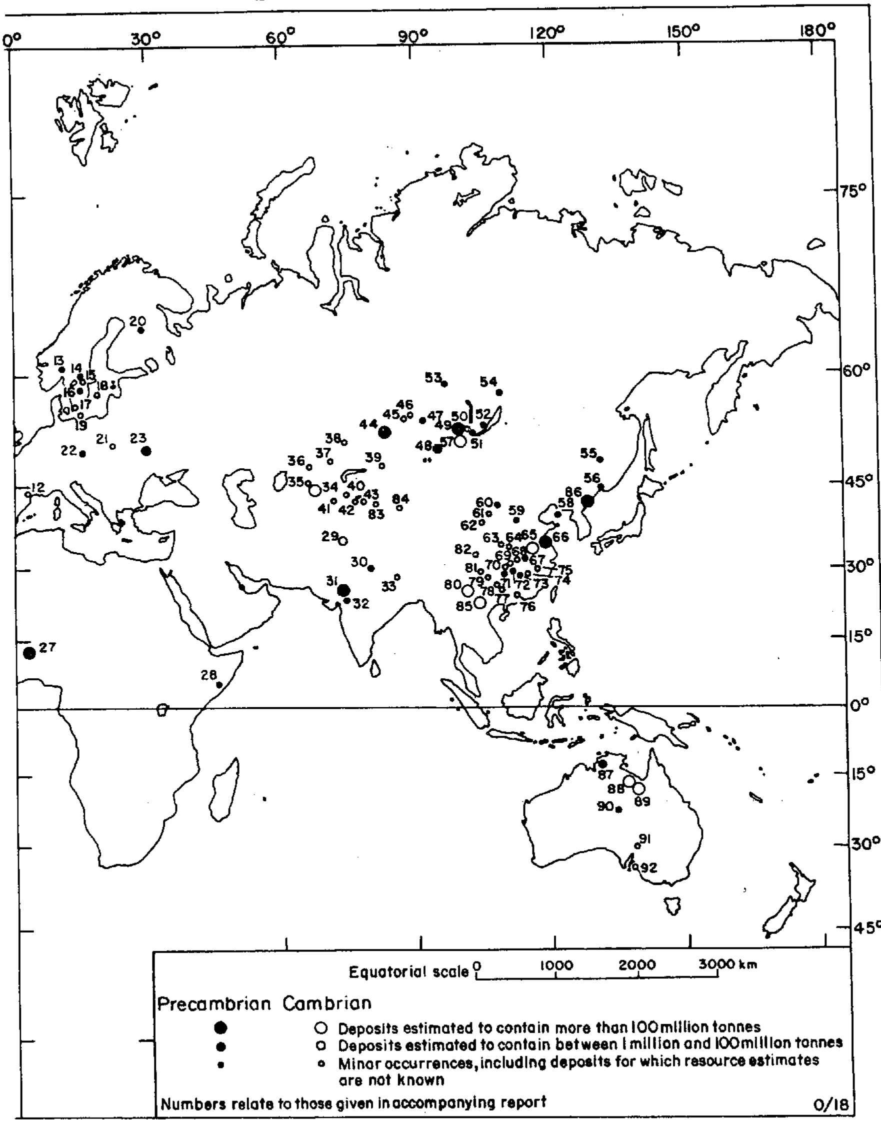

0°
30°
60°
90°
120°
150°
180°
75°
60°
45°
30°
15°
0°
15°
30°
45°
Equatorial scale 0 1000 2000 3000 km
Precambrian Cambrian
Deposits estimated to contain more than 100 million tonnes
Deposits estimated to contain between 1 million and 100 million tonnes
Minor occurrences, including deposits for which resource estimates are not known
Numbers relate to those given in accompanying report
0/18

Table 8 Estimated Resources of Precambrian and Cambrian Sedimentary Phosphate Rock

Age and location	Quantity million tonnes	Reported grades Per cent P_2O_5
Precambrian		
Australia		
Rum Jungle, Northern Territory	2	10-12
Brazil		
Patos de Minas, Minas Gerais	420(a)	13
China		
Haichow, Kiangsu Province	2	30
India		
Udaipur, Rajasthan (b)	100	15-34
Jhabua, Madhya Pradesh (c)	2	12-32
Korea		
Sinpung, near Tanchon	90	12.5
Upper Volta		
Parc Nationaux du 'W'	500	15-32
USA		
Upper Peninsula, Michigan	(d)	15
USSR		
Zhitomir, Ukraine	9(e)	–
Gornaya Shoriya, Kemerovsk	270	6-11
Slyudyanka, Irkutsk	(f)	4-20
Ukha-Ghol, Buryat	2,600	16
Cambrian		
Australia		
Duchess-Lady Annie Areas, Queensland	2,000	17
Alexandria-Wonarah area, Northern Territory	500-1,000	14
China		
Yuenyang, Yunnan Province	42	23
Fengtai, Anhwei Province	2	20
USSR		
Karatau, Kazakhstan	1,700	26
Hubsugul, Mongolian Peoples Republic	1,000	20-22
Vietnam		
Lao Cai, Yuan Kiang	1,000 (g)	18-19
Pakistan		
Hazara District (Kakul-Dalola)	17 (h)	> 18

(a) Proved reserves amount to 236 million tonnes

(b) Jhamar Kotra deposits

(c) Preliminary estimate only

(d) Estimates not published, but resources are likely to be substantial

(e) Proved and probable reserves of apatite. Borehole samples of rock show only 1-4% P_2O_5.

(f) Details not available, but resources perhaps exceed 500 million tonnes.

(g) Probable resources. Known reserves of rock exceeding 22% P_2O_5 have been estimated at 84 million tonnes.

(h) Probable identified resources. Proved resources amounts to between 3 and 4 million tonnes.

with the well-known Karatau phosphate field of southern Kazakhstan. In Europe, most of the occurrences are in the form of thin, reworked phosphate nodule beds, although some interesting new discoveries have been made in Cambrian strata in northern and southern France, where a national inventory of phosphate resources was begun in 1975. The known distribution of Cambrian phosphate rock in Europe suggests that a phosphate province of this age may exist.

Sedimentary phosphate rock of undoubted Precambrian age has, until comparatively recently, again been confined largely to Asia. Particularly noteworthy are the low grade occurrences found near Lake Baikal in the Buryat and Irkutsk regions within a sequence of dolomite and calcitic marbles, quartz-diopside marbles, gneisses and diopside-quartzites, and the deposits found in parts of China in the Yungtai and Toushanto Suites, some of which are believed to have been worked for many years. Commercial deposits have been found also in northern India in the Aravalli Group exposed in Rajasthan and Madhya Pradesh. In India and in the USSR and China many of the Precambrian deposits are characteristically associated with stromatolites, particularly of the *Collenia* group. The identification, relatively recently, of phosphate-bearing sediments of Precambrian age in parts of Africa (Morocco, Senegal and Upper Volta), and also in the USA and Brazil indicates that further discoveries of the same age are very probable as sytematic phosphate exploration proceeds. It thus seems very likely that several Precambrian phosphate provinces will eventually be delineated.

Resources

At least 92 occurrences (Fig. 13) of Precambrian or Cambrian sedimentary phosphate rock have been recorded in the literature, of which deposits in Australia, Brazil, China, India, Korea, the USSR and Vietnam have been or are being worked on a commercial scale. On the basis of the published estimates, total resources appear to amount to over 10,000 million tonnes of phosphate rock containing more than 4% P_2O_5 (Table 8), most of these resources being found in the USSR, and China. More than half (54) of the recorded occurrences are of Cambrian age and these appear to contain over 6,000 million tonnes of phosphate rock with 14% P_2O_5 or more. However, only a very small proportion of this resource is likely to be commercially attractive in terms of either mineable thickness or quality of phosphate rock.

The substantial resources of phosphate rock in Precambrian to Cambrian sediments in the USSR and China contrast sharply with those known to occur in other countries at present. For example, around 40 per cent of the total phosphate resources in the USSR are of this age, with the Cambrian Karatau field in southern Kazakhstan and the Precambrian Gornaya Shoriya deposits in Kemerovsk being among the largest in Siberia. The phosphate deposits of the Georgina Basin in Australia constitute the largest known resource of phosphate rock of Cambrian age outside Asia.

Distribution of known resources

The number given below relate to locations shown in Figure 13.

North America

Canada

1 Manuel's Brook, Conception Bay, St John's Newfoundland
Lower Cambrian
Reference: DALE, 1915.

2 Saint John, southwestern New Brunswick
Lower Cambrian (Hanford Brook Formation), Upper Cambrian (Johannian Series)
Reference: MATTHEW, 1893.

3 Ernie Campsall deposit, Hinchinbrooke, Frontenac County, Ontario.
Precambrian (Grenville Series)
Reference: HARDING, 1947.

USA

4 Upper (Keweenaw) Peninsula, Michigan
Precambrian (Marquette Range Supergroup; Baraga Group)
References: CANNON 1976; MANCUSO *et al.*, 1975.

5 Wolf Creek Canyon, north of Helena, Montana
Precambrian (Spokane Formation, Belt Series)
Reference: GULBRANDSEN, 1966.

6 Dunn Creek, Sevier County, eastern Tennessee
Precambrian (Ocoee Series)
Reference: HAMILTON, 1961; WEDOW *et al.*, 1966.

South America

Brazil

7 Patos de Minas, Minas Gerais State
Late Precambrian (?)
References: CATHCART, 1977; GUIMARAES and DUTRA, 1969.

Europe

United Kingdom

8 Cailleach Head, Loch Broom, Scotland
Late Precambrian (Aultbea Formation, Torridon Group)
Reference: PEACH *et al.*, 1907.

9 Criccieth – Cadr Idris area, Harlech Dome, North Wales
Lower Cambrian (Dolgelly and Tremadoc Beds)
Reference: HICKS, 1875.

10 St David's, western Pembrokeshire, South Wales
Cambrian (Menevian Series)
Reference: HICKS, 1875.

France

11 Cotentin Peninsula, Manche Department
Cambrian
Reference: NOTHOLT *et al.*, 1977.

12 Monts de Lacaune, Tarn Department
Lower Cambrian
Reference: NOTHOLT *et al.*, 1977.

Norway

13 Biskopåsen, Lake Mjösa, north of Oslo
Late Precambrian (Biskopåsen Conglomerate, Lillehammer Subgroup)
Reference: SPJELDNAES, 1967.

Sweden

14 Västmanland and Värmland, southern Sweden
Precambrian (Gryhthytte Slate)
Reference: SUNDIUS, 1923.

15 Örebro area, southern Sweden
Middle Cambrian (*Oelandicus* Shale)
References: ANDERSSON, 1896; THORSLUND and JAANUSSON, 1960.

16 Lake Vättern, southern Sweden
Precambrian (Visingsö Formation)
Reference: HEDSTRÖM, 1930.

17 Simrishamm area, Kristianstad
Lower Cambrian (*Holmia* Series)
Reference: REGNELL and HEDE, 1960.

18 Gotland, Baltic Sea
Lower Cambrian
References: ANDERSSON, 1896; HEDSTROM, 1928.

Denmark

19 Bornholm Island, southern Baltic Sea
Lower Cambrian (Rispebjerg Sandstone)
Reference: POULSEN, 1960.

Finland

20 Eastern Finland
Precambrian (Jatulian Schists)
Reference: ISOKANGAS (In press).

Poland

21 Gory Pieprzowe, near Sandomierz, southwest of Lublin
Cambrian
Reference: KOZLOWSKI, 1931.

Czechoslovakia

22 Chvaletice, Zelezne Hory Mountains
Precambrian (Ore Formation)
Reference: GRUSZCZYK and POUBA, 1968; SLAVIK, 1936.

USSR

23 Ovruch Ridge, Zhitomir, central Ukraine
Precambrian (Ovruch Series)
References: KOVALENKO and SEMENOV, 1964; SVIRIDOV, 1967.

Africa

Morocco

24 Taguedit, southern Haut Atlas
Upper Precambrian (Adoudounian)
Reference: VILAND, 1977.

Mauritania

25 Northern Dhar Adrar area, western Taodeni Basin
Cambrian (Atar Group, Oumat el Ham Series)
Reference: SOUGY, 1964.

Africa contd.

Senegal

26 Eastern Senegal
Precambrian
Reference: SLANSKY (personal comm.) 1978.

Upper Volta

27 Parcs Nationaux de 'W', Niger River area
Late Precambrian (Kodjari Formation, Volta Supergroup)
References: AFFATON, 1973; TROMPETTE, 1978.

Somali Republic

28 El Bur area, southern Somalia
Precambrian
Reference: ILYIN, 1978.

Asia and the Far East

Pakistan

29 Abottabad area, Hazara District
Cambrian ? (Galdanian/Abbottabad formations)
References: LATIF, 1972; BHATTI, 1977.

India

30 Pithoragarh, Kumaun Himalaya,
Precambrian (Gangolihat Dolomites)
References: PATWARDHAN, 1973; VALDIYA, 1969, 1972.

31 Udaipur, Rajasthan
Precambrian (Aravalli Group, Matoon Formation)
References: BANERJEE, 1971 a,b; KRISHNA RAO *et al.*, 1971; NATH, 1967; NATH *et al.*, 1967.

