CHAPTER 10

APPLIED GEOLOGY IN NEW SOUTH WALES

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"We could now look back on the Ranges—nor could the eye follow their outline and glance over the boundless plain beyond them, without feeling conviction that they had once looked on the waters of the ocean as they overlooked a sea of scrub".*

and of the mineral specimens collected from the outcrop of the Broken Hill lode it is recorded that:

"These had to be jettisoned later in the desert when the party seemed on the point of perishing from thirst and weakness."

From Captain Charles Sturt's
"Expedition into Central Australia".

INTRODUCTION

The application of geology to technological development can be traced back to the early days of gold prospecting—and later, tin prospecting—within the Colony. The discovery of the rich alluvial gold deposits in the Bathurst district in the 1850's† and in the southern highlands and the far south coast in the 1860's, followed by the discovery of the alluvial tin deposits of the northern New England in the early 1870's† initiated a mining industry that was to become one of the State's biggest income earners.

Among the early settlers were many Cornishmen well experienced in mining and prospecting. They were followed onto the newly discovered mining fields by large numbers of Chinese and by those unlucky prospectors who had failed to "strike it rich" in the southern States. The alluvial "pay wash" was followed upstream to the source, resulting in the discovery of many productive lode deposits. Some of these lodes were essentially gold in quartz; others proved to be copper, silver-lead and zinc with dispersed gold which had been shed during oxidation and erosion of outcropping lode.

* The Barrier Ranges at Broken Hill.

† Specimens of gold were actually found on the Fish River near Bathurst in 1823. Likewise it is reported that tin was found in the Inverell district in 1849 by a shepherd named Wills.

It was here that problems in structural geology and applied mineralogy first arose. Lodes were frequently dislocated, strata were folded and faulted, ore values within the lode showed wide variation, unfamiliar minerals needed identification, minerals deleterious in smelting processes were encountered and so on.

The assistance of trained geologists—or geological surveyors as they were called in those days — was sought and the need arose for support from mining engineers (many of whom eventually took over the management of those deposits that proved productive), from assayers and chemists and from financiers willing to take a chance with deposits that looked encouraging at the surface.

Much of this assistance came from the newly established Geological Survey of the New South Wales Department of Mines, under the direction of C. S. Wilkinson, whose early reports were incorporated in the "Legislative Assembly Papers" in the 1870's.

Assistance was forthcoming, also, from private geologists and mining consultants, some of whom had come from England to report to their principals on the mineral potential of the colony. G. J. Ulrich, a mining engineer, for example, published papers on the newly discovered mining fields in the *Quarterly Journal of the Geological Society (London)* in the 1870's. Another mining engineer, S. Herbert Cox, published a paper, in the *Journal of the Royal Society of New South Wales* in 1886 on the same subject. In 1890, C. W. Marsh published a paper on the Broken Hill mining field in the *Journal of the Royal Society of New South Wales.* Special mention is warranted of the outstanding contributions of the Rev. W. B. Clarke, F.R.S., who, in addition to his dedication to ecclesiastical matters, was a skilled geologist and mineralogist.

Professor S. Liversidge, F.R.S., was appointed to the Chair of Chemistry and Mineralogy in the University of Sydney in 1872.* It was he who published the first account of the minerals of New South Wales.

The outstanding work of Sir Edgeworth David, F.R.S., firstly as a member of the Geological Survey and, later, as Professor of Geology in the University of Sydney, is legendary. His stratigraphic work on the Permian rocks of the Hunter Valley did much to establish and sustain the important coal mining industry in that area. Much of our knowledge of the tin and tungsten deposits of the northern New England district (Emmaville-Torrington) is due to his work there as a geological surveyor with the Department of Mines. In World War I, Professor

* A. M. Thomson preceded Liversidge as Professor of Geology and Mineralogy.

David resigned temporarily from the Geology Chair at Sydney to accompany the Australian Expeditionary Forces as Lieutenant-Colonel in charge of tunnelling and underground installations in France. The early application of geology to military engineering is here vividly demonstrated.

The growth of industry, and agricultural expansion resulted in the demand for an ever-increasing range of geological application. This development gave rise to specialization which was as much manifest in the geological sciences as it was in other forms of human endeavour. Mine geology, mineral exploration and mineralogy applied to ore dressing became important disciplines in their own right. Coal petrology and coalfield geology attained individuality. The days of the "water diviner" were numbered; the problems of locating sub-surface water for farms and for irrigation was placed on a sound scientific footing—the era of the geohydrologist had begun. Geologists gained employment with engineering construction companies, and major construction works supported departments of engineering geology whose work encompassed applied petrology, rock and soil mechanics, applied structural geology, geophysics and related aspects of the science.

The application of geology continues to grow and to diversify. In addition to the major applications indicated above, geology (and mineralogy) is being utilized in the glass and ceramic industries, in quantity and quality control in the "blue metal" quarrying industry, in industries concerned with building stones and cement products. Highways, railways, building foundations, airport runways and harbour dredging have posed geological problems. Geologists have been concerned with the preservation of national parks and reserves and with the stabilization of beaches. Geology has also been applied to crime detection in such ways as in the identification of soil types adhering to motor vehicles and to footwear and in distinguishing genuine gemstones from "fakes".

The following sections of this Chapter will be devoted to the historical background, the technological development and the achievements of some of the more important fields of applied geology.

Mineral Deposits: The Problem of Ore Genesis

[This section is somewhat specialized and may be omitted at first reading by the uninitiated. (Editor)]

The search for mineral deposits, particularly those of the metallic ores hidden in the sub-surface, is rendered more efficient when the origin of ore, tenable for a well delineated geological setting, can be predicted.

Against a background of mining and prospecting pre-occupied with reef and vein deposits, many of them within or in close proximity to intrusive igneous rocks, it is not surprising that theories of ore genesis were dominated by the traditional magmatic-hydrothermal concepts.

There were other more subtle reasons why thinking about ore genesis was dominated by the hydrothermal theory. Most of the early literature featured the hydrothermal deposits of the American continents. The great store of knowledge built up from the prodigious studies of the ore deposits associated with the Coast Range Batholiths of the western United States was readily available in the literature and was, of course, written in English. Contributions from Britain, with a long "igneous tradition" dating back to the time of James Hutton (1726-1797), tended toward the magmatic-hydrothermal line of thinking. Alternative theories on ore genesis were featured in German, French and Scandinavian literature but these were rarely studied partly due to language difficulties and partly due to the general acceptance of the more orthodox magmatic-hydrothermal theory.

As a result, university teaching was strongly orientated toward the magmatic-hydrothermal approach to ore genesis theory and geologists were taught "to look for the nearest granite outcrop as the source of ore" and to classify ore deposits according to the temperature and pressure at which they formed. The fact that such temperatures and pressures, designated by the *hypohydrothermal,* the *mesohydrothermal* and the *epihydrothermal* sub-divisions, can very rarely be assessed or that many types of mineral deposits form over a range of temperatures and pressures, did not deter the widespread use of this "pigeon-hole" method of describing and classifying most of the ore bodies of the State. A similar procedure was current throughout Australia.

Many of our early discovered gold reefs and veins, such as those in the Bathurst district, the Parkes-Forbes area, the far south coast and southern highlands, consisted of quartz cutting across the enclosing strata or "grain" of the country rock and were usually not far distant from an intrusive igneous mass. The deposits of tin, tungsten and molybdenum of the northern New England district, of the Ardlethan mining field and at Whipstick on the south coast are either contained in granite or occur in veins and greisens at or near the margin of granite. The molybdenum at Yetholme occurs in a contact metamorphic zone as do the copper ores at Attunga near Tamworth. Copper ores and ores of the base metals are found throughout the State and are frequently localized along or within discordant structures closely adjacent to intrusive igneous rocks. For these a pneumatolytic *cum* hydrothermal origin could hardly be doubted.

