9/1974

THE AUSTRALIAN NATIONAL UNIVERSITY

RESEARCH SCHOOL OF EARTH SCIENCES

ANNUAL REPORT - 1973

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INTRODUCTION

The Research School of Earth Sciences came into being on 1 July, 1973. The nucleus of the new School was formed by the separation of the Department of Geophysics and Geochemistry from the Research School of Physical Sciences. However, this report covers all research during 1973 (by arrangement with the Acting Director of the Research School of Physical Sciences).

The earliest fields of interest of the Department of Geophysics were rock mechanics, geochemistry and palaeomagnetism. These programs still continue but have been modified from time to time.

The initial impetus for the revival of interest in continental drift came from studies of the fossil magnetism of rocks. In the early sixties, the papers on sea floor spreading appeared. Later development has become known as plate tectonics. These ideas underlie much of the research in the earth sciences during the past decade. Today, broadly speaking, the major relative movements of plates, be they continental, or oceanic, during the past 100-200 million years, have been determined, but there is much still to be done to determine the details of the processes which are going on at the present time. Interest is turning also to the question of whether relative changes in the positions of the continents occurred in earlier times or whether the present is the first major drift episode in the history of the Earth. There is great similarity between such features as the Appalachians, the Urals and the kind of structures which have evolved, or are evolving, during the present drift episode but it is difficult on the basis of structural geology alone to determine whether the older orogenies were associated with major changes in the relative positions of the continents. It appears that much of the information which will provide answers to these questions must come from palaeomagnetic studies of the ancient rocks, combined with determinations of these rocks. Isotopic age measurements were, of course, another major field of interest of the Department of Geophysics and Geochemistry, and will continue to be one in the new School.

Studies of Precambrian dykes in the Yilgarn and Gawler Blocks of Western and Southern Australia have shown that there are at least seven different periods of intrusion of these dykes ranging in age from 750 to 2700 million years. Palaeomagnetic studies of these dykes combined with some earlier work make it possible to define a polar wander path for the Precambrian of Australia. The polar wander path is continuous for the two Blocks, although younger orogenic features lie between them. The natural inference is that these Blocks have remained in their same relative positions

throughout the Precambrian, a result which is consistent with similar conferences made recently in respect of the African Precambrian cratons.

Other studies of the isotope geochemistry group are concerned with assigning ages to the greenstone belts characteristic of the more ancient rocks of the Precambrian of Western Australia, and the granites characteristic of the Palaeozoic terrain in south-east Australia. Rocks of ages of roughly 2600 million years, i.e. with ages similar to those in Western Australia have been found in the Vestfold Hills region in Antarctica.

One of the aspects of the plate tectonic processes currently attracting much attention is that of the existence of fixed, or slowly moving, hot spots in the mantle which leave the imprints of the motion of the lithospheric plate above them in the form of linear chains of volcanic activity, the age decreasing smoothly along the chain. This concept was originally developed for the chain of volcanoes lying to the northwest of Hawaii. Potassium-argon dating of volcanic rocks from the Marquesas Island chain has shown that in these cases also the volcanic activity has migrated from northwest to southeast, the rate of migration being 10 cm/year.

It was thought initially that the hot spots might be fixed relative to the interior of the Earth. Some recent studies suggest that this may not be the case. Further studies of the ages of the volcanic activity in the volcanic chains of the Pacific and other oceans will hopefully lead to more understanding of the hot spot phenomenon and thence to the plate tectonic process as a whole.

Early measurements of the heat flow in Australia suggested that the heat flow in the eastern part of the continent was almost twice that in the western portion of the continent. This early result has been confirmed by a more recent, more extensive series of measurements. In general, teleseismic P arrivals are late in eastern Australia and early in western Australia. The similarity to the western United States is remarkable. Magnetic deep soundings too show evidence of a conductivity increase near what is thought may be the boundary between the widely different regimes of the eastern and western Australia. An array of portable magnetometers has been built and is being used to look for possible hotter-than-average spots in the crust and mantle of eastern Australia.