32 Jhabua, Madhya Pradesh
Precambrian (Aravalli Group
References: ANON., 1976; KHAN *et al.*, 1978.

Nepal

33 Kathmandu area, eastern Nepal
Lower Palaeozoic (? Cambrian) (Sangarni suite)
Reference: KAZITSYN, 1973.

USSR

34 Lesser Karatau Range, southern Kazakhstan
Lower Cambrian (Chulak-tau suite)
References: BEZRUKOV, 1941; BUSHINSKII 1969; GIMMEL'FARB and TUSHINA, 1966; MENG, 1959; KHOLODOV, 1969; KHOLODOV and KHORYAKIN, 1961, 1968; SMIRNOV, 1959; SMIRNOV and TUSHINA, 1960; TUSHINA, 1968.

35 Greater Karatau Range, southern Kazakhstan
Lower Cambrian (Kulan-tau suite)
Reference: BUSHINSKII, 1969.

36 Ulutau Mountains, near Baykonur, central Kazakhstan
Lower Cambrian (Bulantinskaya suite); Middle Cambrian (Kurum-sak suite)
References: KNIPPER, 1957; POPOVA, 1959; POPOVA and SARBASOV, 1963.

37 Atasu area, eastern Kazakhstan
Lower and Middle Cambrian
Reference: BOROVIKOV, 1960.

USSR contd.

38 Shiderty River area, northeastern Kazakhstan
Middle Cambrian (Sasyksor suite)
Reference: GIMMEL'FARB, 1965.

39 Chingiz - Tarbagatai mountains, eastern Kazakhstan
Cambrian (Sasyksorsk suite)
Reference: POLYANSKI, 1977.

40 Kendyktas Mountains, Kazakhstan
Upper Cambrian (Narkyzyl suite)
Reference: DVORTSOVA, 1958.

41 Dzebagly Mountains, Talasskiy Alatau, Kirgiz
Middle Cambrian (Kurum-sak suite)
References: BUSHINSKII, 1969; SOKOLOV, 1946.

42 Issik-Kul' Lake, Kirgiz
Middle Cambrian to Lower Ordovician (Shorter Series)
Reference: BUSHINSKII, 1969.

43 Sarydhaz Range, eastern Kirgiz
Lower Cambrian (Berkuta suite)
Reference: ADYSHEV, *et al.*, 1967.

44 Gornaya Shoriya, near Novokuznetsk, Kemerovsk Oblast
Precambrian (Upper Riphaean, Yenesei suite)
Reference: SPANDERASHVILI, 1962; SUKHARINA *et al.*, 1961.

45 Belaya-Usa, north-east of Novokuznetsk, Kemerovsk Oblast
Lower Cambrian (Usa suite)
Reference: BUSHINSKII, 1969.

46 Bateni Range, eastern Kuznetsk Ala-Tau, Khakasskaya Oblast
Lower Cambrian (Martyukhinskaya suite)
Reference: BOROVKOV, 1969; BUSHINSKII, 1969; SOKOLOVA, 1961.

47 Seyba River basin, Eastern Sayan Range, Tuvinsk Oblast
Precambrian (Riphaean, Pavlovka suite)
Reference: BUSHINSKII, 1969.

48 Sangilen Range, Tuvinsk Oblast, Krasnoyarsk
Late Precambrian (Chartyss suite)
Reference: BOROVKAYA and ZAITSEV, 1966; YUDIN, 1965.

49 Ukha-Gol, Eastern Sayan, western Buryat ASSR
Precambrian (Upper Riphaean - Vendian, Zabitskii Series),
References: SEMEIKIN *et al.*, 1976; VOLKOV *et al.*, 1972.

50 Eastern Sayan, western Buryat ASSR
Lower Cambrian ? (Bokson suite)
Reference: BUSHINSKII, 1969.

51 Slyudyanka, southern Lake Baikal, Irkutsk Oblast
Precambrian (Pre-Riphaean Slyudyanka suite)
References: DELITSIN, 1961; SAKHAROVA, 1956.

52 Srednyaya Ilikta River basin, western Lake Baikal, Irkutsk Oblast
Precambrian (Riphaean, Uluntui suite)
Reference: EGOROVA, 1960; MATS *et al.*, 1956.

53 Irkineevaya River, Yenesei Range, western Krasnoyarsk
Precambrian (Riphaean, Sukhoi Range suite)
Reference: BUSHKINSKII, 1969.

54 Baikal - Patom Plateau, northeastern Irkutsk Oblast
Precambrian (Riphaean, Patom Series)
Reference: EGOROVA, 1960.

55 Little Khingan Mountains, Khabarovsk
Precambrian (Riphaean, Rudosnaya suite)
Reference: BUSHINSKII, 1969.

56 Khanka Lake, Maritime Territory
Precambrian (Riphaean, Rudosnaya suite); Lower Cambrian
(Prokhory suite)
Reference: BUSHINSKII, 1969.

Mongolian People's Republic

57 Hubsugul area, northern Mongolia
Late Precambrian – Lower Cambrian (Hubsgul Series)
References: DONOV *et al.*, 1969; GIMMEL'FARB and EGOROVA, 1969; ILYIN, 1976; ZAITSEV, 1970.

China

58 Liaotung Peninsula, Liaoning Province
Precambrian (Sinian) (Tiao yu tai suite)
Reference: BUSHINSKII, 1969; MA LIN, 1966.

59 Wutai Shan area, northeastern Shansi Province
Precambrian (Sinian)
Reference: BUSHINSKII, 1969.

60 Hara Narin Ula, northern Inner Mongolia
Precambrian (Payunopo System)
Reference: BUSHINSKII, 1969.

61 Northern Holan Shan range, southeastern Ningsia Hui
Lower Cambrian
Reference: BUSHINSKII, 1969.

62 Southern Holan Shan range, Ningsia Hui
Lower Cambrian
Reference: BUSHINSKII, 1969.

63 Chinling Shan, southern Shensi Province
Lower Cambrian
References: HUO, 1962; BUSHINSKII, 1969.

64 Funiu Shan area, central Honan Province
Lower Cambrian
Reference: BUSHINSKII, 1969.

65 Fengtai, central Anhwei Province
Lower Cambrian (Mantow suite)
Reference: HSIEH, 1948; BUSHINSKII, 1969.

66 Tung Hai, near Haichow, northeastern Kiangsu Province
Precambrian (Yungtai suite)
References: BUSHINSKII, 1969; LIU, 1922; LIU, 1957; TANAKADATE, 1931.

67 Hwaiyang Shan area, northern Hupeh Province
Precambrian ?
Reference: BUSHINSKII, 1969.

68 Han Kiang River area, Siangyang, northern Hupeh Province
Lower Cambrian; Precambrian (Sinian) (Toushanto suite)
Reference: BUSHINSKII, 1969.

69 Southern Shinpao Shan area, western Hupeh Province
Lower Cambrian
Reference: BUSHINSKII, 1969.

70 Ching Kiang river, western Hupeh Province
Lower Cambrian, Precambrian (Middle Sinian) (Toushanto suite)
Reference: BUSHINSKII, 1969.

71 Southern Suehfeng Shan, southwestern Hunan Province
Precambrian (Sinian) (Toushanto suite)
Reference: BUSHINSKII, 1969.

72 Northern Suehfeng Shan, southwestern Hunan Province
Precambrian (Sinian) (Toushanto suite)
Reference: BUSHINSKII, 1969.

73 Chayuanpu, eastern Hunan Province
Precambrian (Sinian)
Reference: BUSHINSKII, 1969.

China contd.

74 Kiuling Shan area, northwestern Kiangsi Province
Lower Cambrian (Kuanyintang suite)
Reference: BUSHINSKII, 1969.

75 Kinhwa area, Chekiang Province
Lower Cambrian
Reference: BUSHINSKII, 1969.

76 Shinkwan area, northern Kwantung Province
Lower Cambrian
Reference: BUSHINSKII, 1969.

77 Chiangnanyo Massif, Kweilin, northern Kwangsi Province
Lower Cambrian (Shuikow suite)
Reference: BUSHINSKII, 1969.

78 Liping area, southeastern Kweichow Province
Lower Cambrian
Reference: BUSHINSKII, 1969.

79 Tsunyi area, northern Kweichow Province
Lower Cambrian
Reference: BUSHINSKII, 1969.

80 Yuanyang (Kunyang) area, southern Yunnan Province
Lower Cambrian (Mei-shu-ts'un formation)
References: BUSHINSKII, 1966; CHIANG *et al.*, 1969; HO, 1942, HSIEH and CHAO, 1948; WANG, C.C., 1942; WANG, Y.L., 1942.

81 Yangzte Kiang River, southeast of Sichang, southern Szechwan Province
Lower Cambrian (Leipo suite)
Reference: BUSHINSKII, 1969.

82 Pingwu area, northern Szechwan Province
Lower Cambrian (Tienying suite)
Reference: BUSHINSKII, 1969.

83 Kelpin Tagh Range, Sinkiang Uigur
Lower Cambrian
Reference: BUSHINSKII, 1969.

84 Kuruq Tagh Range, Sinkiang Uigur
Lower Cambrian
Reference: BUSHINSKII, 1969.

Vietnam

85 Lao Cai, Yuan Kiang, northern Vietnam
Lower Cambrian (Koksan suite)
References: BUSHINSKII, 1969; FROMAGET, 1941.

Korea

86 Sinpung, near Tanchon, North Korea
Precambrian (Mach'onnyang Series)
References: ANON., 1963; BUSHINSKII, 1969.

Australasia

Australia

87 Rum Jungle, south of Darwin, Northern Territory
Late Precambrian (Castlemaine Hill Beds)
Reference: PRITCHARD and COOK, 1965.

Australia contd.

88 Alexandria-Wonarah area, northeastern Northern Territory (Georgina Basin)
Middle Cambrian (Wonarah and Burton beds)
References: HOWARD, 1971; HOWARD and PERRINO, 1976.

89 Duchess – Yelvertoft area, northeastern Queensland (Georgina Basin)
Middle Cambrian (Beetle Creek Formation)
References: COOK, 1972, 1976; FLEMING, 1974, 1977; HOWARD, 1972; HOWARD and COONEY, 1976; de KEYSER, 1969; de KEYSER and COOK, 1972; ROGERS and KEEVERS, 1976; RUSSELL, 1967; RUSSELL and TRUEMAN, 1971; THIEME, 1970; THOMSON and RUSSELL, 1971.

90 Alice Springs area, northeastern Amadeus Basin, Northern Territory
Precambrian (Areyonga Formation)
Reference: WELLS *et al.*, 1967.

91 Flinders Range, South Australia
Cambrian (Parachilna Formation)
Reference: CALLEN, 1971a.

92 Myponga – Kapunda area, near Adelaide, South Australia
Lower Cambrian (Mount Terrible Formation); Precambrian (Umberatana Group, Brighton Limestone Facies)
References: BLISSETT and CALLEN, 1969; CALLEN, 1971b; JOHNS, 1962.

Bibliography

ANON., 1963. Mineral Resources of Korea. Vol. 6A. Non-Metallics and Miscellaneous Metals. 121 pp. (Korea : Mining Branch, Industry & Mining Divison, USOM.) Apatite, pp. 34-37.

ANON., 1966. Precambrian phosphorite in Montana and Tennessee. *Prof. Pap. U.S. geol. Surv.*, 550-A, p. 7.

ANON., 1976. Jhabua rock phosphate. *Phosphorus & Potassium*, 84, p. 34.

ADYSHEV, M.M., KALMURZAYEV, K.Ye. and SHABALIN, V.V. 1967. Distribution of phosphorus in Cambrian-Ordovician sediments of the Sary Dzhaz river basin (central Tien Shan). *Dokl. Acad. Sci. U.S.S.R.*, 173 pp. 190-191.

AFFATON, P. 1973. Étude géologique et structurale du nord-ouest Dahomey, du nord-Togo et du sud-est de la Haute-Volta. 223 pp. *Doctoral Thesis, University of Provence, France.* Phosphates, pp. 60-62 (In French).

ANDERSSON, J.G. 1896. Über cambrische und silurische phosphoritführende Gesteine aus Schweden. *Bull geol. Inst. Univ. Uppsala*, 2, pp. 133-238 (In German).

BANERJEE, D.M. 1971a. Aravallian stromatolites from Udaipur, Rajasthan. *Jl geol. Soc. India*, 12 (4), pp. 349-355.

______1971b. Precambrian stromatolitic phosphorites of Udaipur, Rajasthan, India. *Bull. geol. Soc. Am.*, 82 (8), pp. 2319-2329.

BLISSETT, A.H. and CALLEN, R.A. 1969. Myponga phosphate deposit. *Mineral Res. Rev. Adelaide, 1967*, 127, pp. 93-102.

BOROVIKOV, L.I. 1960. Les phosphates de la region de l'Atasu dans le Kazakhstan central. *Prospect. Prot. Sous-sol*, 5, pp. 11-13 (French translation of *Zazv. Okhr. Nedr.*).