There are many deposits, however, that are not demonstrably associated with intrusive igneous rocks—some of these are "discordant" with respect to the bedding or the foliation of the country rock; some appear to be "concordant" or layered in an apparently stratigraphic disposition as, for example, the immense base metal deposits at Broken Hill. In deference to the magmatic hydrothermal theory of ore genesis it was customary to postulate the presence of intrusive igneous rock, deep below the orebody, and from which stratiform ore was believed to have been emplaced by "metasomatic replacement" of "favourable strata" by ore fluids from an intrusive magma beneath, or at some distance—often several miles from the site of mineralization.

During the 1940's and 1950's some of the senior geologists working on the Broken Hill mining field began to question the universal applicability of the metasomatic replacement theory for all strata-bound and layered deposits. Similar doubts arose with respect to the stratiform Mount Isa lead-zinc deposits and the layered sulphide deposits at Nairne in South Australia.

A sedimentary origin for many of the world's iron ores and manganese ores had long been recognized and such an origin had been accepted for the Australian occurrences of haematite at Yampi Sound, N.T., and the Middleback Ranges in South Australia, as well as the manganese deposits of Groote Eylandt. It was not difficult to envisage the metamorphic "upgrading" of a ferruginous or a manganiferous sediment to haematite — or even magnetite, or to pyrolusite and psilomelane respectively. Such ideas were, of course, quite current for iron and manganese ore elsewhere in the world.

The question arose—could the layered or stratiform sulphide ores arise by some process of sedimentation? A sedimentary theory had replaced the traditional hydrothermal replacement theory for the layered sulphide orebodies of Rammelsberg and Mansfeld in Germany and thinking on the strata-bound Rhodesian copper ores vied for favour as between a replacement origin, on the one hand, and a sedimentary origin on the other. Other orebodies such as those of Franklin Furnace, New Jersey (zinc ores) were now recognized as having undergone post-depositional metamorphism. It was now agreed that many orebodies, far from resulting from a single process of formation, had a complex history involving initial deposition, metamorphism along with the enclosing rocks and structural and mineralogical reconstitution.

The stratiform or layered deposits, represented by some of the world's largest orebodies (e.g., the Rhodesian copper belt, gold-uranium ores of the Witwatersrand, copper-lead-zinc of Rammelsberg, Blind River uranium deposits of Canada, and in Australia: Broken Hill, Mount Isa, possibly Rosebery, Nairne, MacArthur River), were closely under review as to their origin. A number of alternative theories appears feasible.

The metasomatic replacement origin for conformably layered ore envisages ore fluids, discharged from some intrusive igneous source, coursing through the country rock until a stratum possessing certain physical and chemical properties is encountered. Here a simultaneous dissolution of the stratum and a precipitation of ore ensues—the process proceeding laterally along the "favourable" stratum thereby maintaining a stratiform or layered disposition. There are inherent problems, however, in this theory when one considers not only the mechanics of simultaneous removal of country rock (or its constituent mineral particles) and instantaneous precipitation of ore, but of the necessarily progressive nature required of the process. Of course, metasomatic replacement does occur (cf. the process of fossilization best illustrated by the petrifaction of wood or the pseudomorphism of crystals) but it is difficult to visualize this process operating laterally along a particular stratum, to the exclusion of adjacent strata, and over a distance of perhaps twenty to thirty miles as would be required in some cases. As a more localized process, however, metasomatism is universally acknowledged for some types of deposits.

Detailed study of the Rammelsberg copper-lead-zinc deposits has suggested an origin by way of *submarine volcanic exhalations*. It is envisaged that ore-bearing fluids were emitted on the floor of the Devonian Goslar trough, there to be intermingled with sediment syngenetically, with subsequent lithification and folding. It is presumed that the ore fluids travelled as colloidal suspensions or that some reactions occurred (e.g., with H_2S) precipitating insoluble sulphides.

Some layered sulphide deposits are conceived as forming entirely by surficial processes. Pre-existing mineralized terrain undergoing prolonged oxidation and denudation results in soluble salts—especially sulphates—being carried into embayments along with sediments. Under anaerobic conditions, sulphide-fixing bacteria assimilate metal sulphates and leave insoluble sulphide muds which are later "lithified" and, in many cases, folded and metamorphosed during a later orogenic cycle. Typical of this type of origin is the dispersed pyrite (and other sulphides) in graphitic slates.

The problem of the origin of stratiform layered ores remains as one of the unresolved mysteries of applied geology. Unambiguous clues are difficult to obtain and much of the evidence appears to have been destroyed by post-depositional folding and metamorphism. Attempts have been made to resolve the problem, at least between an inorganic or an organic origin, by sulphur isotope analysis—and this in terms of the immediate source of the sulphur. Since "igneous" sulphur gives an S^{32}/S^{34} value close to that of "primeval" sulphur* and organically derived sulphur shows a wide spread of S^{32}/S^{34} values with respect to "primeval" sulphur, the isotopic composition of sulphur in sulphides appears to offer a useful line of enquiry.

Many sulphur isotope analyses of ore from stratiform orebodies suggest an igneous source for the sulphur and yet a metasomatic replacement origin, from a plutonic body at depth, appears untenable; evidence for a stratigraphic control is compelling. This, together with the persistent occurrence of finely bedded sediments now considered to be of volcanic origin, has brought a volcanic origin for very many strata-bound deposits into strong favour. Organic processes do not seem to be indicated.

If current views on a volcanic origin for many (if not all) of the stratiform deposits are correct, what then of the many veins, disseminations, mineralized shear zones and various other ore occurrences that transect the bedding or foliation of the country rock and are not demonstrably associated with batholiths? Very often there is evidence of vulcanicity in the vicinity (flows, tuffs or ultrafine ash—the latter often confused with shales, slates, etc.). The question arises could these transgressive deposits arise from a volcanic rather than a plutonic source such that the transgressive structure represents something in the nature of a fumarole or a solfataric† channelway? It is envisaged, here, that some mineral precipitation may occur *en route* to the surface in connection with vulcanicity.

It is interesting (and very pertinent) that virtually all of Australia's large non-ferrous ore deposits have recently been considered by some workers to be related directly or indirectly to volcanic processes, viz., Broken Hill, Mount Isa, Kalgoorlie, Rosebery, Mount Lyell, Mount Morgan, though proof as to the real origin is not forthcoming. The changing ideas and theories on ore genesis of large orebodies, apparently not associated with large plutonic rock masses, is nowhere better illustrated than with the immense Broken Hill silver-lead-zinc deposits.

In 1916 the Broken Hill orebody was considered to have arisen by way of metasomatic replacement of particular beds, selectively, by sulphides and gangue minerals transported hydrothermally from an igneous source at depth. Somewhat similar ideas were advanced in 1922 where emplacement was considered to have resulted from the movement of ore fluids along certain stratigraphic intervals, giving rise to saddle

* That is, by comparison with some standard S^{32}/S^{34} ratio—meteoric sulphur is generally used.

† i.e., sulphur-emitting.

reefs. Metasomatic replacement was again invoked in 1939 and it was estimated that 2,240 million tons of "solution" would have been required to transport the metals.

A detailed mineralogical study of Broken Hill ore, in 1951, by Professor Ramdohr of Heidelberg, saw a distinct change of thinking. Ramdohr, noting that there were both high temperature and low temperature minerals present in the ore, suggested that the orebody was originally formed as a low temperature deposit and was then regionally metamorphosed to a high temperature assemblage.

Two rather sharply divided schools of thought as to the genesis of the Broken Hill orebodies developed during the 1950's. An origin by way of metasomatic replacement was supported by one group and a syngenetic sedimentary origin by the other. There were serious problems confronting both groups, not the least of which was that of a source, inasmuch as both processes—metasomatic replacement and syngenetic sedimentary—are both more in the nature of depositional mechanisms and do not *per se* denote origins for the ore.