Laboratory studies related to the origin of the different types of basaltic magma are continuing and new presses have been built so that a larger proportion of the experimental runs can be carried through for periods of weeks rather than days.

The pattern of rare earth distribution shows differences which are diagnostic of processes in the upper mantle. The interpretation of these distributions is, however, dependent on knowledge of the partition of these elements during the process of magma formation, and a series of experiments aimed at determination of these coefficients has been carried out recently.

The work described in the preceding sections has been related principally to the properties of the outermost one to two hundred kilometers. However, there are important and significant questions still unanswered with regard to the properties of the deeper parts of the upper mantle. It is now established that there are at least two major discontinuities in velocity at depths of 400 and 700km. It is thought that the deeper of these two transitions may result at least in part from the transformation of the silicates characteristic of the upper mantle to denser polymorphs in which the silicon has six-fold rather than four-fold coordination. In earlier years, three transformations of this type have been achieved in the experimental petrology laboratory and this year two further transformations were discovered.

Inferences with regard to structure of the Earth rest in part on comparisons of the seismic velocities determined from seismic travel times, surface wave dispersion and the study of the free oscillations of the Earth with laboratory measurements of the velocities of the likely minerals or mineral assemblages. Successful laboratory measurements on a number of high pressure phases have been made and have permitted inferences with regard to possible imperfections of some of the recent seismic models of the Earth's velocities and density.

Further support for the hypothesis that the precursors to PKP result from scattering near the core-mantle boundary has been obtained by computer processing of Warramunga array records. It has been shown theoretically that the amplitudes and slownesses of these precursors can be explained by random variations of about one percent in the density and elastic parameters of a layer of 200km thickness at the base of the mantle.

The largest earthquake in eastern Australia during the past ten years occurred near Picton on 10 March, 1973. This event was well recorded by the stations of the A.N.U. radio telemetry array and by the Sydney Water Board stations. It had a Richter magnitude of 5.5. More than 1000 aftershocks occurred in the three months following the main shock. Using a master shock relocation technique it has been possible to define a trend which probably corresponds to the strike of a buried fault.

The mechanical properties of the materials of the crust and upper mantle must have a significant effect on the tectonic processes in these regions. Studies of the deformation of olivine, a major component of the upper mantle mineralogy were made on synthetic single crystals in an international cooperative program.

The School's interest in and contribution to the lunar samples study program continue. Samples of the basalt from Apollo 17, tne last of the Apollo series, proved to be very similar to those from the Apollo 11 site though ranging somewhat higher in the titanium content. The high pressure group are now at the stage of synthesizing their work on the maria basalts and have shown that these rocks were formed by varying degrees of partial melting of a common pyroxenite source material at depths of 200-500km within the lunar interior. This conclusion has far reaching implications for the thermal history and evolution of the Moon.

I. VISITORS

In April, Dr. E. Farrar of Queens University, Kingston, Ontario, Canda completed a stay of six months during which time he undertook isotopic dating studies.

Dr. E. Leitch of the University of Sydney arrived in November for a visit of several months to carry out isotopic dating on rocks from the New England area of New South Wales.

Dr. A. Ewart, Department of Geology, University of Queensland spent three weeks working on the lead isotope systematics of a basalt-rhyolite association from the Lamington Volcanics, and 1 month on the lead isotopic compositions of Tongan volcanics.

Professor A.E. Beck, University of Western Ontario, Canada; at present on sabbatical leave at the University of Queensland visited for discussions on heat flow and to present a seminar. Professor Beck was the first research student enrolled in the old Department of Geophysics.

Professor J.C. Jaeger, former head of the Department of Geophysics and Geochemistry, spent two periods of a few weeks, in May and in October, visiting the School and maintaining contact with projects in heat flow and rock mechanics.

Dr. N.C. Gay, University of Witwatersrand, South Africa, was a Visiting Fellow from October 12 to December 5; during this time he completed a project with Professor Jaeger and undertook some work with Dr. Paterson.