BOROVSKAYA, I.S. and ZAITSEV, N.S. 1966. Lower Riphean phosphorite in the mountains around southern Siberia. *Dokl. Acad. Sci. U.S.S.R.*, 165, pp. 22-24.

BROVKOV, G.N. 1969. Late Precambrian and Cambrian volcanism and sedimentation in the Kuznetsk Alatau and the Eastern Sayan. *Lithol. Miner. Resour.*, 6, pp. 685-694.

BUSHINSKII, G.I. 1969. Old Phosphorites of Asia and their genesis (Jerusalem: Israel Program for Scientific Translations.) 266 pp.

CALLEN, R.A. 1971a. Sedimentary phosphate exploration. Part 1. The Cambrian of Flinders Ranges. Part 2. The Cambrian and Proterozoic of Fleurieu Peninsula, the Mount Lofty Ranges, and Yorke Peninsula. *Min. Res. Rev. Adelaide.*, 130, pp. 9-34.

______1971b. Wait's Noarlunga phosphate deposits. *Min. Res. Rev. Adelaide.*, 130, pp. 110-120.

CANNON, W.F. and KLASNER, J.S. 1976. Phosphorite and other apatite-bearing sedimentary rocks in the Precambrian of northern Michigan. *Circ. U.S. geol. Surv.*, 746, 6 pp.

CATHCART, J.B. 1977. Phosphorite deposits near Patos de Minas, Minas Gerais, Brazil. *AIME Ann. Mtg, Atlanta, Georgia, Mar. 6-10 Prepr.* 77-H-76, 23 pp.

CHIANG, N.J., WANG, Ch. Ch. and CHEN, Y.C. 1964. Cambrian stratigraphy of eastern Yunnan. *Int. geol. Rev.*, 10, pp. 1153-1172 (English translation).

COOK, P.J. 1972. Petrology and geochemistry of the phosphate deposits of northwest Queensland. *Econ. Geol.*, 67 (8) pp. 1193-1213.

______1976. Georgina Basin phosphatic province, Queensland and Northern Territory – Regional Geology. Pp. 245-250 *in* Economic Geology of Australia and Papua New Guinea, Vol. 4. Industrial minerals and rocks. Edited by C.L. Knight. *Monogr. Ser. No.* 8, *Australas. Inst. Min. Metall.* 423 pp.

DALE, N.C. 1915. The Cambrian manganese deposits of Conception and Trinity Bays, Newfoundland. *Proc. Am. phil. Soc.*, 54, pp. 371-456. (Phosphatic nodules, pp. 408-409).

DELITSIN, I.S. 1961. Quartz-diopside rocks of southwestern Pribaikalia and characteristic features of occurrences of apatite in them. *Trudy Inst. Geol. rudn. Mestorozh.*, 48, pp. 175-201 (In Russian).

DONOV, N.A. EDEMSKII, E.V., ELYANOV, A.A., ILYIN, A.V. and MUZALEVSKII, M.M. 1967. Cambrian phosphorites in the Mongolian People's Republic. *Sov. Geol.*, 3, pp. 55-60 (In Russian).

DVORTSOVA, K.I. 1958. Cambrian phosphorite deposits in the Kendyktas Mountains (South Kazakhstan). *Dokl Acad. Sci. U.S.S.R.*, 123, pp. 961-962.

EGOROVA, O.P. 1960. Genetic types of phosphorites of West Pribaikalia. *Geologiya Geofiz. Novosibirsk*, 7, pp. 31-49 (In Russian, English summary p. 49).

FLEMING, P.J.G. 1974. Origin of some Cambrian bedded cherts, and other aspects of silification in the Georgina Basin, Queensland. *Qd geol. Surv., Publ.*, 358, 9 pp.

______1977. Faunas, lithologies, and the origin of phosphorites in parts of the Middle Cambrian Beetle Creek Formation of northwest Queensland. *Qd geol. Surv. Publ.* 364-21 pp.

FROMAGET, J. 1941. Étude géologiques des gisements de phosphates (apatite) de Cam Duong (Tonkin) et des formations qui les contiennent. *Bull. Serv. géol. Indochine*, 26 (1), 30 pp. (In French).

GIMMEL'FARB, B.M. 1965. Regularity of distribution of phosphorite deposits of the USSR and their genetic classification (Moskva: Izdatel'skvo "nedra") 307 pp. (In Russian).

______and TUŞHINA, A.M. 1966. Principal phosphorite ore deposits of the Kara-Tau. *Lithol. Miner. Resour.*, 4, pp. 483-495.

______and EGOROVA, O.P. 1969. Geology of the Khubsugul phosphorite deposit, Mongolian People's Republic. *Lithol. Miner. Resour.*, 2, pp. 139-144.

GRUSZCZYK, H. and POUBA, Z. 1968. Stratiform ore deposits of the Bohemian Massif and of the Silesia-Cracow area. *Guide Exc.* 23AC, *23rd Sess int. geol. Congr., Prague*, 48 pp.

GUIMARAES, D. and DUTRA, C.V. 1969. Contribuicao ao estudo da Serie Bambui. *Boln Div. Geol. Miner. Bras.*, 243, 27 pp. (In Portuguese) (phosphorite, pp. 17-19).

GULBRANDSEN, R.A. 1966. Precambrian phosphorite in the Belt Series in Montana. *Prof. Pap. U.S. geol. Surv.* 550-D, 199-202.

HAMILTON, W. 1961. Geology of the Richardson Cove and Jones Cove Quadrangles, Tennessee. *Prof. Pap.* 349-A, *U.S. geol. Surv*, 349A, 55 pp. (Phosphate, p. 50).

HARDING, W.D. 1951. Geology of the Olden-Bedford area. *Ann. Rept Ont. Dept Mines, 1947*, 56 (6), 100 pp. (Apatite, pp. 33-40).

HEDSTRÖM, H. 1928. Om ett fosforitkonglomerat på Gotland. *Geol. Fören. Stockh. Förh.* 50 (3), pp. 429-435 (In Swedish).

______1930. Fosforitbollar från Visingsöserien. *Sver. geol. Unders. Afh., Ser.* C, 361, 8 pp. (In Swedish).

HICKS, H. 1875. On the occurrence of phosphates in the Cambrian rocks. *Q. Jnl Geol. Soc. Lond.*, 31 (123), pp. 368-383.

HO, C.S. 1942. The phosphate deposits of Tungshan, Chengchiang, Yunnan (Summary). *Bull. geol. Surv. China*, 35, pp. 41-43.

HOWARD, P.F. 1971. Discovery of phosphorite in northern Australia. *Trans. Soc. Min. Engrs*, 250 (4), pp. 269-273.

______1972. Exploration for phosphorite in Australia – A case history. *Econ. Geol.*, 67 (8), pp. 1180-1192.

______and COONEY, A.M. 1976. D Tree phosphate deposit, Georgina Basin, Queensland. Pp. 265-274 *in* Economic Geology of Australia and Papua New Guinea, Vol. 4, Industrial minerals and rocks. Edited by C.L. Knight. *Monogr. Ser. No. 8, Australas. Inst. Min. Metall.* 423 pp.

______and PERRINO, F.A. 1976. WONARAH phosphate deposit, Georgina Basin, Northern Territory. Pp. 273-278 *in* Economic Geology of Australia and Papua New Guinea. Vol. 4. Industrial minerals and rocks. Edited by C.L. Knight. *Monogr. Ser. No.* 8, *Australas. Inst. Min Metall.* 423 pp.

HSIEH, C.Y. 1948. Palaeogeography as a guide to mineral exploration. *Bull. geol. Soc. China,* 28 (1-2), pp. 1-11.

HSIEH, C.Y. and CHAO, C.H. 1948. Note on the phosphate deposits in China. *Bull. geol. Soc. China,* 28 (1-2), pp. 71-74.

HUO, Shih-cheng, 1962. The genesis of Cambrian phosphate deposits in Shensi. *Acta geol. Sin.,* 42 (4), pp. 435-441 (In Chinese).

ILYIN, A.V. 1978. Late Precambrian – early Cambrian phosphorites in Africa. *Newsl. int. geol. Correlation Progm, Proj. 156,* 2, pp. 8-9.

______and RATNIKOVA, G.I. 1976. Geochemistry of rare-earth elements in late Precambrian – early Cambrian phosphates. *Geokhimiya,* 9, pp. 1370-1374 (In Russian).

ISOKANGAS, P. Finland. *In* Mineral Deposits of Europe, Vol. 1 (In the press).

JOHNS, R.K. 1962. South Australian rock phosphate deposits. *Min. Rev. Adelaide 1961,* 114, pp. 22-30.

KAZITSYN, Yu. V. 1973. Old phosphorite of the Nepal Himalayas. *Dokl. Acad. Sci. U.S.S.R.,* 212, pp. 97-99.

KEYSER, F. de. 1969. The phosphate-bearing Cambrian formations in the Lawn Hill and Lady Annie districts. *Rec. Bur. Miner. Resour. Geol. Geophys. Aust.,* 1969/147, 35 pp.

______and COOK, P.J. 1972. Geology of the Middle Cambrian phosphorites and associated sediments of northwestern Queensland. *Bull. Bur. Miner. Resour. Geol. Geophys. Aust.,* 138, 79 pp.

KHAN, H.H., ZAFAR, M. and GHOSH, D.B. 1978. Geochemical characteristics as applied to the genesis of Precambrian phosphorite, District of Jhabua, M.P., India. *Newsl. int. geol. Correlation Progm, Proj. 156,* 2, pp. 14-16. (Extracts from a paper presented to the Symposium on Archaean of Central India, Nagpur, November, 1976).

KHOLODOV, V.N. 1969. Secondary alterations of bedded phosphorites of Lesser Karatau in the hypergene zone. *Lithol. Miner. Resour.,* 3, pp. 276-288.

______and KORYAKIN, A.S. 1961. Origin of phosphatic conglomerate-breccia in Lesser Karatau. *Dokl. Acad. Sci. U.S.S.R.,* 135, pp. 1140-1142.

______1968. The palaeogeography of the Lesser Karatau (Kazakhstan) during the deposition of 'Lower' Dolomite phosphorite-bearing strata. *Byull. mosk. Obshch. Ispyt. Prir.,* 43, pp. 70-84 (In Russian).

KNIPPER, A.L. 1957. Geosynclinal phosphorites from Ulu-Tau, central Kazakhstan. *Dokl. Akad. Nauk SSSR,* 115 (3), pp. 601-604 (In Russian).

KOVALENKO, D.N. and SEMENOV, V.G. 1964. Ukrainian phosphorite. 179 pp. (Kiev: Institut Geologichnikh Nauk, Adademiya Ukrayinskoyi RSR). (In Ukrainian).

KOZLOWSKI, R. 1931. Fosforyty w utworach kambryjskich Sandomierza. *Spraw. pol. Inst. Geol.,* 6 (4), pp. 752-756 (In Polish, French summary p. 756).

KRISHNA RAO, N. and RAO, G.V.U. 1971. Petrographic study of some Indian phosphroites. *Jl geol. Soc. India,* 12 (4), pp. 356-367.

KUO Shu-shing, 1963. Geology of the phosphorite deposits at the base of the Sinian along the eastern slope of the Taihang Range. *Acta geol. sin.,* 43 (3), pp. 291-302 (In Chinese, Russian summary).

LATIF, M.A. 1972. An occurrence of Palaeozoic phosphate rock in Hazara district, West Pakistan. *Trans Instn Min. Metall., Sect.* B, 81, pp. 50-53.

LIU, C.C. 1922. The apatite deposit at Tunghaihsien, Kiangsu (Summary). *Bull. geol. Surv. China,* 4, pp. 1-2.

LIU, C.Y. 1957. The Pre-Cambrian metamorphosed sedimentary type of phosphorite in China. *Acta geol. Sin.,* 37 (3), pp. 333-350 (In Chinese, English summary pp. 349-350).

MANCUSO, J.J., LOUGHEED, M.S., and SHAW, R. 1975. Carbonate-apatite in Precambrian cherty iron-formation, Baraga County, Michigan. *Econ. Geol.,* 70 (3), pp. 583-586.

MA, Tzu-chi and LIN, Yu-hsing, 1966. The Liaoho Group and the characters of its phosphate-bearing beds in the area between Fengcheng and Penchi, Liaoning. *Acta. geol. Sin.,* 46 (2), pp. 173-181 (In Chinese, English abstract pp. 180-181).

MATTHEW, W.D. 1893. On phosphate nodules from the Cambrian of southern New Brunswick. *Trans N.Y. Acad. Sci.*, 12, pp. 108-120.

MATS, V.D., EGOROVA, O.P. and BABKIN, A.K. 1956. On findings of phosphorites in the Upper Proterozoic deposits of the western Near-Baikal region. *Dokl. Akad. Nauk SSSR*, 110 (2), pp. 264-266 (In Russian).

MENG, Hsiang-hua, 1959. The petrography of phosphorites of the Karatau basin. *Dokl. Acad. Sci. USSR*, 126 (6), pp. 524-526.

NATH, M. 1967. Phosphate deposits in Rajasthan. *Indian Miner.*, 21 (2), pp. 83-101.