The old idea of the lode pegmatites constituting a likely igneous source for the ore had been abandoned and advocates of a metasomatic replacement origin called upon a deep-seated magma as the parent of the ore even though the general environment at Broken Hill does not indicate large-scale plutonic activity of appropriate age. The syngeneticists envisaged an older land surface containing sparsely distributed ore minerals which, undergoing oxidation and erosion, yielded sediments along with soluble salts of the ore minerals—both being carried into basins of sedimentation where the metal salts underwent reduction to sulphides with subsequent "lithification" and metamorphic reconstitution. There was here, though, the matter of a reducing process. Reduction by sulphide-fixing bacteria seemed a feasible answer.

More recently, results of sulphur isotope studies of the ore minerals have been taken to indicate a deep-seated source for the sulphur and, in deference to the strata-bound character of the orebodies, a process of direct volcanic exhalations has been contemplated with ensuing metamorphism attended by structural and mineralogical changes.

In 1965, the authenticity of the conformable nature of the orebody was questioned as a result of detailed structural analysis of the orebody in relation to the foliation of the enclosing rock. It was found that, whilst the orebody is contained within the garnet-sillimanite gneiss, it appears to lie obliquely across the enclosing gneiss and does not parallel the margins of the country rock though the angular difference is not very great.

The origin of this great orebody remains one of the most perplexing problems in the field of applied geology and it seems that we are as far away from a correct interpretation as ever we were.

The challenge of ore genesis interpretation will continue to occupy the minds of geologists for years to come—but our mineral potential calls for periodic review in other ways. This is well exemplified both in terms of international affairs and in technological advancement.

For many years, Australia was self sufficient in tin, with New South Wales contributing substantially to the nation's requirements. As our supplies of tin diminished, we turned to the rich sources of supply in nearby South-East Asia. Over the last decade or so, however, the political uncertainty with which trade with overseas countries is conducted has resulted in a detailed re-evaluation of supposedly worked-out local tin fields such as in the Emmaville-Torrington and the Ardlethan and Albury areas.

The era of atomic energy and the space-age furnish illustrations of how certain minerals attain paramount importance in a rapidly advancing technological environment.

The search for fissionable material focused attention on deposits of uranium and thorium. Several minor "finds" were recorded in the 1950's in New South Wales, while in South Australia and Queensland, major deposits were brought into production. No workable deposits of uranium have so far been found in New South Wales, but the beaches and hinterland sand dunes along the coast produce important quantities of monazite—a rare earth phosphate containing a few per cent of radioactive thorium oxide. The production of atomic energy also requires other minerals such as beryllium and the mineral beryl has become a high-priced and much-sought-after material.

Supersonic aircraft construction has required substantial use of high melting point, superior strength metals such as titanium. Considerable production of this metal has been forthcoming from rutile, which is extracted from the beach sands at several localities along the east coast, particularly from southern Queensland to an area just north of Sydney.

Zircon, zirconium silicate, is used extensively in high temperature refractories. This mineral is recovered from the east-coast beach sands.

These detrital minerals are of considerable importance to the national economy. They derive from the weathering of igneous and sedimentary rocks along the northern coastlines and hinterlands. Some of the minerals may have originated from the ancient rocks to the west and may have been involved in many cycles of sedimentation, being cast progressively into ensuing sediments.

The importance of the beach mining industry has resulted in much detailed study of the distribution of "heavy minerals" in the coastal sands and dunes. Figure 1 illustrates the occurrence of a well-developed "heavy mineral" deposit.

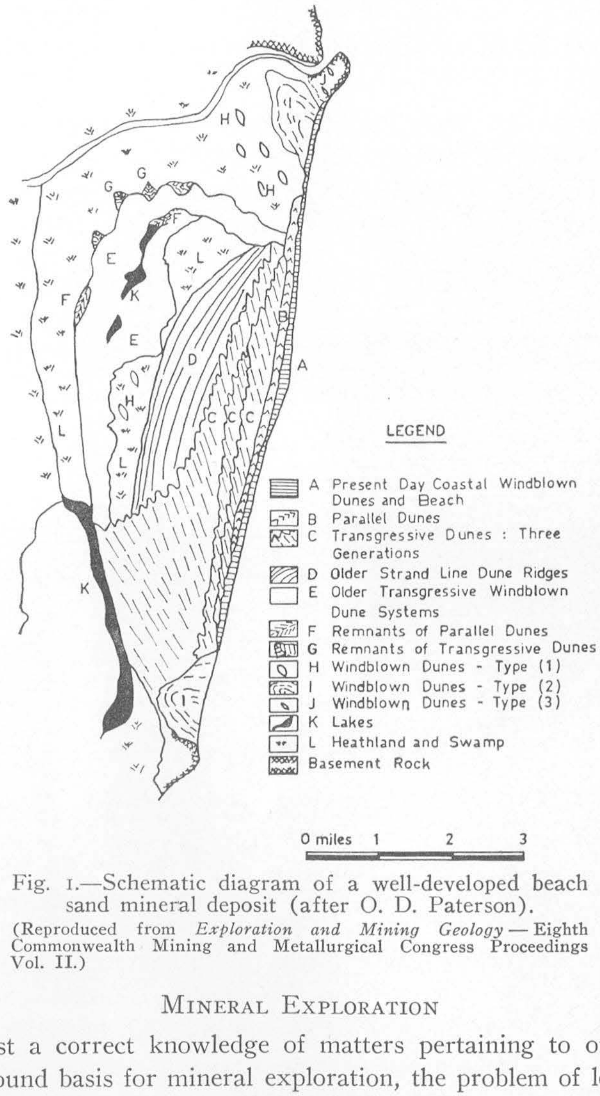


Fig. 1.—Schematic diagram of a well-developed beach sand mineral deposit (after O. D. Paterson).
(Reproduced from *Exploration and Mining Geology* — Eighth Commonwealth Mining and Metallurgical Congress Proceedings Vol. II.)

Mineral Exploration

Whilst a correct knowledge of matters pertaining to ore genesis forms a sound basis for mineral exploration, the problem of locating an orebody still remains. The days of discovering ore from surface exposures are over—*prospecting* (Figure 2) has given way to the highly organized, highly technical process of *mineral exploration* (Figure 3). This is mostly in the hands of the large mining companies. A typical personnel chart for mineral exploration by a large mining company is shown in Figure 4.

A modern exploration programme, involving the expenditure of large sums of money, and spread over three to four years for specific programmes, or constituting a continuing activity, is divided into several stages. Firstly, a mineral exploration area is taken out by negotiation with Federal or State authorities. This area, held then under an "Authority to Prospect", may be thousands of square miles in extent. The conditions under which such prospecting reserves are issued are numerous and involve, among others, two particular requirements.

Fig. 2.—Prospecting in the 1850's.

These are that a specified sum of money must be spent on the programme per annum and that, as time progresses, part of the area must be forfeited. These requirements ensure that the programme will be pursued energetically and that areas will not be held indefinitely with little or no work being done.

Areas are selected on the basis of mineral potential. Areas that have been productive or which support current mining activity naturally rank high in mineral potential. In other cases, areas containing specific rock types are sought as, for example, certain types of granite for tin, tungsten and molybdenum; ultrabasic rocks for chromite, asbestos or nickel.

The assessment of an area involves, firstly, a thorough knowledge of its surface geology and as much of its sub-surface as can be deduced from surface study. This involves geological mapping, air-photo interpretation, and the formulation of ideas on how and where ore may be expected to occur at depth. Air-borne magnetometer surveys, or other rapid geophysical methods capable of covering large areas in minimum time, are of great value in delineating certain localities of interest.

In areas of past or present mining activities, the extrapolation of known mineral environments into areas further afield may lead to a new discovery. The same method of inductive reasoning may be applied to locating extensions of known orebodies which are being worked. This latter aspect of mineral exploration is one that constantly occupies the attention of mining companies.