Dr. B. Gulson, Division of Mineral Chemistry, CSIRO, has made a number of short visits to carry out U and Pb isotopic measurements in connection with CSIRO projects.

Dt. T. Shirahase, Geological Survey of Japan, completed his year's visit with work on the Rb-Sr systematics in the Berridale and New England Batholiths.

Dr. R.T. Pidgeon, of the Isotope Age Group at the Scottish Research Reactor Centre, visited for three months to make U-Pb age measurements using zircons from Kambalda.

Mr. J. Cocker, Geology Department of the University of Tasmania, has spent three months working on the ages and initial $^{87}Sr/^{86}Sr$ of Tasmanian granites.

Dr. C. Adams, Institute for Nuclear Studies, DSIR, New Zealand visited for two months to make Rb-Sr total-rock age determinations on New Zealand granites and gneisses.

Visitors (continued)

Dr. C.M. Gray, Department of Geology, La Trobe University, has made several short visits in connection with collaborative lunar Rb-Sr work.

Dr. B. Mason, Director of the Division of Mineralogy and Meteoritics of the Smithsonian Institute, Washington spent three months in the School, working upon trace element abundances in meteorites.

Dr. Ian M. Steele, Department of Geological Sciences, University of Chicago spent one month working on techniques of spark source mass spectrography and their application to ion microprobe research.

Mr. Philip Hellman, University of Sydney, spent three months as a vacation scholar working on the geochemistry of tektites.

Dr. J.D. Kleeman, University of New England paid several short visits to discuss a collaborative program to study phase transformations during shock waves produced by the rail gun facility.

Dr. C.H. Scholz, Lamont-Doherty Geological Observatory of Columbia University, New York visited for several days in January to discuss mutual research interests with the rock mechanics and mineral physics group.

II. CONFERENCES AND STUDY LEAVE

Professor A.L. Hales attended the Conference on Geodynamics at the I.A.S.P.E.I. Meeting held in Lima, Peru in August, 1973.

Professor A.E. Ringwood delivered the William Smith Lecture to the Geological Society of London in July. The title of the lecture was "The geophysical and petrological evolution of island arc systems"

Dr. B.J.J. Embleton and Mr. J.W. Giddings attended the Second International Conference on Geophysics of the Earth and Oceans held in Sydney in January. Mr. Giddings presented a paper entitled "The role of palaeomagnetism in assessing continental integrity" Dr. Embleton attended the Conference on the Tasman Geosyncline held in Brisbane on May 31 and June 1 and presented a paper entitled "Palaeomagnetism and the tectonic evolution of the Tasman Orogenic Zone".

Dr. M.W. McElhinny and Dr. B.J.J. Embleton both attended the Third International Gondwana Symposium and presented papers on aspects of Palaeozoic and Mesozoic palaeomagnetism respectively.

Conferences and Study Leave (continued)

Dr. Ian McDougall presented a paper at a Symposium on Tertiary and Quaternary volcanism in Australia organized by the Geological Society of Australia and held in Melbourne during February. Dr. McDougall was co-convener of one of the sections of the Third International Gondwana Symposium which was run in Canberra in August, 1973. He also participated in an IDOE/CCOP sponsored workshop on metallogenesis and tectonic patterns in East and Southeast Asia held in Bangkok in September. Dr. McDougall attended the IX INQUA Congress in Christchurch in December and gave a paper on the Pliocene-Pleistocene boundary in Australia.

Dr. M.S. Paterson attended a Gordon Conference on Solid State Geophysics on 13 July - 3 August and gave a paper on "Creep and strain rate studies in olivine-rich rocks".

Dr. F.E.M. Lilley, Mr. D.J. Bennett and Mr. G.W. Boyd attended the "Second International Conference on the Geophysics of the Earth and the Oceans" held at the University of Sydney during January. Dr. Lilley was the Chairman for one session and Mr. Bennett presented a paper on magnetometer array studies of electrical conductivity structure.