——— SANT, V.N. CHAKRAVARTY, D.K., SAXENA, S.P., CHAKRAVARTY, B., and SINGH, G.B. 1969. Precambrian phosphorite near Udaipur, Rajasthan. *Jl Mines Metal. Fuels*, 17 (10), pp. 335-339.

NOTHOLT, A.J.G., HIGHLEY, D.E. and SLANSKY, M. 1977. Phosphate resources of the European Economic Community. 182 pp. (Unpublished report prepared for the Commission of the European Communities).

PATWARDHAN, A.M. 1973. Origin of phosphorite of the Late Precambrian Gangolihat Dolomites of Pithoragarh, Kumaun Himalaya, India. *Sedimentology*, 20 (3), pp. 449-450.

PEACH, B.N., HORNE, J., GUNN, W., CLOUGH, C.T., HINXMAN, L.W., and TEALL, J.J.H. 1907. The geological structure of the North-West Highlands of Scotland. *Mem. geol. Surv. Gt Br.*, 668 pp. (Phosphatic nodules, pp. 287-288).

POLYANSKII, N.V. 1977. Discovery of phosphate shows in Lower Paleozoic deposits of the Chingiz–Tarbagatai meganticlinorium in eastern Kazakhstan. *Lithol. Miner. Resour.*, 12 (1), pp. 108-110.

POPOVA, Z.D. 1959. So-called 'phosphorites' in the central part of the Sarysay depost. *Vest. Akad. Nauk Kazakh. SSSR*, 15 (7) (172), pp. 63-65 (In Russian).

——— 1963. Calcium phosphates of the Sarysay deposit. *Trudy Inst. geol. Nauk, Alma-Ata*, 7, pp. 218-246 (In Russian).

POULSEN, Chr. 1960. The Palaeozoic of Bornholm. *Guide Exc.* A.46 and C.41. *21st Sess. int. geol. Congr., Norden*, 15 pp. (Phosphates, pp. 5-7).

PRITCHARD, P.W. and COOK, P.J. 1965. Phosphate deposits of the Northern Territory. *Publs 8th Commonw. Min. metall. Congr. Aust. N.Z.*, 1, pp. 219-220.

REGNELL, G. and HEDE, J.E. 1960. The Lower Palaeozoic of Scania. The Silurian of Gotland. *Guide Exc.* A.22 and C.17, *21st Sess. int. geol. Congr.*, 87 pp. (Phosphate, pp. 8 and 10).

ROGERS, J.K. and KEEVERS, R.E. 1976. Lady Annie – Lady Jane phosphate deposits, Georgina Basin, Queensland. Pp. 251-265 *in* Economic Geology of Australia and Papua New Guinea, Vol. 4. Industrial minerals and rocks. Edited by C.L. Knight. *Monogr. Ser. No.* 8, *Australas. Inst. Min. Metall.* 423 pp.

RUSSELL, R.T. 1967. Discovery of major phosphate deposits in northwest Queensland. *Qd Govt Min. Jls.* 68 (786), pp. 153, 155, 157.

——— and TRUEMAN, N.A. 1971. The geology of the Duchess phosphate deposits, northwestern Queensland, Australia. *Econ. Geol.*, 66 (8), pp. 1186-1214.

SEMEIKIN, I.N., KOLESNIKOV, V.L., BELOGOLOVOV, V.G. and KHRAPAL, Yu. I. 1976. Geologic structure and ore types of the northern Ukha-Gol phosphorite deposit (E. Sayan). *Sov. Geol. Geophys.*, 17 (9), pp. 61-68.

SAKHAROVA, M.S. 1956. Problems in the search for metamorphic phosphates in Siberia. *Vop. Geol. agron. Rud., Akad. Nauk SSSR*, pp. 134-147 (In Russian).

SLAVIK, S. 1936. Geochemistry of manganese and phosphorus. *Izv. Akad. Nauk SSSR*, 1, pp. 245-250.

SMIRNOV, A.I. 1959. New data on the elemental constitution of the phosphrites in the Karatau basin. *Dokl. Acad. Sci. U.S.S.R.*, 125 (1), pp. 177-180.

——— and TUSHINA, A.M. 1960. The discovery of secondary phosphorites in Karatau. *Dokl. Acad. Sci. U.S.S.R.*, 1961, 130 pp. 171-174.

SOKOLOVA, Y.A. 1961. The distribution of manganese and phosphorus in various types of rocks in the Usinsk formation (Lower Cambrian of Kuznetsk Ala-Tau). *Dokl. Acad. Sci. U.S.S.R.*, 135 pp. 1081-1083.

SOUGY, J. 1964. Les formations paleozoiques du Zemmour noir (Mauritanie septentrionale). Étude stratigraphique, pétrographique et paléontologique. *Annls Fac. Sci. Univ. Dakar*, 15, *Ser. Sci. Terre*, 1, 695 pp.

SPANDERASHVILI, G.I. 1962. The phosphorites of Gornaya Shoriya. *Sov. Geol.*, 5, pp. 58 74 (In Russian).

SPJELDNAES, N. 1967. Fossils from pebbles in the Biskopasen Formation in Southern Norway. *Norg. geol. Unders.*, 251, pp. 53-82.

SUKHARINA, A.N., SAZHIN, A.L. and SPANDERASHVILI. 1961. La région à phosphates de Haute Shorija. *Prospect. Prot. Sous-sol,* 2, pp. 1-16 (French translation of *Razv. Okhr. Nedr.).*

SUNDIUS, N. 1923. Grythyttefaltets geologi. *Sver. geol. Unders. Afh., Ser.* C, 312, 354 pp (In Swedish, English summary pp. 334-353).

SVIRIDOV, V.V. 1967. The volcanic type of phosphate show in the Ukraine. *Dokl. Acad. Sci. U.S.S.R.*, 173, pp. 148-150.

TANAKADATE, H. 1931. An apatite ore deposit in China (Haichau, Kiangsu Province). *Proc. Wld Engng Congr., Tokyo, 1929,* 37 (5), pp. 547-551 (Tokyo: World Engineering Congress).

THIEME, P. 1970. Australian mineral industry : phosphate deposits. *Miner. Resour. Rept. Bur. Miner Resour. Geol. Geophys. Aust.*, 3, 19 pp.

THOMSON, L.D. and RUSSELL, R.T. 1971. Discovery, exploration and investigations of phosphate deposits in Queensland. *Proc. Australas. Inst. Min. Metall.*, 240, pp. 1-14.

THORSLUND, P. and JAANUSSON, V. 1960. The Cambrian, Ordovician and Silurian in Västergötland, Närke, Dalarna and Jämtland, Central Sweden. *Guide Exc.* A.23 and C.18, *21st Sess. int. geol. Congr., Nordern,* 51 pp. (Phosphate, p. 20).

TROMPETTE, R. 1978. Occurrences of phosphorites in the Volta Basin. *Newsl. int. geol. Correlation Progm, Proj. 156,* 2, pp. 7-8.

TUSHINA, A.M. 1968. Lithofacies characteristics of the formation of the phosphorite stratum of Karatau. *Lithol. Miner. Resour.*, 4, pp. 456-465.

VALDIYA, K.S. 1969. A new phosphatic horizon in the Late Precambrian Calc Zone of Pithoragarh, Kumaun Himalaya. *Curr. Sci.*, 38 (17), pp. 415-416.

VALDIYA, K.S. 1972. Origin of phosphorite of late Precambrian Gangolihat dolomites of Pithoragarh, Kumaun Himalaya, India. *Sedimentology,* 19, pp. 115-128.

VILAND, J-C. 1977. Présence d'horizons phosphates à la base de l'Infracambrien supérieur du Haut Atlas de Marrakech (Maroc). *Notes Mems Serv. géol. Maroc,* 38 (268), pp. 13-22 (In French).

VOLKOV, R.I., ZAITSEV, N.S., ILYIN, A.V. and OSOKIN, N.V. 1972. The Ukha-Gol phosphorite deposit in East Sayan Mountains. *Sov. Geol.*, 2, pp. 94-107.

WANG, C.C. 1942. The phosphate deposits of Talungtan, Kunming, Yunnan (Summary). *Bull. geol. Surv. China,* 35, pp. 39-40.

WANG, Y.L. 1942. Phosphate rocks of Chungyitsun, Kunyang, Yunnan (Summary). *Bull. geol. Surv. China,* 35, pp. 35-38.

WEDOW, H., CARPENTER, R.H. and LEHR, J.R. 1968. Phosphorite in the Precambrian Ocoee Series of the East Fork manganese district, Sevier County, Tennessee. *Spec. Pap. geol. Soc. Am.*, 101, p. 380 (Abstract of paper submitted for the meeting in Athens, Georgia, April 13-16, 1966).

WELLS, A.T., RANFORD, L.C., STEWART, A.J., COOK, P.J. and SHAW, R.D. 1967. Geology of the north-eastern part of the Amadeus Basin, Northern Territory. *Rept Bur. Miner. Resour. Geol. Geophys. Aust.*, 113, 93 pp.

YUDIN, N.I. 1965. Phosphorite-bearing Precambrian deposits in the south-eastern part of the Tuva ASSR. *Litol. i polez. Iskop.*, 2, pp. 28-37 (In Russian).

ZAITSEV, N.S. 1970. The Khubsugul phosphate deposit. *Dokl. Akad. Nauk SSSR,* 192 (2), pp. 391-394 (In Russian).

Microbiological Controls on Phosphate Accumulation

by *P.A. Trudinger,* Baas Becking Geobiological Group, Canberra

Abstract

The three main hypotheses for the role of organisms in the formation of phosphate are the biological reduction of phosphate, modification of the CO_2-bicarbonate-carbonate equilibrium, and accumulation of phosphate by phytoplankton. Only the last of these three hypotheses appears to be consistent with current evidence. It is particularly relevant to regions of coastal upwelling where high nutrient levels result in increased productivity and where the levels of phosphate appear to be insufficient to allow chemical precipitation of calcium phosphates. Calculations show that the microflora in upwelling environments could supply sufficient phosphate to form large phosphorite deposits in a geologically reasonable time.

Introduction

The three main hypotheses have been advanced which invoke a role for micro-organisms in the formation of sedimentary phosphorites:

1 biological reduction of phosphate to soluble hypophosphites followed by oxidation of the latter in aerobic environments with the formation of apatite (Gulbrandsen 1969);

2 modification of the CO_2-bicarbonate-carbonate equilibrium which in turn controls phosphate deposition (McConnell 1965); and

3 accumulation of phosphate by phytoplankton, followed by incorporation of the plankton into sediments and the release and fixation of phosphate (Charles 1953; Willcox 1953; Youssef 1965; Bushinskii 1966; Gulbrandsen 1969).

The first hypothesis depends upon the fact that the solubility of calcium hypophosphite is one or two orders of magnitude higher than those of phosphates of calcium. Reduction of phosphate, therefore, provides a potential mechanism for producing elevated concentrations of soluble phosphorus in sea water.

Although a biological basis for this hypothesis is provided by the demonstration of microbial reduction of phosphate (Rudakov 1927, 1929; Tsubota 1959) and oxidation of hypophosphite (Heinen and Lauwers 1974), there is at present no evidence that reduced phosphorous compounds occur to a significant extent in the natural environment.

Table 9 Phosphate Concentrations in Microorganisms

Organism	Phosphorous (% organic carbon)	Reference
Diatoms	2.7	1
	4.2	2
	1.9	3
Dinoflagellates	1.7	1
Green algae	2.3-8.7 (av. 5.2)	4
Brown Algae	0.8	5
"Phytoplankton"	1.9	6
Bacteria	5–10	7

References: 1, Peres and Deveze 1964; 2, Lisitsyn 1966; 3, Vinogradova and Kobalsky 1962; 4, Ketchum and Redfield 1949; 5, Vinogradov 1953; 6, Redfield 1934; 7, Porter 1946.

Table 10 Phosphorous Concentrations in Ocean Waters

Location	Phosphorous (μgatoms 1^{-1})	Reference
Atlantic Ocean		1
(surface)	0.3	
(below 1000m)	1.8	
Pacific Ocean		1
(surface)	0.4	
(below 1000m)	3.0	
Indian Ocean		1
(surface)	0.8	
(below 1000m)	3.0	
Mauritania upwelling system	$>$1.5	2
Peru upwelling system (upper 50m)	1.0 – 2.0	1
Baja California upwelling system (upper 50m)	0.5 – 2	3

References: 1, Dugdale 1972; 2, Kirichek and Sukhoruk 1975; 3, Walsh *et al.* 1974.

Table 11 Primary Productivity in Upwelling Regions

Region	Productivity gm^{-1} Cm^{-2} day^{-1}	Reference
Baja California	7.1	1
Peru	5.7	1
South West Africa	2.5–3.8	2
Unspecified	1.3	3

References: 1, Walsh *et al.* 1974; 2, Steeman-Nielsen and Jensen 1957; 3, Riley *et al.* 1949.