Fig. 3.—Modern mineral exploration—four-wheel-drive vehicle towing a caravan elaborately fitted out as a geochemical laboratory (after Lissiman, Baker and Marshall).

(Reproduced from *Exploration and Mining Geology* — Eighth Commonwealth Mining and Metallurgical Congress Proceedings Vol. II.)

Once one or more specific localities have been decided upon and "unlikely" ground forfeited, geophysical and/or geochemical appraisal is undertaken.

Depending on the nature of the mineral, so the particular geophysical method is adopted. For suspected deposits of ferro-magnetic minerals, or where these minerals are believed to be present, magnetic methods are employed. For sulphide deposits, where a natural electrical field exists or can be induced, several electrical methods are available—self-potential, induced polarization, electro-magnetic and resistivity. From the readings taken contour-type maps are produced indicating centres of high anomaly values which become "target areas" for drilling.

In addition, or as an alternative, geochemical sampling may be carried out. It is first necessary to determine "background value" for the mineral being sought. This involves extensive sampling of rocks and soils over wide areas and trace element analysis to decide the normal content of, e.g., copper, lead, nickel, uranium for the particular area in question. Detailed sampling either of stream sediments, stream water or soil, from specific areas of interest, is followed by trace element determination. Geochemical contour maps are produced showing areas of increased trace element content with respect to background—"threshold" values, i.e., areas surrounding orebodies or areas of disseminated minerals, within which may lie more localized areas, directly above hidden orebodies. These localized areas of *high* trace element content represent geochemical "anomalies" and constitute "target" areas.

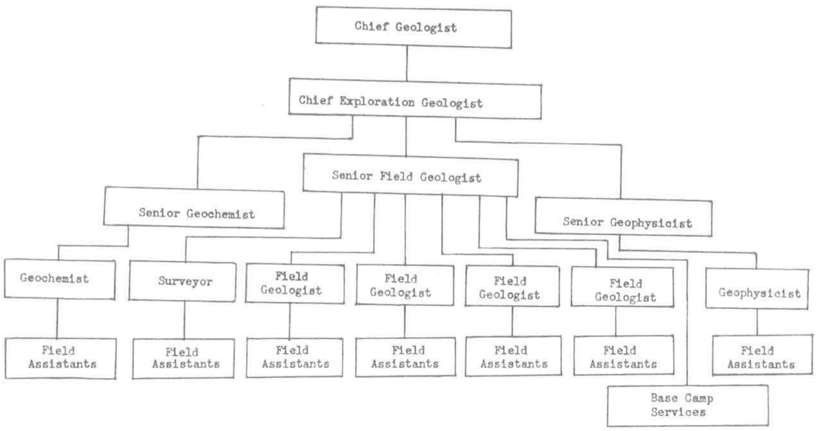


Fig. 4.—Modern mineral exploration:— chart of personnel deployment for a large-scale exploration programme. The Chief Geologist is based at Head Office; the Chief Exploration Geologist plies between Head Office and field stations. All personnel, except base camp servicing staff and field assistants, are professionally qualified.

It is customary, in modern mineral exploration, to investigate areas of interest by all available means: geological appraisal (structural analysis, petrological study, tectonic history, comparative studies with areas of known mineralization), geophysical evaluation and geochemical assessment. The superimposition, as it were, of each of these approaches to exploration is known as "saturation prospecting".

These procedures are followed by the "proving stage", i.e., an evaluation of the deposit in terms of the *tonnage* and *grade* of ore present. This is achieved, mainly, by diamond drilling. The target area is drilled either at particular points or on a grid pattern and the drill core is assayed in three- to five-foot sections. From this information it is possible, if sufficient ore intersections have been made, to draw up patterns of sub-surface ore distribution showing the tonnage and grade of ore at various intervals.

Whilst the geological work is in progress, other important aspects are being considered. These include the workability of the deposit in terms of mining methods, trial batches of ore are subject to ore dressing tests, mineragraphic studies are carried out to determine the range of minerals present and the costing of the enterprise is under close scrutiny.

The chances that any given "target area" will, in due course, become an operating mine are always very slender, but discoveries have to be made and are being made. When it is considered that one new sizeable orebody will more than compensate for a hundred or more unsuccessful attempts, then the high cost of modern mineral exploration can be readily accepted.

Coal and Coalfields

The coal-bearing province of eastern New South Wales is the foremost coal producing area in Australia. Ready accessibility and close proximity to markets have been important factors in its development.

Coal was discovered in the 1790's in the Newcastle area and also at Coalcliff. Exploitation commenced in 1802 at Newcastle, but little geological work was conducted before the 1840's when the Rev. W. B. Clarke commenced his stratigraphic studies of the coalmeasures. It is of interest here that among others to investigate the Newcastle coal-measures were explorers Count Strzelecki and Ludwig Leichhardt and the noted American geologist and mineralogist J. D. Dana. These were followed onto the coalfields by geologists McCoy, Stutchbury, Wilson, Oldham, Odernheimer and Keene. A difference of opinion arose as to the age of the coalmeasures; McCoy contended that the rocks were Mesozoic but Dana and Clarke favoured a Palaeozoic age.

In 1856 the important South Maitland coalfield was discovered by Keene, indicating that a much larger area within the Hunter Valley was economically important.

Special mention is warranted of the detailed mapping of the coal-measure strata of the Hunter Valley by David in the 1880's. It was at this time, and under David's direction, that the first stratigraphic bore holes were sunk in order to test the structure of these coalfields. The detailed mapping of the Western Coalfield was carried out by C. S. Wilkinson in 1875.

In addition to David's "The Geology of the Hunter River Coal Measures", a series of publications recording the results of the various surveys was produced between 1900 and 1920 by the New South Wales Geological Survey.

In 1903, Carne published "The Kerosene Shale Deposits of N.S.W.", which outlined the stratigraphy of a number of coalfields anew. "Kerosene shale" (torbanite) was subsequently used during two World Wars as a source of oil and petroleum by distillation. There was considerable controversy when the shale oil industry closed down in 1945.

Recent studies in coal and coalfield geology may be grouped into two branches: applied studies directly connected with the winning of coal or the proving of future reserves and, secondly, fundamental studies by research workers.

Applied studies are carried out by geologists employed by mining companies and by geologists from government instrumentalities such as the Joint Coal Board and the New South Wales Geological Survey. This work encompasses investigations directly associated with mining operations, exploration ahead of workings or exploration to delineate new coal seams.

The increased rate of development in the New South Wales coal industry has brought a corresponding increase in the detailed geological studies being undertaken in the coalfield. In the days of hand mining, few collieries employed geological staff—the manager relying on his own largely practical knowledge. This system worked reasonably well in many mines when the sudden appearance of discontinuities in the coal seam, or other unexpected phenomena, caused little production loss. The miners had only to pick up a few tools and move to another working place. Nowadays, with conveyor belt systems, complicated electrical installations and elaborate underground ventilation installations, an unscheduled change of working place would result in serious disruptions. To meet the problem of production loss through geological hazards in what is now a high capital industry, the geologist is being brought more and more into colliery planning. The contributions he can make in forecasting geological conditions ahead of workings and in new mining leases is now receiving general recognition.

The successful application of specialized geological knowledge at the coal face demands a specialized knowledge of structural geology, stratigraphy, and an ability to appreciate problems in rock mechanics. The recent introduction of mechanized longwall equipment to areas where poor mining conditions have inhibited conventional bord and pillar methods of mining have led to an upsurge in the study of strata control in which geologists and mining engineers are working in close liaison.

In the early days, studies of the coalfields depended largely on surface mapping supplemented by data from limited underground working and meagre bore information. Coal seams do not lend themselves to surface mapping and, through weathering effects, often become indiscernible in outcrop and give false impressions of thickness and quality. Associated shales and mudstones, likewise, do not form strong outcrops. It is a tribute to the skill of the earlier workers that they accomplished so much in stratigraphic delineation.