In February, in Melbourne, Dr. Lilley attended a symposium on "Tertiary and Quaternary Volcanism in Eastern Australia" and presented a paper on heat flow and electrical conductivity measurements over Western Victoria.

Dr. A.R. Crawford visited Hyderabad, India in March at the invitation of the Secretary-General, International Geodynamics Project, to attend a meeting of Working Group 3(b) (Himalaya) at the National Geophysical Research Institute of India. Dr. Crawford also attended a meeting in Adelaide in May arranged by the Sub-commission on Precambrian Stratigraphy of the International Union of Geological Sciences and spoke on Madagascar in Gondwanaland.

Dr. Crawford acted as Convener of Section 1 (Palaeo-geography) of the Third International Gondwana Symposium held in Canberra in August, acted as Chairman of the morning session and by invitation Chaired a special evening session. He also published an article about the Symposium in The Canberra Times.

Conferences and Study Leave (continued)

In June Dr. Cleary presented a paper at a Symposium in Canberra on granites in the Lachlan Mobile Belt. In December Drs. Cleary, Muirhead and Fitch presented papers at a symposium in Canberra on seismic surveillance in eastern Australia. Dr. Cleary also was a contributing author to two papers presented at the I.A.S.P.E.I meeting at Peru in August.

Mr. M. Gamlen presented a paper at the Second Conference of the Australian and New Zealand Association for Mass Spectrometry in February 1973, also attended by Dr. W. Compston. Dr. W. Compston attended the Fourth Lunar Science Conference in Houston, and en route visited isotope laboratories at the University of Texas at Dallas, the U.S.G.S. at Denver and the California Institute of Technology, Pasadena. Dr. Compston also presented papers at the ANZAAS Conference in Perth (August), and at the Symposium on the Origin of Granites in Canberra (June).

Dr. S.R. Taylor attended the following Conferences: the Fourth Lunar Science Conference in Houston, Texas in March at which a paper on the chemical composition of the lunar highlands was presented; the International Geochemical Conference, sponsored by the International Association of Geochemistry and Cosmochemistry in Patna, India, in March, chairing one session and giving a paper on lunar geochemistry; Geological Society of America Annual Meeting, Dallas, Texas, in November; International Symposium on Mars, Pasadena, California, in December.

Dr. Taylor was the scientific organizer and chairman for a NASA symposium on scientific results from the Apollo missions at Indiana University in March.

Dr. R.C. Liebermann attended the XVII General Assembly of the International Association of Seismology and Physics of the Earth's Interior in Lima, Peru in August, where he delivered an invited paper co-authored by Professor A.E. Ringwood and entitled "Velocity-density systematics and polymorphic phase transformations". While overseas, Dr. Liebermann also attended the Gordon Conference on Geophysics in New Hampshire and visited several universities in the U.S. to discuss mutual research interests.

Dr. D.H. Green attended the Fourth Lunar Science Conference in Houston in March 1973 and followed this by visiting and lecturing at the Geophysical Laboratory, Washington, Universities of Chicago, Arizona (Tempe), New Mexico (Albuquerque), California (Los Angeles) and the California Institute of Technology (Pasadena). In August, Dr. Green attended the Bureau meetings of the Inter-union Commission for Geodynamics at Lima, Peru.

Dr. S.J.B. Reed gave an invited review lecture 'Electron Microprobe Analysis' at the August ANZAAS Meeting in Perth.

Three papers on usage of liquid scintillation spectrometers for low-level counting based on the work of the ANU radiocarbon dating laboratory in cooperation with the Australian Atomic Energy Commission and University of Sydney were presented at the International Conference on Liquid Scintillation Counting, Sydney, August, 1973.

One paper on Problems of dating high sea level stand was presented at INQUA, Christchurch, December, 1973.