The second hypothesis is based on the observation that the formation of carbonate-hydroxyapatite in experimental systems was catalysed by the enzyme, carbonic anhydrase (McConnell *et al.* 1961, 1962). This enzyme is widely distributed amongst organisms, including bacteria (Veitch and Blakenship 1963) and algae (Litchfield and Hood 1962), and it catalyses the reversible dissociation of carbonic acid:

$$H_2CO_3 \rightleftharpoons H_2O + CO_2$$

It thus has the potential to modify reactions which depend on the concentration of carbon dioxide. It has been pointed out, however (Bachra and Trautz 1972) that the chemical hydration of CO_2 is so rapid (measured in seconds) that additional enzymic catalysis would be of doubtful geochemical significance.

Of more importance with respect to carbonate equilibria are respiration and fermentation which release CO_2, and photosynthesis which fixes CO_2. The reactions also modify pH and alkalinity (Krumbein 1979) which, in turn, influence mineralization reactions in interstitial and other waters. They often have a controlling influence on carbonate deposition (Borowitzka 1977; Krumbein 1979), but to the author's knowledge their effects on phosphate fixation have not been specifically discussed in the literature.

The most widely accepted biological mechanism for phosphate deposition is that of phosphate accumulation by phytoplankton. Phosphorous is required by all living organisms, being a component of the informational molecules, nucleic acids, the energy transfer molecule adenosine-triphosphate, and the molecules (phospholipids etc.) from which cell membranes are constructed. In addition, many microorganisms accumulate large amounts of polyphosphates which they synthesise during periods of phosphate excess to be utilized later when nutrient supplies are deficient. The phosphate requirements of microorganisms vary widely. However, Finenko and Krupatkina–Akanina (1974) have reported that diatoms, which are frequently major components of the microflora of upwelling regions, require about 0.03 μgatoms l^{-1} in marine waters (Dugdale *et al.*, 1964) and O.3 μgatoms l^{-1} in fresh waters (Vollenweider 1968). Phosphate concentrations in excess of these values might be expected to lead to polyphosphate accumulation.

The variability in phosphate concentrations of living microorganisms (Table 9) is probably due, in part, to the dependence of phosphate content upon the availability of phosphate in the medium (Ketchum 1939; see above). The concentrations represent considerable enrichments of phosphorous. A carbon: phosphorous ratio of 50:1, which appears to be fairly typical of marine phytoplankton, is equivalent to about 60,000 μgatoms of P l^{-1} of cell mass. This would correspond to a phosphorous enrichment factor of about 30,000 with respect to average ocean waters (ca 2 μgatoms P l^{-1}) and to considerably higher factors with respect to the nutrient-depleted, photic surface zones of the oceans.

Some of the most favourable regions for extensive growth of phytoplankton are those of coastal upwelling where elevated concentrations of nutrients are available. Table 10 shows that the surface photic zones of oceans are generally depleted in phosphorous and, where these mix with coastal waters in upwelling regions, surface concentrations of phosphorous may reach values of around 1.5 μgatoms l^{-1}. A similar situation applies to nitrate (Dugdale 1972), another growth-limiting nutrient, with the result that upwelling regions become sites of high productivity. Rates of primary production in upwelling regions have, in general, been reported to range from 1-7gC m^{-2} day $^{-1}$ (Table 11) although higher values have occasionally been recorded: e.g. 25 gC m^{-2} day^{-1} (Walsh *et al.* 1974) and 27 g dry wt (= 14 g C) m^{-2} day^{-1} (Peres and Devèze 1964). These rates may be compared with those of 0.05-0.15 gC m^{-2} day^{-1} for tropical open-ocean waters (Ryther 1963). The high productivity in upwelling regions has a profound effect on the phosphate economy of the waters. Federov and Sorokin (1975, for example) , reported that uptake of phosphorous by plankton in the upper waters of the Peru upwelling system corresponded to 10 – 100% of the standing stock of phosphate. (Interestingly, a large proportion of the phosphate uptake appeared to be due to bacteria). On the basis of an average C:P ratio of 50:1 (Table 9), a primary productivity of 1·7gC m^{-2} day^{-1} would require 0.02 - 0.14 gP m^{-2} day^{-1}. If incorporated into sediment this would be sufficient to produce a 50 m thick phosphorite deposit in about 2.5 x 10^5 - 1.5 x 10^6 years (assuming an average compaction factor of 3). Using similar arguments Gulbrandsen (1969) and Cressman and Swanson (1964) derived values of the order of 2 x 10^5 years for the precipitation of Phosphoria phosphorites by biogenic processes. These calculations, however, assume that steady-state conditions of upwelling and primary production prevail over extended periods of time, that all phosphorous in phytoplankton reaches the sediment, and that there is no loss of phosphorous from the sediment. These assumptions are certainly invalid but it is not possible, at this time, to make realistic assessments of the necessary correction factors. It is worth noting, however, that the estimates of phosphorous incorporation into sediments could be too high by factors of 40-200 and still allow the formation of a Phosphoria-type deposit during Permian time. (Whether or not the quantity of phosphorous in the Phosphoria Formation could be derived from sea water is another question).

Several features indicate that many phosphorite deposits were laid down in anaerobic environments. These include associations with pyrite and black shales (Pettijohn 1957), the presence of U(IV) (Altschuler *et al.* 1958), and the presence of hydrocarbons (Powell *et al.* 1975). Similarly the phosphate-bearing sediments of upwelling regions may be highly anaerobic due to the depletion of oxygen during oxidation of organic matter and the subsequent onset of sulphate reduction. Redox potentials of -200mV, for example, have been reported for sediments of Walvis Bay (Romankevich and Baturin 1972). On the other hand the development of reducing conditions in sediments is often accompanied by a fall in pH and the *release* of phosphate from sediment into the overlying waters (Einsele 1938; Mortimer 1942; Hallberg *et al.* 1972, 1975; Schippel *et al.* 1973). The chemical circumstances which determine whether phosphate is fixed or released in anaerobic sediments remain to be resolved.

The biological accumulation hypothesis overcomes some of the problems involved in attributing phosphate enrichment in sediments to chemical precipitation from the water column (see Gulbrandsen 1969). Nevertheless, a problem which arises in attempts to evaluate a biological contribution to phosphate deposition is that there are no known diagnostic tests for "biogenic" precipitates for phosphate. The presence of fossil micro-organisms (Cayeux 1936; Slansky 1978, this volume; Riggs 1978, this volume) may indicate a rich microflora in the sedimentary environment but cannot *per se* distinguish between a causal or coincidental relationship between the organisms and phosphate deposition. One approach to this problem would be to analyse the complete carbon and phosphate budget of a phosphogenic upwelling region, covering incorporation by the biomass, sedimentation and fixation and retention in sediments. From such studies a clearer idea of the significance of organisms in phosphate deposition should emerge.

Acknowledgements

The author is indebted to many colleagues at the IGCP Project 156 Phosphorite Symposium for discussions which led to a re-evaluation of some of the ideas expressed in this paper in its original form. The Baas Becking Laboratory is supported by the Commonwealth Scientific and Industrial Research Organization, the Bureau of Mineral Resources, and the Australian Mineral Industries Research Association Ltd.

References

ALTSCHULER, Z.S., CLARKER, R.S. and YOUNG, E.J., 1958. Geochemistry of uranium in apatite and phosphorite. *U.S. Geol. Surv. Prof. Pap.*, 314D, 90 pp.

BACHRA, B.M. and TRAUTZ, D.R., 1962. Carbonic anhydrase and the precipitation of apatite. *Science*, 137, 337-338.

BOROWITZKA, M.A., 1977. Algal calcification. *Oceanogr. Mar. Biol. Ann. Rev.*, 15, 189-223.

BUSHINSKII, G.I., 1966. The origin of marine phosphorites. *Lithol. Mineral Resour.*, 3, 292-311.

CAYEAU, L.S., 1936. Existence des nombreuses bactéries dans les phosphates sédimentaires de tout ages. *C.R. Acad. Sci. Paris*, 203, 1198-1200.

CHARLES, G., 1953. Sur l'origine des gisements de phosphates de chaux sédimentaires. *19th Int. Geol. Cong. Algiers, 1952, C.R. Sec.* 11(11), 163-184.

CRESSMAN, E.R. and SWANSON, R.W., 1964. Stratigraphy and petrology of the Permian rocks of south-western Montana. *U.S. Geol. Surv. Prof. paper*, 313C, 569 pp.

DUGDALE, R.C., 1972. Chemical oceanography and primary productivity in upwelling regions. *Geoforum*, 11, 47-61.

DUGDALE, R.C., GOEHRING, J.J. and RYTHER, J.H., 1964. High nitrogen fixation rates in the Sargasso Sea and the Arabian Sea. *Limnol. Oceanogr.*, 9, 507-510.

EINSELE. N., 1938. Uber chemische und kolloidchemische Vorgange in Eisen-Phosphat-Systemenunter Limnochemischen und Limnogeologischen Gesichstpunkten *Arch. Hydrobiol.* 33, 361-387.

FEDEROV, V.I. and SOROKIN, Yu. I., 1975. Mineral phosphate consumption by phytoplankton and bacteria in the eastern part of the Pacific Ocean measured with phosphorous 32. *Trud. Inst. Okeanol. Akad. Nauk. S.S.S.R.*, 102, 199-205.

FINENKO, Z.Z. and KRUPATKINA-AKANINA, D.I., 1974. Effects of inorganic phosphorous on the growth rate of diatoms. *Mar. Biol.*, 26, 193-201.

GULBRANDSEN, R.A., 1969. Physical and chemical factors in the formation of marine apatite. *Econ. Geol.*, 64, 365-382.

HALLBERG, R.O., BAGANDER, L.E. and ENGVALL, A.-G., 1975. Dynamics of phosphorous, sulfur and nitrogen at the sediment-water interface. In: J.O. Nriagu (Editor), *Environmental Biogeochemistry, vol. 1, Carbon, Nitrogen, Phosphorus, Sulfur and Selenium cycles.* Ann. Arbor. Science, pp. 295-303.

HALLBERG, R.O., BAGANDER, L.E., ENGVALL, A.-G. and SCHIPPEL, F.A. 1972. Method for studying geochemistry of sediment-water interface. *Ambio*, 1, 71-73.

HEINEN, W. and LAUWERS, A.M., 1974. Hypophosphite oxidase from *Bacillus caldolyticus. Arch. Mikrobiol.*, 95, 267-274.

KETCHUM, B.H., 1939. Development and restoration of deficiencies in the phosphorus and nitrogen composition of unicellular plants. *J. Cell. Comp. Physiol.*, 13, 373-381.

KETCHUM, B.H. and REDFIELD, A.C., 1949. Some physical and chemical characteristics of algae grown in mass culture. *J. Cell. Comp. Physiol.*, 33, 281-298.

KIRICHEK, A.D. and SUKHORUK, V.I., 1975. Role of coastal upwelling in the formation of hydrochemical regime on northwestern AFrican coast. *Khim – Okeanogr. Issled. Morei Okeanov. Mata. Vses. Konf. Khim, Morya,* 6th 1972, pp. 111-117.

KRUMBEIN, W.E., 1979. Calcification by bacteria and algae. In: P.A. Trudinger and D.J. Swaine (Editors), *Biogeochemical Cycling of Mineral-Forming Elements.* Elsevier: in press.

LITCHFIELD, C.D. and HOOD, D.W., 1962. Evidence for carbonic anhydrase in marine and freshwater algae. *Int. Ver. Theor. Angew. Limnol. Verhandl.*, 15, 817-828.

LISITSYN, A.P., 1966. *Recent Sedimentation in the Bearing Sea.* Israel Progr. Sci. transl. p. 508.

McCONNELL, D., 1965. Precipitation of phosphates from seawater. *Econ. Geol.*, 60, 1059-1062.

McCONNELL, D., FRAJOLA, W.J. and DEAMER, D.W., 1961. Relation between inorganic chemistry and biochemistry of bone mineralization. *Science*, 133, 281-282.

McCONNELL, D. FRAJOLA, W.J. and DEAMER, D.W., 1962. A reply to comments by B.M. Bachra and O.R. Trautz. *Science*, 137, 337-338.

MORTIMER, C.H., 1942. The exchange of dissolved substances between wind and water in lakes. *J. Ecol.*, 30, 147-201.

PERES, J.M. and DEVEZE, L. 1964. *Oceanographie Biologique et Biologie Marine. Tome 2. La Vie Pelagique* Presses Univ. de France, Paris (Communicated by M. Slansky).

PETTIJOHN, F.J., 1957. *Sedimentary Rocks.* Harper and Bros., New York, 2nd Ed., 475 pp.

PORTER, J.R., 1946. *Bacterial Chemistry and Physiology*, John Wiley, New York, 1073 pp.

POWELL, T.G., COOK, P.J. and McKIRDY, D.M., 1975. Organic geochemistry of phosphorites: relevance to petroleum genesis. *Bull. Am. Ass. Pet. Geol.* 59, 618-632.

REDFIELD, A.C., 1934. *On the Proportions of Organic Derivatives in Sea water and their Relation to the Composition of Plankton.* James Johnstone Memorial Volume, University of Liverpool, pp. 176-192.

RILEY, G.A., STOMMEL, M. and BUMPUS, D.F., 1949. Qualitative ecology of the plankton of the western North-Atlantic. *Yale. Univ. Oceanogr. Lab.* 12, 169 (Communicated by M. Slansky).