Present-day studies have the advantages of technical progress. Air photographs provide ready information on topography, structural geology, and sometimes rock types, including the incidence of dykes. Photogrammetry enables accurate contour maps to be compiled from air photos.

After inspecting data available from surface mapping, the exploration geologist calls into play an indispensable tool, the core drill. Notwithstanding advances made in geophysical logging of non-cored bores, there is no substitute for a cored sample, which, when recovered in good condition, permits virtual *in situ* inspection of a coal seam. It also provides material for chemical analysis, without which an assessment of seam quality is impossible. With such dependence on the core drill, exploration geologists have given much thought to means of improving core recovery and have played a leading part in the development of new and better drilling equipment.

The first step in exploration drilling is the sinking of scout bores for a preliminary assessment of the area. If closer investigation is warranted, information from scout bores guides the layout of a follow-up drilling programme, usually on a grid pattern. The intensity of boring varies with the geological conditions and the type of mining. An underground colliery holding in average conditions is usually considered to have been fully explored and its reserves measured when it has been drilled at half-mile intervals. Open-cut mining, in shallow, dipping seams, requires drilling at much closer spacing, ideally 300-foot intervals. Steeper seams require even closer boring.

In discussing exploration programmes, the role of geophysics as a useful adjunct to core drilling must not be overlooked. Seismic surveys, in particular, provide a quick means of determining broad geological structure over a wide area and have been finding increased use in recent years, both on land and on water. Gravimetric surveys used in conjunction with seismic methods have also proved useful in places. Local success in determining the presence of igneous intrusions has been achieved with magnetometers.

A further application of geophysics is geophysical logging of coal seams. A finely focused resistivity tool capable of entering a three-inch hole has been undergoing development and holds promise of delineating, within seams, non-coal bands down to two inches or less in thickness. Such a tool would be very useful in open-cut proving operations, where coal samples for analysis are not required in every bore. Non-core drilling, which is cheap and fast, could be interspersed among cored holes and logging carried out geophysically.

The Coal Research Laboratory of the C.S.I.R.O. Division of Mineral Chemistry (formerly Division of Coal Research) has for many years conducted research into the properties and behaviour of coals and other carbonaceous materials in New South Wales and many other Australian localities. One of the earliest tasks of the Division was to make detailed and reliable analysis of a number of coals, where previously information had been inadequate or, in some cases, almost non-existent. This work still continues as existing coalfields are developed and new areas are opened up. In addition to such analyses and assays, much research has been carried out on the chemical and petrographic constitution of different coals, as well as cokes, carbons and other products made from coal. This research effort has included the assessment of coals in terms of possible use, petrographic aid in seam correlation, regional studies of rank variation and studies of boron and other trace elements in coal as indications of geological environment.

Parallel studies have been carried out in the universities, in addition to extensive work in a wide range of fields, including stratigraphy, structure, sedimentology, petrology, mineralogy, palaeontology and palynology.

Engineering Geology

The development of engineering geology in New South Wales can be divided into two distinct periods separated by the time around World War II. Geology was applied to engineering works in a sporadic way during the initial period. After World War II, and particularly after 1949, the application of engineering geology was consolidated, and its use in a systematic way became standard practice in many engineering organizations.

A brief review of the first period shows that there was some appreciation within the engineering profession of the need for geological advice. During this period, numerous investigations of proposed dam sites were carried out by geologists of the Geological Survey of New South Wales especially for the Metropolitan Water, Sewerage and Drainage Board. Dam sites were also investigated on behalf of the Water Conservation and Irrigation Commission and the Hunter District Water Board. During this period, also, Dr. W. R. Browne and Mr. L. L. Waterhouse, of the University of Sydney, acted as consultants on Water Board projects. These gentlemen contributed very substantially to the early investigations into the proposed dam site at Warragamba and, in particular, to the siting of the dam. This work involved a detailed study of lithology, structural geology and other aspects relating to water retention capabilities along the Warragamba River.

Although the main activity of geologists in the field of engineering during this first period was directed toward water supply, other aspects were investigated periodically, mainly by officers of the Geological Survey. These investigations included sources of supply of construction materials, foundations and landslides.

Prior to World War II there had been growing interest in the utilization of the water of the Snowy River and its catchment draining the Southern Alps. In 1937, proposals for dam sites and tunnel lines were investigated geologically by C. St. J. Mulholland of the Geological Survey. During this same period, H. G. Raggatt investigated hydro-electric schemes involving the Shoalhaven River and rivers of the New England district.

In 1946, the feasibility of developing the water resources of the Snowy Mountains had been established and the Investigating Committee requested both the Bureau of Mineral Resources and the Geological Survey of New South Wales to carry out geological studies. In 1949, the Snowy Mountains Hydro-Electric Authority, with its own geological staff, under D. G. Moye, was established. The work of this group covered a wide range of geological investigations ranging from seismic and other geophysical studies, structural geology, petrology as well as regional geological studies. Laboratory investigations and instrumentation play an important part in this work.

The following summary of engineering geology, in respect to the Snowy Mountains Scheme, is taken from an engineering geology symposium held in 1964. Acknowledgement is made here to the geological staff of the Snowy Mountains Hydro-Electric Authority.

Geological Factors

Geological conditions are important in the engineering of all of these works.

The dams are founded on rock or soil which must be strong enough to carry safely the combined load of the dam and the thrust of the impounded water, and impervious enough to prevent excessive seepage from the reservoir, the reservoir rim also must be impervious and the reservoir slopes must be stable against excessive sliding.

The tunnels are excavated in rock and the amount of support required both temporarily during construction and permanently during operation greatly affects time of construction and cost; the rock in many water tunnels not leading directly to power stations is left bare with concrete lining only in limited areas where required by design (such as at portals), and in those areas of weak rock which required steel rib supports during excavation. However, in *unlined tunnels close attention is paid to all areas with lesser defects, such as zones of loose blocky jointed rock and narrow seams of crushed rock and clay. Such areas are reinforced and protected against erosion by various combinations of grouted rock bolts, steel mesh and pneumatically applied mortar. Ground water inflows during excavation are a serious hazard, and a knowledge of ground water pressure is required for design. Most of the tunnels operate as pressure tunnels and have to resist high internal water pressures.*

Hydro-electric power stations are located usually in steep terrain and it is essential that, not only should the station and the penstocks leading to it have firm foundations, but also that both station and penstocks should be safe from risk of damage by slides coming from the steep slopes. Freedom from the hazards of land-slides is one of the advantages of under-ground power stations. These require a complex assemblage of large chambered tunnels and shafts for the water-conduits, the mechanical and electrical machinery, and for ventilation and access. The underground openings are excavated in pre-determined locations to specified size and shape, and must be permanently stable. They involve all the problems of tunnel construction but on bigger and more complex scale.

All works use large quantities of concrete, made preferably from natural sand and gravel, if available, or, if not, from crushed rock, and many dams are made from earth fill and rock fill rather than from concrete. The type of dam adopted is governed, not only by the site conditions, but also by the types and quantities of naturally occurring constructional materials available from the vicinity of the site.

Stages in the Development of Projects

All projects advance through four well-defined stages:

(1) Preliminary investigation, examination of alternatives and site selection.

(2) Detailed design, preparation of drawings and specifications; preparation of information for the use of tenderers.

(3) Construction by contract; contract supervision.

(4) Commissioning, operation and maintenance.

Engineering geology is important at all stages.

During the first stage completely infeasible sites (quite rare) are rejected and major geological difficulties at others may be avoided altogether or at least minimized by site selection. Sufficient geological information about all feasible alternatives is a necessary part of the data required for the engineering comparison of costs and benefits, on which site selection is based.

During the design stage, the detailed information required for design is obtained—the distribution of rock types, their durability, weathering, joints, faults, water-table, permeability, strength and deformability of the rocks, stability of slopes; drawings incorporating factual geological information (but not geological interpretations) are included in contract documents and made available for the information of tenderers and the contractor.