Lecturers on 'The use of R.C. as a Research Tool in Archaeology' were presented at ANZAAS, Perth and at Auckland University, New Zealand and "Liquid Scintillation mass-spectrometry" at Waikato University, Hamilton, New Zealand in December.

Mr. H. Polach was invited by the INQUA Commission of Palaeopedology to act as coordinator of the sub-commission on 'Dating Techniques in Palaeopedology'.

Professor A.E. Ringwood spent the period May-August as an Overseas Fellow at Churchill College, Cambridge. During this period he worked mainly upon problems connected with the origin of the Earth and Moon. He also attended the Royal Society conference upon Mars and the annual meeting of the Meteoritical Society in Davos, Switzerland.

Dr. S.R. Taylor was on study leave from May. The following institutions were visited: Departments of Geology and Chemistry, University of Western Australia; Institute of Geochemistry, University of Rome; Department of Geology, University of Florence; Max-Planck Institut für Kernphysik, Heidelberg, Mineralogical Institute, Tubingen University; Geochemistry Department, University of Göttingen; Department of Geochemistry, Charles University, Prague. Sample collecting trips were made to many of the Italian volcanic areas, to the tektite localities in Czechoslovakia and to the Ries and Steinheim meteorite impact craters in Germany. At present Dr. Taylor is at the Lunar Science Institute, Houston, where he is writing a book on the scientific aspects of the Apollo lunar mission. A total of 21 lectures on various aspects of lunar geology, island arc volcanic rocks, continental evolution, tektites and analytical methods in geochemistry have been given.

III. Ph.D. THESES SUBMITTED

The following theses were submitted during the year:

M. BARBETTI	-	Archaeomagnetic and radiocarbon studies of aboriginal fireplaces
D.W. SIMPSON	-	P-wave velocity structure of the upper mantle in th Australian region
D.J. MORRISON-SMITH	-	A mechanical and microstructural investigation of the deformation of synthetic quartz crystals
M.H. WORTHINGTON	-	The inversion of seismic data using Monte Carlo and linear programming techniques

IV. GENERAL MATTERS

Professor A.L. Hales has been appointed Bureau Member of Inter-Union Commission for Geodynamics. (The Geodynamics Commission is an inter-Union (IUGG-IUGS) Commission of the International Council of Scientific Unions set up to co-ordinate the geodynamics project). Professor Hales has also been appointed editor for the special issue of the Proceedings of the Conference on Geodynamics, held in Lima in August and to be published in the Journal "Physics of the Earth and Planetary Interiors".

Professor A.E. Ringwood, Dr. W. Compston and Dr. S.R. Taylor were reappointed as Principal Investigators for lunar samples for the three year period 1973-1976.

Dr. M.S. Paterson has been invited to serve as a Supplementary Reporter in Tectonophysics for the Third Congress of the International Society of Rock Mechanics, Denver, September 1974; in this connection, he has prepared a review paper on "Laboratory studies of flow in olivine-rich rocks".

Drs. D.H. Green and M.W. McElhinny have been appointed to the Editorial Board of the international journal "Tectonophysics".

Drs. I. McDougall and M.W. McElhinny have been appointed members of the newly established I.U.G.S. sub-commission of the Ihternational Commission on Stratigraphy on the Magnetic Polarity Time Scale.

Dr. A.R. Crawford acted as National Secretary of the Australian Geodynamics Committee and prepared a report from correspondence received.

General matters (continued)

Seminars: During the year, fifty-three seminars were given by staff, scholars and visitors. Visiting lecturers were:

Prof.A.E. Beck, University of Western Ontario
Prof.J. Clarebout, Stanford University
Dr. L.A. Frakes, Florida State University
Dr. N. Gay, Bernard Price Institute, Johannesburg
Dr. J. Gramberg, Delft University of Technology
Dr. C. Gray, La Trobe University
Prof.W.M. Kaula, University of California
Dr. B. Mason, Smithsonian Institution
Dr. A.J. Naldrett, University of Toronto
Dr. R.J. Pidgeon, Scottish Reactor Centre
Dr. A.J.R. Prentice, Monash University
Prof.J. Rodgers, Yale University
Prof.S.K. Runcorn, University of Newcastle-upon-Tyne
Dr.H.H. Schmitt, Apollo 17 Astronaut
Prof.R. Stanton, University of New England
Dr. P. Sydenham, University of New England
Prof. H.C. Urey, University of California
Prof. J.J. Veevers, Macquarie University.