ROMANKEVITCH, Ye. A. and BATURIN, G.N., 1972. Composition of the organic matter in phosphorites from the continental shelf of southwest Africa. *Geochem. Int.* 9, 464-470.

RUDAKOV, K.J., 1927. Die Reduktion der mineralischen Phosphate auf biologischen Wege. *Zbl. Bakteriol. Parasitkd. Abt.* 2, 70:229-245.

RYTHER, J.H., 1963. Geographic variations in productivity. In: M.N. Hill (Editor), *The Sea, vol. 2. Interscience, New York,* pp. 347-380.

SCHIPPEL, F.A., HALLBERG, R.O. and ODEN, S., 1973. Phosphate exchange at the sediment-water interface. *Oikos*, suppl. 15, pp. 64-67.

STEEMAN-NIELSEN, E.S. and JENSEN, E.A. 1957. Primary oceanic production. *Galathea Rep.*, 1, 49-136.

TSUBOTA, G., 1959. Phosphate reduction in the paddy field. *Soil Plant Tokyo*, 5, 10.

VEITCH, F.P. and BLAKENSHIP, L.C., 1963. Carbonic anhydrase in bacteria. *Nature*, 197, 76-77.

VINOGRADOV, A.P., 1953. *The Elementary Chemical Composition of Marine Organisms.* Sears Foundation, New Haven, Conn.

VINAGRADOVA, A.A. and KOVALSKII, V.V., 1962. Element composition of Black Sea plankton. *Dokl. Nauk. Akad. S.S.S.R.*, 147, 1458-1460.

VOLLENWEIDER, R.A., 1968. *Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication.* O.C.D.E. Directorate for Scientific Affairs, Paris.

WILCOX, N.R., 1953. The origin of beds of phosphate chalk with special reference to those at Taplow, England. *19th Int. Geol. Congr. Algiers, 1952, C.R. Sec. 11*(11), 119.

WALSH, J.J. KELLEY, J.C., WHITLEGE, T.E. and MacISSAC, J.J., 1974. Spin-up of the Baja California upwelling system. *Limnol Oceanogr.* 19, 553.

YOUSSEF, M.I., 1965. Genesis of bedded phosphates. *Econ. Geol.*, 60, 590.

The Possible Role of Dinoflagellates in Phosphate Sedimentation

by *D. Fauconnier* and *M. Slanksy,* Bureau des Recherches géologiques et minières, Orléans, France.

Abstract

The relatively high content of phosphorous in the mineral fraction of dinoflagellates, and the particular abundance of this oceanic plankton close to modern or recent phosphatic nodule deposits, led to research into the possible links between this phytoplankton and phosphate sedimentation. Albian-Cenomanian phosphatic sequences of the Paris Basin and a Paleocene sequence of the Gafsa Basin, Tunisia, have been studied with this object in mind. Data obtained show in both cases an association of phosphate with sediments rich in dinoflagellates, with periodic disequilibrium in relative abundance of species, as in "red tides". This association appears valid at the scale of the sequence but is not generally true in detail because during diagenesis, apatite neoformations seem to grow, at least in part, out of dinoflagellate cysts. It seems also that these cysts may contribute to silicate neoformations such as glauconite or montmorillonite.

Introduction

Organic matter and phosphate are frequently associated in ancient deposits, and the same association is found in modern or recent deposits which are situated in parts of the oceans with high organic productivity. The primary production of organic matter by phytoplankton, which abound in such regions, may attain 27 tonnes/ km^2/day dry weight (Peres and Deveze, 1964). Another estimate (Riley *et al.* 1949) attributes to phytoplankton an annual production of organic carbon of 475 tonnes/km^2 in regions of high productivity; that is, an annual production of P in the order of 21 tonnes P_2O_5/km^2 utilising a C/P ratio of about 50 for these organisms. Of the phytoplankton, diatoms are often the most abundant, especially in high latitudes, followed by dinoflagellates of which the number of cells may reach 3 to 10 million/litre and even 50 million in the special case of the "red tides". The coccolithophorids are common in warm and clear waters. According to Peres and Deveze (1964), diatoms and dinoflagellates have the following partial chemical composition, expressed in oxides relative to 100 gm of organic carbon.

	Diatoms 100 gm	Dinoflagellates 100 gm
P_2O_5	6.18	3.9
Fe_2O_3	13.7	4.8
CaO	17.5	3.8
SiO_2	119.2	14.1

Compared to organic carbon, diatoms have a higher P_2O_5 content. However, if

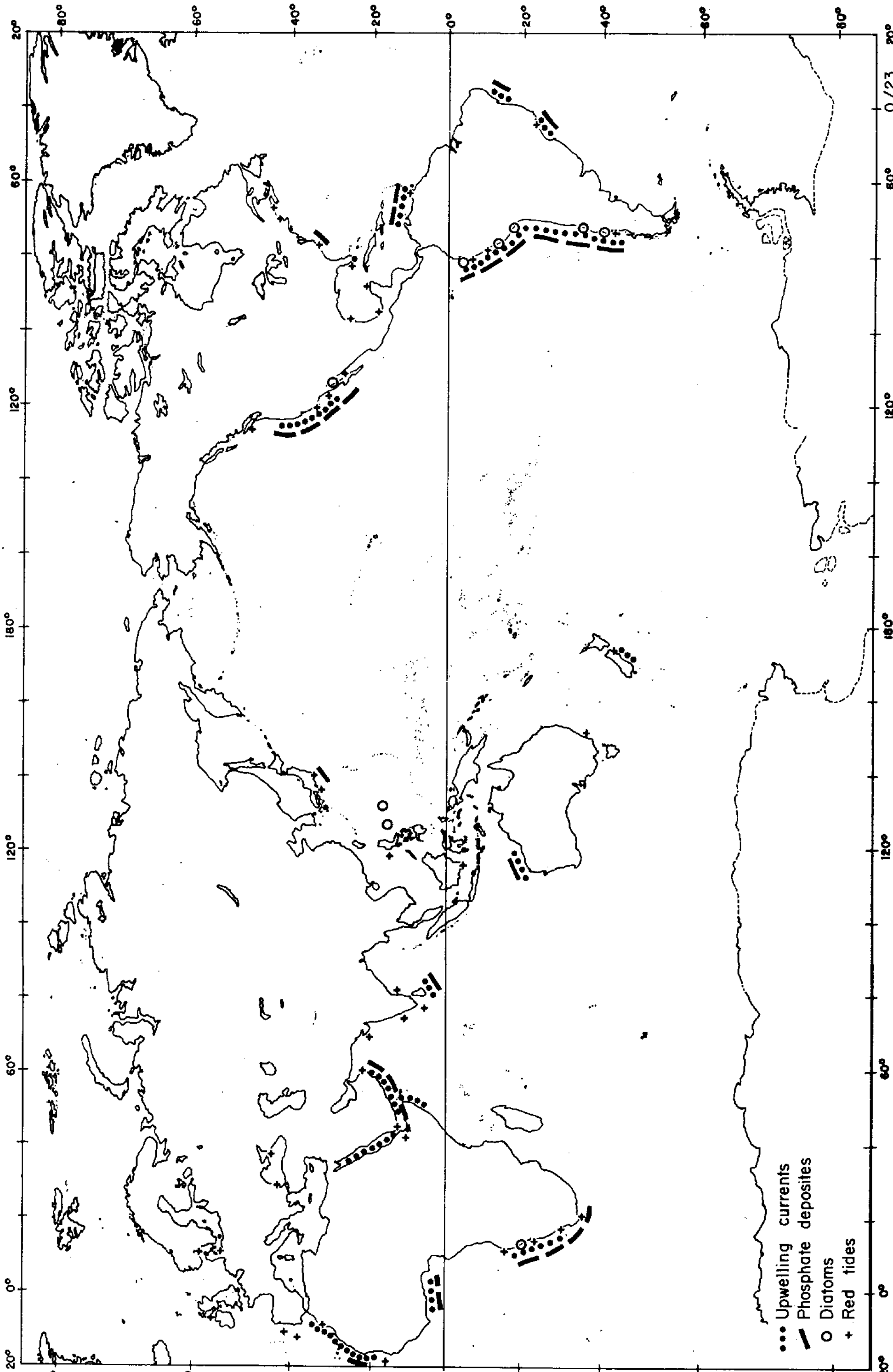


Fig 14 Distribution of upwelling systems and associated phenomena adabted from BRONGERSMA-SANDERS (1957) and McKELVEY (1967)

only the mineral fraction is considered, phosphorous is more abundant in the dinoflagellates (14.6% of the total P_2O_5 + Fe_2O_3 + CaO + SiO_2) than in the diatoms (2.6%) where the silica of the frustules is largely dominant. In the coccolithophorids, $CaCO_3$ is dominant, lowering considerably the proportion of phosphorous in the mineral fraction.

Thus, if the composition of the mineral fractions is considered, the accumulation of diatoms on the sea floor appears to favour the formation of cherts or clays rich in silica, such as sepiolite, attapulgite or montmorillonite (this hypothesis has been confirmed for the argillaceous neoformations in the eastern Mediterranean (Chamley 1971)), and accumulations of coccoliths favour the formation of chalk or of fine grained limestone. The accumulation of dinoflagellates, on the other hand, appears to most favour the neoformation of phosphates especially when this microplankton periodically undergoes abnormal population variations (the phenomenon of "red tides"), which, in favouring one species or a small number of species, is responsible for mass mortalities of other pelagic or benthic populations. This process is thus capable of notably increasing the quantity of phosphorous accumulating at the sea floor. Some fish may contain more than 40% P_2O_5 in their mineral fraction, and there are certain crustaceans whose mineral phase is almost wholly composed of calcium phosphate. Observations made in modern oceans demonstrate that the phenomenon of "red tides" is frequently close to modern or recent deposits of phosphatised nodules (see Fig. 14), for example, along the coasts of California, Peru and Chile, or along the west coast of southern Africa.

The possible role of dinoflagellates in phosphatic sedimentation led us to investigate the possible links between this phytoplankton and phosphate, within ancient mineralised sequences, in the hope of finding characteristic relationships which can be used in exploration. The research has been oriented primarily towards the areas of Albian and lower Cenomanian sediments in the Paris Basin; a phosphatic Paleocene sequence in the Gafsa Basin; a few samples from other areas were also studied for comparison. This research has been made possible by the development of a method for measuring the abundance of dinoflagellate cysts (the cysts are the only fossil form of this phytoplankton). The relation between the determined abundance of each sample, expressed by the number of cysts/gm of rock and the real abundance of the dinoflagellates in the original deposit may vary with the method of preparation, the representativeness of the sample and the diagenetic processes. However, the results to date appear coherent and seem sufficiently representative that they can sensibly be used.

Albian and Lower Cenomanian of the Paris Basin

The Albian of the Paris Basin contains many beds of phosphatised nodules which were very actively exploited during the last century and occasionally at the beginning of this century, especially in the northern part of the Basin (Boulonnais), the north-east (Ardennes, Meuse and Marne), the south-east (Yonne), and the south (Cher). More than 1,200,000 tonnes of phosphatised nodules averaging 20 to 30% P_2O_5 were mined in these regions, the department of Meuse being the biggest producer. The lower Cenomanian also has a glauconitic facies, locally enriched in phosphatised nodules, which have been mined in the north and north-east parts of the Basin, and in the region of Rouen. Where the Albian and Cenomanian nodules are present they have an irregular distribution with discontinuous beds, which are generally very thin, averaging less than 25 to 30 cm in the Albian and a little