During construction it is necessary to confirm by direct inspection that the actual geological conditions conform sufficiently closely to those assumed in the designs; if not, design changes must be made. Many decisions in regard to matters of detail are left to the construction stage—excavation levels and slopes are fixed after foundations are opened up in accordance with design criteria, details of treatment of individual defects in unlined tunnels are determined after excavation, and so on; the scope of the geological problems to be encountered should be determined by the design stage, but within these limits many new problems are encountered during construction and are overcome more efficiently with the aid of geological information; detailed records of geological conditions and treatment are made for use during operation and maintenance of the project, and in the planning of future projects.

The completed works cannot be tested fully until they come into operation. It is important to check that they are behaving as designed, and so during commissioning, checks are made for leakage from dams and tunnels, erosion of spillways, landslides on reservoir slopes.

Methods of Geological Investigation

Geological mapping is basic. The whole of the Snowy Mountains region has been mapped on a series of $\frac{1}{2}°$ long. $\times$ $\frac{1}{4}°$ lat. sheets chiefly by the Geological Survey of New South Wales for the Authority. These maps are an indispensable background for the more detailed mapping required for engineering projects. This more detailed mapping is carried out on standard scales—4 inches = 1 mile, 1 inch = 200 feet, 1 inch = 50 feet, 1 inch = 20 feet, 1 inch = 10 feet. Contoured base maps are prepared by the Authority's photogrammetric unit from conventional aerial photography and from terrestrial photography by phototheodolite. The latter is particularly useful in rugged terrain such as at many dam sites.

Air photo interpretation is always attempted, but although its usefulness is limited in many areas by deep soil and thick vegetation, even in these areas lineaments which often indicate faults, and landslides, can be detected.

The amount of information available for examination of the surface is limited, and sub-surface exploration is often necessary.

Diamond core drilling is the chief method used. The total footage drilled for exploration up to September, 1963 (excluding drilling for grouting) is 221,200 feet or 40·2 miles. Every effort is made to obtain complete core recovery, since the core most easily lost is from the weakest parts of the rock which are usually of the greatest significance. Cores are stored in boxes of the same length as the hole, all losses being made up with wooden blocks painted red for emphasis, placed in the positions from which the material was lost. All cores are geologically logged at a scale of 1 inch = 10 feet and systematically photographed at a scale of 1 inch = 1 foot.

Electric logs are made of uncased water-filled drill holes using a single electrode, hand-cranked self-potential and resistivity logger. These logs are useful in rock like granite, which, when fresh and completely sound, has a uniformly high resistivity. Zones of *weathering, faults and many kinds of joints have contrasting relatively low resistivities and show up well on the resistivity log. The logs are particularly useful if core has been lost, in indicating the cause of core loss.*

Most drill holes are systematically tested for permeability at intervals of 10 to 20 feet by pumping in measured quantities of water at known pressures. Results are converted into Lugeon Units. In fractured rocks it is not possible to derive a true coefficient of permeability from these measurements but nevertheless the measurements are useful for assessing semi-quantitatively the water-tightness of foundations and the need for grouting, the risk of water flow into underground openings and the general compactness of jointed rock.

Water-level measurements in drill holes are taken over a long enough period to reflect the influence of seasonal rainfall.

Shallow excavations are frequently made for exploration, especially where the soil layer is thin. They usually take the form of bulldozed or hand-dug trenches, and shallow test pits. Exploratory tunnels have been used in dam abutments at Guthega, Jindabyne and Tumut Pond, and at Tumut 1 and Tumut 2 underground power station sites.

Continuous use is made of a 12-channel seismic refraction unit on problems such as the depth of weathering in granite, and the thickness of river alluvium. During the past three years, a single-channel hammer seismograph has also been employed on similar problems, mainly to depths of 50 feet or less. It has been especially useful in road investigations to assess the "rippability" of materials in deep cuttings.

Natural scale, three-dimensional, transparent geological models are used extensively for correlation and interpretation of the results of exploration. Drill holes are usually represented by rods and the ground surface by a moulded "Perspex" sheet.

Systematic application of these methods of geological investigation should result in a three-dimensional picture of the site showing the distribution of rock types, zones of weathering and alteration, the joint system, faults, and water table; and in a semi-quantitative measurement of the permeability of the rock-mass. This is essential information for the designer, and sufficient for many purposes.

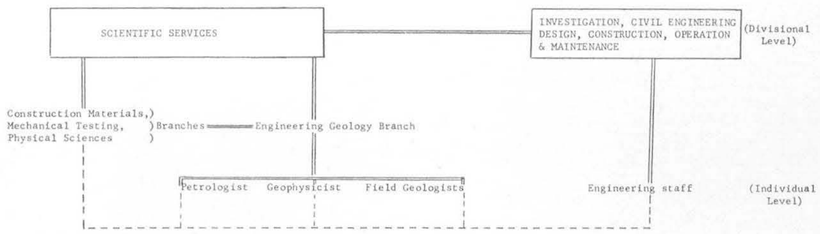
However, for works where loads of high intensity are applied to the rock over large areas, for example, in an arch dam, the designer needs information on the mechanical properties of the rock mass—its strength, deformability and state of stress. Ideally, the designer would compute the factor of safety of the rock foundations, that is the ratio of their strength to the stresses imposed on them by making excavations into them and then loading them with structures and with water pressure. In the present state of development of rock mechanics, many of the problems involved in determining properties of the rock mass in situ *have not been solved, and so the true factor of safety of foundations generally cannot be calculated.*

Samples of rock are tested in the Engineering Laboratories, Cooma, for strength and elastic properties but it is uncertain how properties so determined on small sound specimens compare with properties of the rock mass in place. Some measurements have been made on rock in place by plate bearing tests, jacking tests and seismic velocity methods.

Rock stresses around underground openings have been measured by the flat-jack method and the initial state of stress computed by applying to the measurements a stress concentration factor for the shape of the openings. This factor is determined by experimental photoelastic methods on model openings of the same shape.

The mechanical behaviour of dams, underground power station caverns, and pressure shafts is usually observed instrumentally, and compared with the behaviour predicted from design assumptions.

A chart showing the relations of the geological section within the Snowy Mountains Authority and as part of the Scientific Services Division is shown in Figure 5.



NOTES:
1. ═══ formal organization.
2. – – – day-to-day relationship.
3. Drilling branch of the Investigations Group which operates closely with Engineering Geology is not shown.

Fig. 5.—Organization of scientific services—Snowy Mountains Hydro-Electric Authority.
(By courtesy Scientific Services Section, S.M.H.-E.A.)

Engineering Geology and the Quarrying Industry

Geology applied to the quarrying industry has become a highly specialized facet of applied geology in which basic geology and petrology are closely linked with civil engineering.

Geological work in this field may be considered under three headings:

1. Selection of deposits for various products such as aggregate, roadbase, building stones and brick clay.

2. Delineation of various rock types within quarries by engineering and petrological tests on samples from the quarry face or from drill core.

3. Translating materials specifications into practical terms for purposes of tendering for contract.

In selecting deposits for quarrying it is necessary, usually, to translate *geological maps* into *material maps*. This specialized study takes due cognizance of accessibility, quarry development, transport costs and, particularly, the purpose for which the stone is to be used.

Material for concrete aggregate, for example, should be fine grained, tough and free from physical flaws. Basalt, generally, meets these requirements. Quartzite, limestone and microdiorite, in that order, are the next most commonly used aggregates.

The engineering geologist is then concerned with the attitude of the mass to determine the most suitable site for quarrying; here he works in close liaison with the quarry engineer. In particular, the geologist must decide on the quantity and quality of material available, the probable working depth indicated by the type and structure of the rock mass and the areal extent of suitable material that can be quarried. In planning a quarry, consideration must be given to such matters as proximity to transport and roads and the availability of power and water.