1. PALAEOMAGNETISM

1.1 Laboratory modernisation (M.W. McElhinny, B.J.J. Embleton)

During the year, the palaeomagnetic laboratory acquired a new Digico Computerized Spinner Magnetometer. This is the third spinner magnetometer in operation in the laboratory, so that the three original astatic magnetometers have now been completely replaced. The new magnetometer has an impressive sensitivity limit, more than an order of magnitude greater than either the PAR or Schonstedt instruments. Intensities of 2×10^{-8} emu.cm^{-3} have been measured on this machine.

A second furnace for bulk specimen work has been constructed inside a second 10 coil field-free space, automatically controlled through fluxgate detectors and feedback arrangements. The system now occupies the space previously taken by the sensitive astatic magnetometer, which has been dismantled.

The automatic alternating field demagnetizer has been moved to a new location closer to the magnetometers and arrangements are much more satisfactory (for ARM experiments).

1.2 Precambrian dykes (J.W. Giddings, M.W. McElhinny, B.J.J. Embleton)

Over 100 dykes have been sampled in the Yilgarn and Gawler Blocks of Western and South Australia. The palaeomagnetic measurements indicate that seven groups of directions may be defined, each of which corresponds to a separate period of intrusion. Cross-cutting and other relationships have enabled the relative ages of the groups to be determined. These relationships have now been confirmed from preliminary Rb-Sr age determinations in progress, and enable a polar wander path to be drawn for the Precambrian of Australia. The preliminary path shows two important features. First it appears that all poles from previously undated Precambrian iron ore formations fall on this path. From this, it is possible to deduce their respective ages. Further, the path appears to be a continuous one that takes no account of which Precambrian block the results come from. This suggests that some of the Australian Precambrian blocks have remained in their same relative positions irrespective of the presence of younger intervening orogenic belts.

The dyke project is being extended to Queensland through co-operative field work with members of the B.M.R. Intrusives in the Mt. Isa geosyncline are currently being investigated.

1.3 Adelaide Geosyncline (J.W. Giddings and B.J.J. Embleton)

Work on the Late Precambrian to Cambrian sequences in the Adelaide Geosyncline has enabled this section of the polar wander path to be extended back and confirmed in detail. The poles are consistent with those from northern and central Australia and therefore confirm the unity of these parts of Australia since the early Phanerozoic and late Precambrian. These results have enabled some of the early work of Briden in South Australia and Tasmania to be reinterpreted. Where remagnetization has occurred, this happened in the late Cambrian rather than the early Tertiary as was previously supposed. This seems to be more consistent with the geology. Taken together the results do not confirm the presence of a large shear which was postulated to have taken place in the Ordovician between Tasmania and South Australia.

1.4 Late Precambrian glaciations and Gondwanaland. (M.W. McElhinny, J.W. Giddings, B.J.J. Embleton)

During the year, two review papers were prepared. In the first all Phanerozoic results were reviewed, first in the context of Australia and second in the context of Gondwanaland. This synthesis shows two important features. Measurements from the Tasman Orogenic Zone are consistent with the view that a series of island arcs and intra-arc basins merged with a unified Australian assemblage during the later Palaeozoic. Further, there is a requirement that some continental landmass occupy the space of what is now the Wharton Basin. It is proposed that this is Tibet, a northerly extension of peninsular India that lay adjacent to Western Australia.