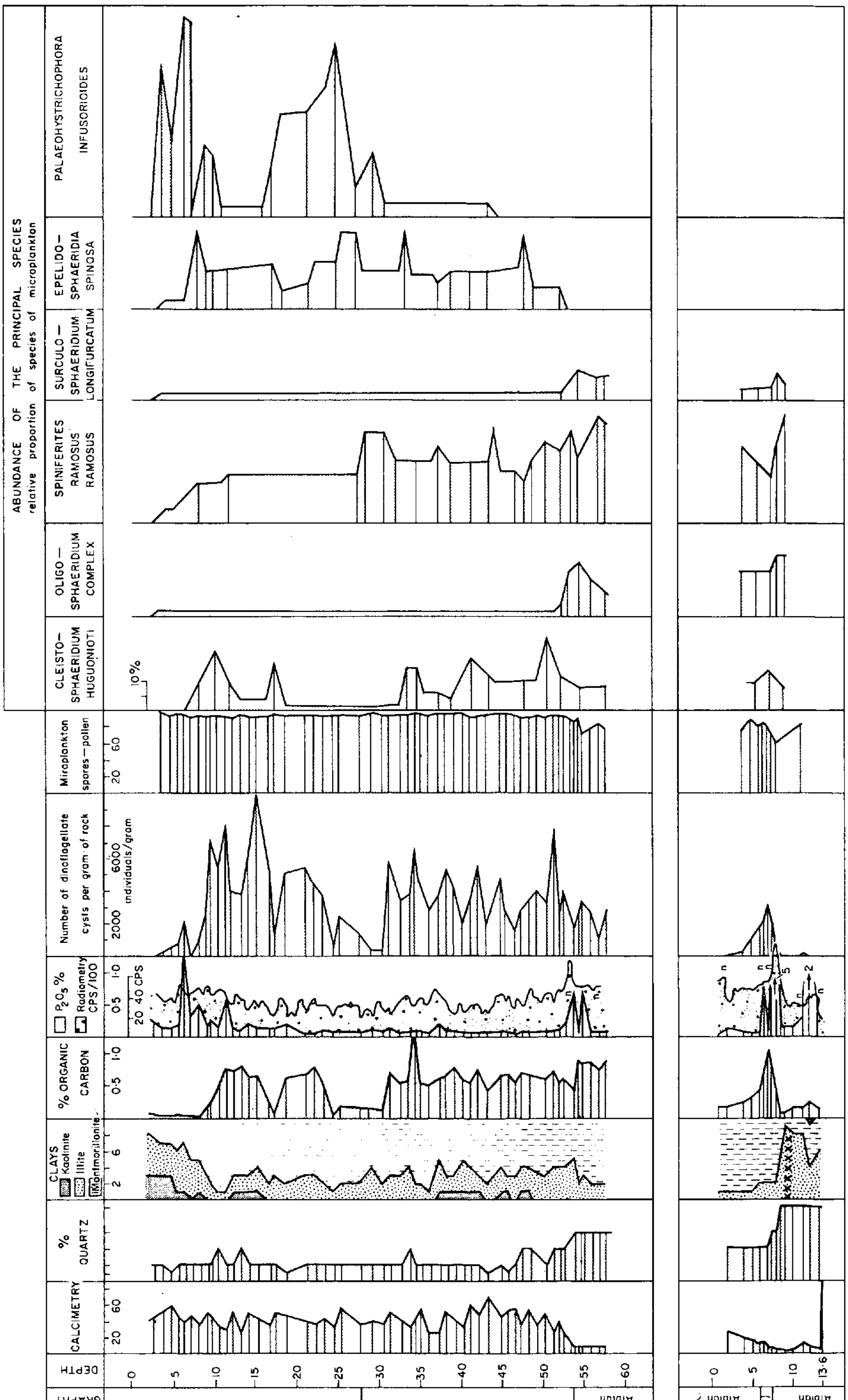


Fig 15 RETHEL CORE HOLE

thicker in the Cenomanian. These beds have a variable stratigraphic position, for example, in the Boulonnais a condensed section of 13 m contains two beds of 3 and 8 cm thickness in the lower Albian, one bed of 5 cm in the middle Albian, three beds of 3, 5 and 5 cm in the upper Albian and one bed of 1 m thick of very glauconitic chalk with phosphatised nodules (concentrated principally in the lower part) at the base of the Cenomanian (Wissant and Destombes 1965).

These stratigraphic levels have been studied using seven sections distributed throughout the Paris Basin, and are described in detail elsewhere (Fauconnier 1977). The only section present here is that from the Tethel region (Fig. 15) within which the lower Albian is dominantly sandy and often glauconitic; the middle Albian is represented by a silty argillaceous limestone, and the overlying units are essentially chalky. The Cenomanian is progressively enriched in glauconite. These facies are representative of the sedimentary sequence in the Paris Basin within which the phosphatised beds are intercalated; however in the section considered, these beds are marked only by slight anomalies in P_2O_5 content. The section (Fig. 15) demonstrates:

(i) the generally high percentage of dinoflagellate microplankton within the total palynological content (microplankton + spores + pollen), which appears in column 7 of Figure 15, indicates a low continental influence and an open sea situation;

(ii) the abundance of dinoflagellates in column 5 varies sympathetically with the level or organic carbon, emphasising the importance of this group of phytoplankton in the organic content of the rock. Beginning in the middle Albian, the average abundance of microplankton in the 56 samples studies from the Rethel district is above 3,400 individuals/gm or rock with maximum values between 5,000 to 10,000;

(iii) as is found to occur during "red-tide" certain dinoflagellate species periodically dominate the microplankton: the species *Paleohystrichophora infusorioides* reaches abundances of up to 70% in a sample of anomalous phosphatization at 6.4 m in drill-hole RE 2.

These features of abundance, of disequilibrium of species, and of the influence of dinoflagellates in the organic content of the sediments, are also found in stratigraphically equivalent parts of the other sections studied in the Paris Basin. The dinoflagellates disappear completely when the upper Albian becomes characterised by a biogenic opal facies and a lack of phosphate nodules. The importance of dinoflagellates also diminishes notably when the Cenomanian becomes rich in chalk or limestone.

In almost all sections, the levels with phosphatised nodules are situated within those parts of the sections rich in microplankton and each bed itself may be directly associated with a particular peak in the number of cysts/gm of rock in some cases. More frequently there is an association, within the same sample, of an increase in P_2O_5 and a relative abundance of one or two species; such as the case of the sample taken at 6.4 m depth at Rethel. Conversely, there are numerous peaks of relative abundance of these species which do not coincide, even locally, with phosphate anomalies.

As the section at Rethel shows, in many cases a direct relationship exists between the content of organic carbon and the abundance of microplankton. Nevertheless, some samples are poor or lacking in dinoflagellates in spite of a significant organic carbon content. This is the case, for example, for the phosphatised nodules themselves, which have a P_2O_5 content of between 24 and 26% in the samples

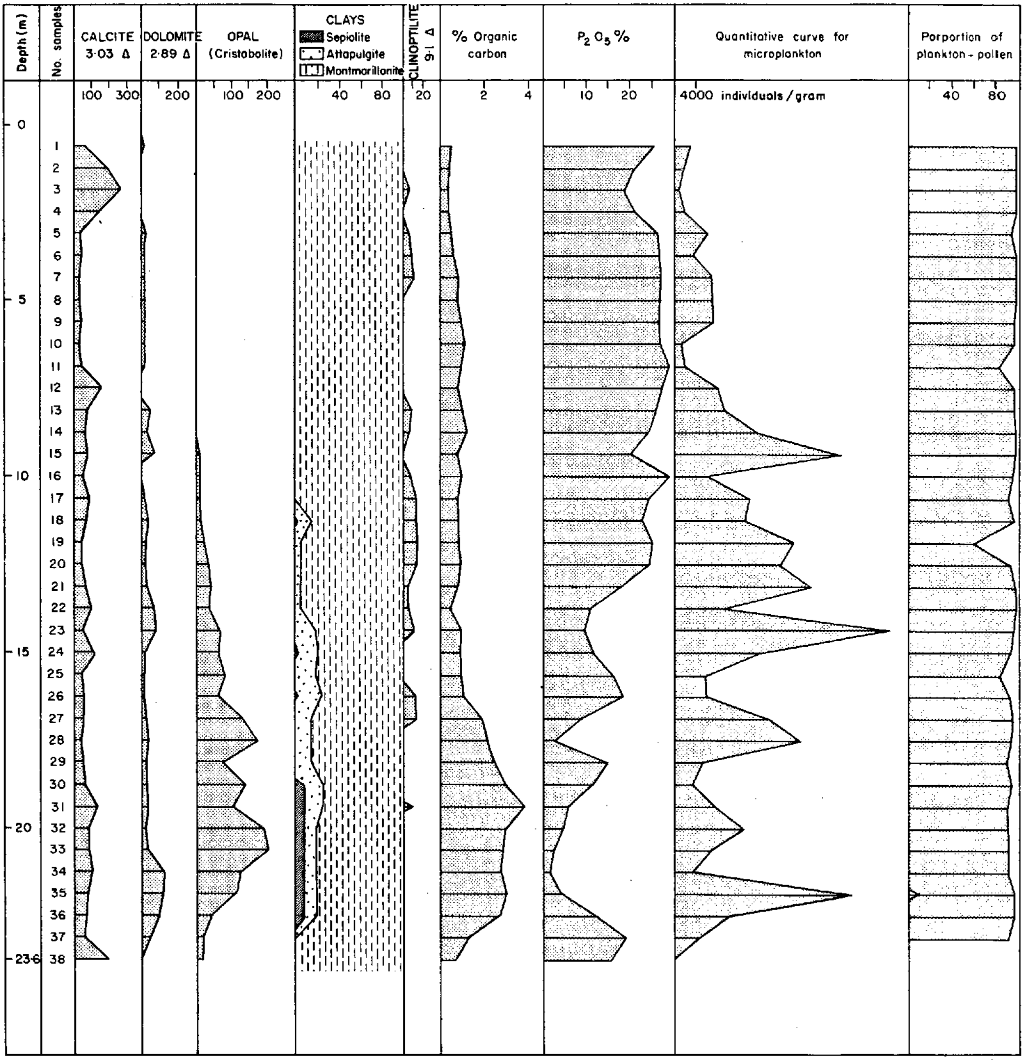


Fig 16 M'RATA (Tunisia) COREHOLE

studied, and an organic C content between 1.15 and 1.8% are, on the contrary, totally lacking in microplankton.

Similarly, when the gangue to the phosphate nodule beds is very glauconitic, as in the case of the lower Albian or the Cenomanian in the same Wissant section, the cysts of dinoflagellates are rare or absent in spite of a significant content of organic matter; this is also the case in the lower Albian at Rethel where the content of organic matter is always weaker. The persistence of organic carbon and its direct relationship with the abundance of microplankton suggests that the more or less complete disappearance of the cysts may be attributable to the intensity of the diagenetic processes responsible for the neoformation of the apatite and glauconite. The abundance of dinoflagellates may also decrease due to weathering, as in the upper part of the drill-holes at Rethel, or by oxidation following deposition; in this case, the content of organic carbon diminishes simultaneously. Finally, it is noticed, that many of the sections studied in the Paris Basin show that when the littoral influence increases during the Albian, and the dinoflagellates become more abundant, montmorillonite developes in the clay fraction. When the montmorillonite is ferruginous it may become glauconitic.

The Paleocene of the Gafsa Basin

In order to facilitate interpretation, the results obtained in the Paris Basin have been compared to those obtained from a study of a drill-hole at M'Rata which penetrated a richly phosphatic paleocene sequence in the Gafsa Basin in Tunisia. This drill-hole has been studied from a mineralogical and geochemical point of view by Sassi (1974) and from a palynological point of view by Chateauneuf *et al.* (1978). Fig. 16 presents a part of the results obtained. In this figure the contents of calcite, dolomite, opal and clinoptilolite are represented by the high values associated with certain peaks in X-ray diffraction diagrams. Standardised control samples have shown that the variations in these high values correctly characterise true variations in mineralogical composition. In order to appreciate this, one can note that sample 3 contains 40% calcite and 0% dolomite, sample 36 contains 8% calcite and 16% dolomite, sample 32 contains 63% SiO_2 and that the quantity of clinoptilolite reaches more than 10%.

This sequence, which is much more phosphatic than the sections studied in the Paris Basin, is associated with a much more abundant microplankton flora: 16 of the 38 samples studied have more than 10,000 cysts/gm of rock, with a maximum of 40,000. But in spite of their abundance, the dinoflagellates at M'Rata have less influence on the organic content of the deposits, particularly in the lower half of the section where the paralellism in the content of opal and organic carbon is evidence of the presence of a large population of diatom phytoplankton. These diatoms, whose presence was shown by Lucien Cayeux in 1941, appear to have favoured the neoformation of clay minerals rich in silica, such as attapulgite and sepiolite. Conversely, the phosphatic sedimentation appears to have developed mainly after the decrease and disappearance of biogenic opal.

In spite of fairly severe variations, the "quantitative curve of microplankton" shows that the abundance of dinoflagellates grows from the moment that opal decreases in importance and the grade of phosphate increases generally to about 20 to 25% P_2O_5. In passing, one may note that the same species of dinoflagellates which periodically proliferate in the Paris Basin, are found in the Gafsa Basin. The abundance of dinoflagellates increases with the development of phosphatic sediments generally. However, in detail the higher abundances of microplankton coincide with a marked reduction in the grade of P_2O_5, while the part o the section which is most mineralised only presents abundances of 7,000 to 8,000 individuals/gm of rock. Sample 8 from M'Rata, with a grade exceeding 26% P_2O_5, has an abundance of dinoflagellates of about 7,000 cysts/gm of rock. After removal of the argillaceous gangue, this sample has been subjected to a density separation of phosphatic grains, using bromoform. The phosphate grains have a variable density; the densest, that is the richest in phosphate, are poor in dinoflagellates (500 cysts/gm. approximately); the least rich in phosphate are the richest in dinoflagellates (4,000 cysts/gm). In the same sample, the abundance of dinoflagellates appears, therefore to vary inversely with the grade of phosphate, from the clay of the gangue up to the grains of the highest phosphate content. This variation confirms the hypothesis of a diagenetic disappearance of the cysts of dinoflagellates during the process of apatite mineralisation which was suggested for the nodules in the Albian of the Paris Basin.

Other Phosphatic Formations Studied

During other preliminary studies, the presence of dinoflagellates in other phosphatized formations has been verified, notably within the Chalk of the Paris Basin and in the deposits at Quseir in Egypt.