Micropetrology and mineragraphy can provide valuable clues to such matters as adhesion of aggregate to bitumen road surfaces and on the detailed mineral constitution with respect to the possible incidence of deleterious minerals such as marcasite. On the macro scale, a study of the joint patterns and other structural features is vital to the production of rock spalls of up to two tons for such purposes as retaining walls, airport runways extending into the sea and artificial harbours. In terms of rock soundness, basalt would appear to be ideal for these purposes, but the relatively close jointing of basalt may lead to its breaking down into smaller blocks; a less jointed more massive rock type is usually preferred. Durability, such as required for a sea wall, requires laboratory testing of such properties as toughness and an interpretation of long-term effects. Here a knowledge of the sea wall construction is important: maximum environmental strain will be imposed in the inter-tidal zone since the constant wetting and drying in this zone is a major factor in rock decomposition.

Diamond drill core is valuable in supplying information on rock soundness, tensile strength and durability of the rock. Cores should be logged to record rock types and rock variation, joint patterns and core recovery.

The construction of three-dimensional models illustrating the location of suitable stone, incidence of deuterically altered rock and other information may be of considerable use in quarry planning and development.

The study of crushing characteristics of quarried rock or of the distribution of various screen sizes available from deposits of river gravels is an important part of the work of an engineering geologist during the operation of a quarry. Unusual specifications are sometimes contained in orders for quarried stone. For example, where electrical installations are involved it may be desired to have a concrete aggregate which conducts heat away from the electrical installation so as to avoid over-heating; a study of thermal conductivity rates of various rock types thus becomes important. The use of finely crushed rock for use in sand blasting or tumbling, as in the polishing of spectacle frames, requires a detailed study of the hardness (in the Moh's scale) of the rock and of its constituent minerals.

One of the more serious problems in concrete aggregate is that of shrinkage. This problem is currently being investigated by the C.S.I.R.O. Detailed investigation of the reactions of silicate minerals when incorporated in aggregate and of the nature and amount of interstitial clay minerals within igneous rocks is likely to resolve this problem.

The importance of the quarrying industry in the Australian economy can be seen when one considers that some 33 million tons of aggregate are produced in Australia annually, i.e., 2·9 tons per head of population.

Building stones are coming more and more under the scrutiny of applied petrologists. Problems of discoloration of polished marble slabs, cracking of stone slabs, weathering of sandstones and marble, undue pitting in paving stones and terrazzo are currently being investigated. Some of these problems involve micropetrology, chemical analysis for trace elements, as well as a study of quarrying, slabbing and polishing in so far as the answer to these problems may be found at any one, or more, of these various processes of manufacture.

Geology and Mineralogy in Industry

One of the more recent developments in applied geology and mineralogy is the increasing application of these disciplines to manufacturing industry. Geologists and mineralogists are now taking their place alongside industrial chemists and chemical engineers in such industries as glass and ceramic manufacturing, cement, rubber and paint works.

Many of these industries use natural raw materials such as pigments, sand, clay minerals, graphite, feldspar, limestone and a host of minor mineral commodities. Most of the larger firms concerned with these products employ field geologists whose work entails exploration for new deposits and the geological supervision of production from the various sites of operation. Other geologically trained personnel are engaged in laboratory work testing and examining the detailed composition and purity of the mineral raw material and also the finished products, utilizing a variety of mineralogical techniques.

Two industries will serve as examples of geology and mineralogy in industry—the glass and the rubber manufacturing industries.

The manufacture of glass necessitates a continuous supply of high quality, non-metallic minerals particularly quartz sand. This involves the exploration for and testing of new deposits and the constant review of existing deposits. Mining programmes have to be drawn up, negotiations for right of entry have to be carried out and cost factors for a low-priced raw material carefully considered. Much of this work is executed by or involves geologists.

In addition to the above work, which would be regarded as "standard" geological activity, there is considerable work carried out in the laboratories utilizing mineralogical techniques.

The tendency of glass to develop "stones"—incipient centres of crystallization—must be carefully controlled; if not kept in check they may give rise to a drop in overall quality and efficiency of the final product. The early identification and an understanding of the origin of these bodies within the glass, as a means of eradication, is imperative. Their identification involves standard petrological techniques supported by X-ray diffraction and optical emission spectrography. The examination of thin sections under the petrological microscope is standard procedure.

In addition to recurring problems, unexpected difficulties sometimes confront the industrial mineralogist. On one occasion, for example, glass from a flat glass plant was found to contain complex copper sulphide "stones". These were traced back to fragmented copper detonators used at the limestone quarry supplying the plant.

With the outbreak of World War I, several countries, including the United States, found that supplies of optical glass had been cut off. A research section was set up under G. W. Morey, of the Geophysical Laboratory in Washington. The classical work, "Properties of Glass", by Morey, is still widely used. Additionally, much of the work of noted petrologists N. L. Bowen, O. Tuttle and J. W. Greig on phase equilibria in the various systems involving silica is of direct applicability to glass and ceramic manufacture and experimentation. Greig's work on the postulated immiscibility of silicate melts, carried out with a view to examining mechanisms for magmatic differentiation showed that immiscibility was an unlikely process in that regard but it laid the foundation for the manufacture of heat-resistant silicate glasses.

Manufacture of glasses such as opal glasses, fluoride opal glasses, low expansion boro-silicate glasses and soda-lime silica glasses are all closely related to the early work on silicate mineralogy.

Glass melting reactions, aimed at increasing furnace production rates, are currently being planned. It is hoped that an understanding of reactions involved in melting may lead to means of accelerating melting rates. In this work it is planned to study, initially, simple binary systems and to examine the effect of varying the parameters such as: time, temperature, grain size, and the addition of melting accelerators. A study of more complex systems will follow. The close relations between this work and fundamental igneous petrology is very evident. This work will involve modern instrumentation—differential thermal analysis, thermal gravimetric analysis, X-ray diffraction, high temperature microscopy, micropetrology and mass spectrometry.

Gas bubbles in glass are an imperfection which limits production rates in certain glasses. The removal of these bubbles is termed "refining" in the glass industry. An elimination of such imperfections is of considerable importance in streamlining production. Research into this problem clearly involves physical chemistry as applied to a consideration of gas-silicate systems in the field of igneous petrology.

The photomicrographic laboratory of a leading rubber manufacturing firm is under the direction of a mineralogist. The work of this laboratory is concerned with the examination of raw materials, particularly "fillers" used in rubber manufacture. Natural and synthetic silicates receive considerable attention in this regard. Methods of study are akin to those used in conventional mineralogy. Light and electron microscopy, X-ray diffraction, differential thermal analysis and chemical methods are employed.

Sulphur migration in rubber is studied by tracing the movement of S^{32} using autoradiography.

Micro-hardness testing of wires used as beading in tyres and phase contrast examination of metal surfaces, including metallographic study of lead, used in battery manufacture, follow mineralogical lines.

Oil and Natural Gas

Despite the expenditure of many millions of dollars on oil exploration, particularly in New Guinea, the early outlook as regards commercial oil production was not encouraging. Some oil had been produced from the Lakes Entrance area in east Gippsland and small showings of gas and oil were forthcoming from bores at Roma and Springsure in southern Queensland. Traces of bituminous material were known also from the Kimberley district.

After World War II, oil exploration was prosecuted with renewed vigour. This was due to several factors: the continued belief, notwithstanding past failures, that commercial oil could be found in Australia; the need to reduce Australia's enormous import costs for overseas crude oil; the uncertainty of supplies from Middle East countries because of political factors; and the waning reserves of some of the American producers—this latter factor led to substantial overseas capital and technical knowledge being applied to oil search in Australia.

Whereas previous exploration was concentrated on those areas where oil and gas showings were known, the new phase of exploration was based, firstly, on a detailed survey of sub-surface structures deemed favourable to the accumulation and storage of oil and gas. This immense survey utilized modern geophysical methods, particularly seismic and gravity surveys, supported by considerable stratigraphic drilling, formation testing and laboratory investigations. The knowledge acquired on sub-surface structure, often at depths of many thousands of feet, completely revolutionized oil exploration. This has resulted in the delineation of a number of major structural environments within which current exploration is conducted. Few of these lie within New South Wales, though various organizations within this State are vitally concerned with the exploration programme. These environments are listed below.