The Chalk of the Paris Basin The Chalk of the Paris Basin contains phosphatized levels from the Turonian to the Campanian (and even to the Maestrichtian in the Mons Basin of Belgium). The studies of Monciadini, a micropaleontologist with the B.R.G.M., have shown that the mineralisation within France is distributed over at least 8 different stratigraphic levels, the principal phosphatised levels, situated in the Santonian and the Campanian have been actively exploited in the past; an estimated 16 million tonnes or more have been mined since 1886 and small mines exist at the present time. In outcrop or in excavations, the phosphatic chalk is too oxidized to be favourable for palynological studies, but in at least one case, dinoflagellates are present. The drill-hole at "Grande Paroisse", situated at about 70 km southeast of Paris, close to Montereau, intersects the same stratigraphic units at depth, and has provided much better samples. There, the cysts of dinoflagellates are abundant in samples taken from the Turonian and Senonian, especially in those levels of phosphatised granules of the Campanian between 100 and 125 m depth. Some species present periodic relative abundances which may reach 35% dinoflagellate cysts in the organic fraction.

The deposit at Quseir The phosphate-rich levels of the deposit at Quseir are distributed between the Campanian and the Maestrichtian. They are generally very rich in bone debris. Dinoflagellates are very rare in the ore-body itself but are more abundant in the associated black clays, without exceeding 4,000 cysts/gm of rock in the richest sample. The phytoplankton of these clays is essentially dominated by the genus "*Botryococcus*", a green alga which, in a marine environment is only known in a very littoral situation; after Chu (1943) this alga grows in an environment rich in phosphorous. The paucity of pollen in those samples rich in "*Botryococcus*" is evidence of a dry period on the land-mass adjacent to the phosphate deposits.

Conclusions

1 The Albian–Cenomanian of the Paris Basin and the drill-holes at M'Rata in the Paleocene of Tunisia show an association of phosphate with sediments rich in dinoflagellates. There is periodic disequilibrium in the relative abundance of species of dinoflagellates, as in the case of "red tides". The most mineralised sequence is the richest in dinoflagellates.

2 The phosphate-rich units of the Turonian–Senonian of the Paris Basin appear to show a comparable association. At Quseir, in Egypt, the role of dinoflagellates seems to be rather less obvious, the very littoral environment favouring the development within the biophase of green algae of the genus "*Botryococcus*", and of vertebrates.

3 The association between phosphate and dinoflagellate microplankton appears valid in a general way, but is not true in detail because the diagenesis leading to the neoformation of apatite appears to be unfavourable to the preservation of cysts.

4 Do these cysts simply disappear during the course of diagenesis or do they also play a geochemical role as the hypothesis put forward in the introduction suggests, having regard to the chemical composition of the mineral fraction of the dinoflagellates? In order to answer this question, some cysts from the Albian in the section at Rechel have been studied with the microprobe at Castainy. Preliminary results show that within the chitin of the cysts there exists a mineral fraction which may contain up to 0.16% MgO; 0.10% FeO (without distinguishing the type of Fe present), 0.08% P_2O_5, 0.12% Al_2O_3, 0.23% K_2O, significant quantities of CaO and large quantities of SiO_2.

5 The origin and the representativeness of the mineral fraction contained in the cysts cannot yet be evaluated from these preliminary analyses. However, results suggest that the dinoflagellates may contribute to phosphatic neoformations. They may also contribute to silicate neoformations such as glauconites, which are sometimes found intimately associated with appatite within the same grain, or to montmorillonite which is also common in some phosphatised sequences.

6 In a sedimentary basin, those deposits rich in dinoflagellates are not able to evolve to phosphorites during the course of diagenesis if the conditions favourable to the neoformations of apatite and to its concentration do not occur together. For the explorationist the abundance of dinoflagellates may provide a supplementary tool for selecting the levels most likely to contain an ore body within a stratigraphic series devoid of other indication of mineralisation.

References

BRONGERSMA-SANDERS, M., 1957: Mass mortality in the sea. *Geol. Soc. Amer. Mem.* 67 (1), pp. 941-1010.

CHAMLEY, H., 1971: Recherches sur la sédimentation argileuse en Méditerranée. *Thèse Doctorat es Sciences,* Univ. Aix Marseille.

CHATEAUNEUF, J.J. FAUCONNIER, D., SASSI, S. and SLANSKY, M., 1978: Étude palynologique d'une coupe du Paléocène phosphaté du Bassin de Gafsa et interprétation sédimentologique des résultats. *Bull. BRGM,* sous presse.

CHU, S.P., 1943: The influence of the mineral composition of the medium on the growth of planctonic algae. *J. Ecol.,* 31 (2), pp. 109-148.

DESTOMBES, P. et DESTOMBES, J.P., 1965: Distribution zonale des Ammonites dans l'Albien du Bassin de Paris. *Mem. BRGM,* 34. Colloque sur le Crétace inférieur, pp. 255-270.

FAUCONNIER, D., 1977: Les Dinoflagelles de l'Albien et du Cenomanien inferieur du Bassin de Paris. Répartition stratigraphique et relations avec la nature du dépôt. *Thèse Université d' Orléans.*

McKELVEY, V.E., 1967: Phosphate deposits. Contribution to economic geology *U.S. Geol. Surv. Bull.,* 1252-D.

PERES, J.M. & DEVEZE, L., 1964: *Oceanographie biologique et biologie marine, 2 La vie pelagique.* Presses Univ. de France, Paris.

RILEY, G.A. & STOMMEL, M., BUMPUS, D.F., 1949: Qualitative ecology of the plankton of the western North-Atlantic *Yale Univ. Oceanogr. Lab,* 12, pp. 1-69.

SASSI, S., 1974: La sédimentation phosphatée au Paléocene dans le Sud et le Centre-Ouest de la Tunisie. *Thèse Doctorat es Sciences, Orsay.*

SLANSKY, M. and FAUCONNIER, D., 1973: Influence possible de certains facteurs biologiques sur la géochimie des sédiments. *Bull. BRGM* IV (4), pp. 209-228.

Appendix II: Participants

Australia

Mr J. Balkau* — Mines Exploration Pty Ltd,
PO Box 1820,
MOUNT ISA, QLD 4825

Dr P.J. Cook — Research School of Earth Sciences,
Australian National University,
PO Box 4,
CANBERRA, ACT 2600

Mr N.J. Crase* — Mines Exploration Pty Ltd,
PO Box 57,
ST MARY'S, S.A. 5042

Mr A. Driessen — Bureau of Mineral Resources,
PO Box 378,
CANBERRA CITY, ACT 2601

Miss S. Elgueta — Research School of Earth Sciences,
Australian National University,
PO Box 4,
CANBERRA, ACT 2600

Mr J.M. Freeman* — Mines Exploration Pty Ltd,
PO Box 1820,
MOUNT ISA, QLD 4825

Mr P. Green — Geological Survey of Queensland,
Dept of Mines, Mineral House,
2 Edward Street,
BRISBANE, QLD 4000

Prof. L.B. Gustafson — Research School of Earth Sciences,
Australian National University,
PO Box 4,
CANBERRA, ACT 2600

Mr D. Hackett — ICI Australia Limited,
PO Box 1334,
MOUNT ISA, QLD 4825

Dr R.A. Henderson† — Geology Department,
James Cook University of North Queensland,
TOWNSVILLE, QLD 4811

* Attending field workshop only.

† Attending seminar only.

Australia (cont'd)

Mr A. Hodgkin	20 Clianthus Street, O'CONNOR, ACT 2601
Prof. P.F. Howard	School of Earth Sciences, Macquarie University, NORTH RYDE, NSW 2113
Mr M.J. Jackson*	Bureau of Mineral Resources, PO Box 378, CANBERRA CITY, ACT 2601
Dr M. Muir*	Bureau of Mineral Resources, PO Box 378. CANBERRA CITY, ACT 2601
Mr P.N. Pritchard†	Robertson Research, MELBOURNE, VIC 3000
Mr J.K. Rogers	BH South Limited, PO Box 57, ST MARY'S, S.A. 5042
Mr W.J. Rose*	Mines Exploration Pty Ltd, PO Box 1820, MOUNT ISA, QLD 4825
Dr J.H. Shergold	Bureau of Mineral Resources, PO Box 378, CANBERRA CITY, ACT 2601
Mr J. Smit*	B.H.P. Research Laboratories, PO Box 274, CLAYTON, VIC. 3168
Mr P.N. Southgate	Geology Department, James Cook University of North Queensland, TOWNSVILLE, QLD 4811
Dr P.A. Trudinger†	Baas-Becking Laboratory (CSIRO) PO Box 378, CANBERRA CITY, ACT 2601
Mr N.A. Trueman†	Mines Exploration Pty Ltd, PO Box 57, ST MARY'S, S.A. 5042
Dr H.H. Veeh†	School of Earth Sciences, Flinders University, BEDFORD PARK, S.A. 5042

France

Dr M. Slansky	Bureau de Recherches géologiques et minières, B.P. 6009, 45018 ORLÉANS Cedex

India

Dr D.M. Banerjee	Geology Department, University of Delhi, DELHI 110007.
Dr R. Choudhuri	Rajasthan State Mines & Minerals Ltd., 3 Saheli Marg, UDAIPUR 313001
Mr G.P. Deshmukh	Geological Survey of India JAIPUR
Mr H.H. Khan	Geological Survey of India, Shamla Hills Road, BHOPAL (M.P.) 462002
Mr A. Pant	Geological Survey of India, B12 Niralanagar, LUCKNOW
Dr A.M. Patwardhan	Centre of Advanced Study in Geology, Panjab University, CHANDIGARH 160014
Mr V.N. Sant	Mineral Exploration Corporation Ltd., 8 Hindustan Colony, Amravati Road, NAGPUR 440010

Malaysia

Mr Foo Khong Yee	Geological Survey of Malaysia, PO Box 1015, IPOH

New Zealand

Dr D.J. Cullen	N.Z. Oceanographic Institute, PO Box 12346, WELLINGTON NORTH
Dr J. Rogers†	N.Z. Fertilizer Manufacturers Research Assoc. (Inc.), PO Box 23-637, Hunters Corner AUCKLAND

Pakistan

Mr N.A. Bhatti	Geological Survey of Pakistan, LAHORE

Peoples Republic of China

Mr Chia Hsien-cheng	Tientsin Institute Geology & Mineral Resources, Tsintang High 26, TIENTSIN

Prof. Yeh Lien-chun	Geological Institute, Academia Sinica, PEKING
Dr Hsing Yu-sheng	State Bureau of Geology & Mineral Resources, PEKING
Dr Chang Hui-min	Tientsin Institute Geology & Mineral Resources, Tsintang Highway 26, TIENTSIN
Dr Liang Yu-tso	Inner Mongolian State Bureau of Geology, PAO-T'AU
Mr Wang Chung-wu	Yunnan State Bureau of Geology, KUNMING
Mr Liu Ming-chuan	State Bureau of Geology & Mineral Resources, PEKING

Republic of South Africa

Dr J.M. Bremner	Marine Geoscience Unit, Department of Geology, University of Cape Town, RONDEBOSCH 7700

Thailand

Mr S. Sektheera	Economic Geology Division, Department of Mineral Resources, Rama VI Road, BANGKOK 4

U.K.

Mr A.J.G. Notholt	Institute of Geological Sciences, Mineral Resources Division, Exhibition Road, South Kensington, LONDON SW7 2DE

U.S.A.

Dr W.C. Burnett	Department of Oceanography, Florida State University, TALLAHASSEE, FLORIDA 32306
Dr J.B. Cathcart	U.S. Geological Survey, Federal Center, DENVER, COLORADO 80225
Dr R.A. Gulbrandsen	U.S. Geological Survey, Middlefield Road, MENLO PARK, CALIFORNIA

PROTEROZOIC-CAMBRIAN PHOSPHORITES

Dr G.H. McClellan	International Fertilizer Development Center, PO Box 2040, MUSCLE SHOALS, ALABAMA 35660
Prof. A.R. Palmer	Department of Earth & Space Sciences, State University of New York STONY BROOK, NEW YORK 11794
Dr S.R. Riggs	Geology Department, East Carolina University, GREENVILLE, NORTH CAROLINA 27834
Dr R.P. Sheldon	U.S. Geological Survey, Resources Systems Institute, East-West Center, 1777 East-West Road, HONOLULU, HAWAII 06848
Prof. A.M. Ziegler	Department of Geophysical Sciences, University of Chicago, 5734 Ellis Avenue, CHICAGO, ILLINOIS 60637

USSR

Acad. A.I. Yanshin	Institute of Geology and Geophysics, Siberian Division, Academy of Sciences of the USSR, 630090 NOVOSIBIRSK
Dr E.A. Eganov	Institute of Geology and Geophysics, Siberian Division, Academy of Sciences of the USSR, 630090 NOVOSIBIRSK
Dr Y.N. Zanin	Institute of Geology and Geo-hysics, Siberian Division, Academy of Sciences of the USSR, 630090 NOVOSIBIRSK
Ms I. Lozovoya	Institute of Geology and Geophysics, Siberian Divison, Academy of Sciences of the USSR, 630090 NOVOSIBIRSK