1. Central Intracratonic Basins, e.g., The Amadeus and Georgina Basins.
2. The West Australian Basins, e.g., Perth, Carnarvon, Canning-Fitzroy and Bonaparte Gulf Basins.
3. Basins associated with the evolution of the Tasman Geosyncline, e.g., Adavale Basin, and the post-orogenic basins such as the Bowen-Surat, the Clarence-Moreton and the Sydney Basins.
4. Peripheral Basins of Mesozoic to Tertiary age, e.g., Gippsland, Otway and Bass Basins.
5. Other areas such as the N.W. Continental Shelf, the Sāhul and Arafura Shelves and the Great Barrier Reef.

Some success has been forthcoming, first with the discoveries at Rough Range in the Carnarvon Basin in 1953 and subsequently at Cabawin and Moonie in the Surat Basin. More recent discoveries at Barrow Island and, most importantly, in the Bass Strait, have revolutionized the outlook as regards Australia's future oil potential.

In the Amadeus Trough, the Mereenie Anticline, 150 miles west of Alice Springs, is estimated to contain gas reserves of the order of 10^{12} cubic feet in the Cambro-Ordovician Pacoota Sandstone.

In the Carnarvon Basin, several sub-basins result from the N-S trending Wandagee Ridge. Sediments range from Devonian to Miocene with a strong development of Permian. Toward Barrow Island the Mesozoic sediments thicken and upwards of 5,000 feet of Cretaceous is known. Stratigraphic traps on the flanks of the Wandagee Ridge form one of the principal targets. Production from Barrow Island is from the Lower Cretaceous Windalia sands and also from Upper Jurassic sediments.

The Canning-Fitzroy Trough contains more than 30,000 feet of sediments ranging from Ordovician to Triassic. Apart from structural traps on the flanks of growth structures, attention is being directed toward prominent reef complexes of Middle to Upper Devonian age. Here, too, there is considerable thickness of Permian—some 14,000 feet.

Prospects in the Bonaparte Gulf Basin are similar to those of Fitzroy Trough, with special interest attaching to recently discovered reef complexes. All Palaeozoic systems excepting Silurian are represented and there is a strong development of Carboniferous pyritic shales. The section increases in thickness seawards and offshore drilling appears likely.

The Bowen-Surat Basin is an elongated structure some 600×90 miles which may connect, in the sub-surface, with the Sydney Basin. It effectively separates the more highly tectonized portions of the Tasman Geosyncline into the Lachlan and the New England Geosynclines. Sedimentation has been almost continuous from Carboniferous to Triassic and in the Surat Basin into Cretaceous times. Depth of the basin is not known with certainty, but sediments are of considerable thickness—east of Roma, for example, there are 15,000 feet of Triassic sediments alone.

Gas reserves near Roma are estimated to be at least 2×10^{11} cubic feet.

Australia's first commercial oilfield, at Moonie, produces from the Lower Jurassic Precipice Sandstone.

Seismic reflection methods revealed the Adavale Infra-basin of Palaeozoic rocks completely concealed beneath Mesozoic. Rocks comprise lower Palaeozoic to Permian to depths of 22,000 feet in places.

Gas accumulations of some 9×10^{11} cubic feet have been proved in the Gidgealpa and Moomba structures within the Cooper's Basin of NE South Australia and are thought to be indigenous to the Permian standstones though deeper Cambrian dolomites may be contributing.

The offshore Bass Basin possesses imposing thicknesses of Mesozoic to Tertiary sediments and particularly favourable reservoir characteristics. The Gippsland Basin has prospective sediments to 15,000 feet, as indicated by aeromagnetic and marine seismic surveys. Jurassic and Cretaceous sediments are both paralic and continental, interspersed with marine transgressions. Upper Cretaceous and Eocene contain brown coals and other estuarine sediments, followed by marine Oligocene sediments. The main gas sands occur above the thicker Tertiary coals and below a thick limestone and marl. Folding is evident and this may be due to marginal effects attending the Kosciusko epeirogenic uplift. Preliminary assessment of the gas reserves in the Barracouta, Marlin and other structures are of the order of 5×10^{13} cubic feet.*

In New South Wales, the oil shale industry flourished during the latter half of the nineteenth century and the early twentieth century, and although the growing use of electricity pushed kerosene into the background, attempts to maintain the industry were being made up to 1945.

The absence of petroleum seepages, as were known in the early days of the oil industry in America, did not provide an incentive in this State, and it was not until 1910 that a Mr. Duke drilled three shallow wells on the banks of Redbank Creek near Richmond in search of oil.

From 1910 to 1954, twenty-five wells of an aggregate footage of 43,509 were sunk, but no oil was forthcoming and gas production was limited to small quantities recovered from a well sunk alongside the Balmain colliery shaft. Cable tool and diamond drilling methods were used in drilling these wells. A rotary rig was used to drill the last few hundred feet of Kulnura No. 1 well in 1938. Geological surveying methods were used in locating only seven of the twenty-five wells drilled. Geophysical methods were not employed.

Between 1954 and 1967, 94 wells were drilled for an aggregate of 323,345 feet, and drilling for structural data accounted for a further 29,033 feet. The first aeromagnetic and gravity surveys were undertaken in 1954, and since then, 23 separate aeromagnetic and 27 separate gravity surveys have been completed. Since the first seismic survey by a petroleum exploration company, in the Camden-Wallacia area, 59 separate seismic surveys have been completed. Although the first aeromagnetic survey was partially extended offshore east of Sydney, offshore surveys have been a comparatively recent development. Between 1962 and 1967, offshore operations have consisted of three aeromagnetic surveys and two seismic surveys between Batemans Bay and Port Macquarie and particularly between Sydney and Newcastle. Since 1954, almost all wells have been located on the basis of geological control, and since 1962 with the addition, also, of geophysical survey control. During this time, a number of oil and gas showings have been recorded, and some of the gas showings have approached the volumes and pressures required for commercial exploitation but, to date, no truly commercial discoveries have been made.

The few syndicates and individuals who drilled the 15 wells between 1910 and 1925 did not receive much support—the geological profession,

* The foregoing has been extracted from a paper by J. C. Cameron, "Australia's oil and gas potential", Proceedings of the Seventh World Petroleum Congress, Mexico, March, 1967.

in particular, viewed the projects with scepticism. This was no doubt due to the lack of geological advice as regards locality, and the fact that none of the wells went beyond 500 feet. The situation improved somewhat from 1925 to 1938, when petroleum exploration companies entered the search and 10 wells were drilled to greater depths and under geological supervisions. However, between 1938 and 1954, petroleum exploration was literally at a standstill.

The discovery of oil at Rough Range in 1954 triggered off a marked rejuvenescence in oil search, with overseas companies joining with local companies, and in 1955 it was deemed necessary to pass legislation (The N.S.W. Petroleum Act) aimed at assisting and rationalizing oil search in this State.

So far, no commercial petroleum discoveries have been made in New South Wales, and the prospects may not be as bright as those in neighbouring States, where large sedimentary basins and wide shelf areas are known; but with only 119 petroleum wells drilled to date, judgement may well be tempered with some reserve.

Interest is still maintained in the dry gas prospects connected with the Permian coal measures of the Sydney Basin. In the Hunter Valley, sediments may extend to over 25,000 feet, and in the Cumberland Basin, just west of Sydney, geophysics indicates some 15,000 feet of sediments.

The possibility of the Surat Basin extending from southern Queensland into northern New South Wales, with localized deepening, cannot be discounted in the search for oil. Interest also attaches to the examination of certain features such as sub-surface unconformities involving mid-Palaeozoic rocks.

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