A late Precambrian to early Palaeozoic synthesis of Gondwanic results shows how a revised pole path can be drawn which explains the widespread occurrences of Late Precambrian glaciations in terms of polar migration. This involves fairly rapid polar movement, but is consistent with Gondwanaland remaining a unit at least back to about 750 m.y. ago.

1.5 Madagascar (M.W. McElhinny and B.J.J. Embleton)

Arguments about the configuration of Gondwanaland revolve essentially around where one places Madagascar in a reassembly. Does it fit off northeast Africa (Kenya) or further south next to Mozambique? When this question is decided all other pieces will pretty well fit into place. In order to resolve this question once and for all 140 samples of sediments ranging from Upper Carboniferous to Middle Jurassic from the Sakoa, Sakamena and Isalo Groups of the Gondwana (Karroo) System in both the southwest (Sakoa coalfield) and northwest regions were collected during an expedition in September. The collection should provide sufficient information to make a unique comparison with the other Gondwanic continents.

1.6 Malaya and Borneo (M.W. McElhinny)

A joint project is being undertaken with Professor N.S. Haile of the University of Malaya, Kuala Lumpur. Samples of Carboniferous, Permian and Mesozoic (Cretaceous?) volcanics and sediments from the Malayan Peninsula show quite conclusively that this was not a part of Gondwanaland but lay near the equator during the Carboniferous and Permian. The first results from western Borneo of Mesozoic (?) volcanics seem to confirm that this represents the extension of the Malayan geosyncline.

1.7 Mesozoic of Western Australia and Kangaroo Island (P. Schmidt, B.J.J. Embleton)

An important problem in Australian palaeomagnetism is the non-agreement of Australian Mesozoic palaeomagnetic poles when compared with the rest of Gondwanaland in its reconstructed position. Since all Mesozoic results are restricted to a narrow belt along the coast of eastern Australia, a project is in progress to see if these refer to the rest of Australia. Late Palaeozoic and Mesozoic sediments have been collected from the Perth and Collie Basins, and volcanics from Bunbury (Bunbury basalt) and Kangaroo Island. Work is still in progress.

1.8 Lord Howe Island (B.J.J. Embleton, I. McDougall)

About forty lava flows collected from a 3,000 feet section on the south of Lord Howe Island have revealed that no field reversals occurred during their extrusion. Furthermore, the palaeomagnetic directions are very tightly grouped again suggesting the period of extrusion was very short. K-Ar work is in progress to confirm this. The work appears to confirm the studies on Norfolk Island, which showed that the observation of low dispersion in palaeosecular variation studies might be related to the rapid building of volcanoes so that only a very short time span is involved.

1.9 Society Islands (B. Duncan, I. McDougall)

Over sixty lava flows have been collected from the islands of Tahiti, Bora Bora, Raiatea, Huahine and Moorea in the Society Island chain. K-Ar ages show a progression down the chain as has been observed in other island chains such as the Hawaiian islands. The palaeomagnetic data will be analysed in terms of palaeosecular variation in order to investigate whether the Pacific secular variation is low in its southern region.

1.10 Archaeogmagnetic studies (M. Barbetti, M.W. McElhinny)

Work on the first archaeomagnetic study in Australia was completed during the year. The project has revealed a number of interesting features of the most recent variations in the geomagnetic field. Variations for the past 2,000 years seem to confirm the overall trend of northern hemisphere data that the world wide field variations can be approximated to a wobbling motion of a centred dipole. Data for the period 25,000 to 30,000 years ago have confirmed the existence of a geomagnetic excursion with departures up to 120° from the field. The time scale of these excursions is about 1,000 to 2,000 years. However, the most startling observation is the fact that the field strength increases by nearly an order of magnitude during this time interval. This cannot reasonably be attributed to the sudden increase in the moment of the earth's centred dipole, and must be the effect of an event at the core-mantle interface beneath the Australasian region.

Further work on field variations over the past 50,000 years in Australia is planned through studies of lake sediments due to begin shortly.

1.11 Rock Magnetic Studies (M.W. McElhinny, J.W. Giddings)

Alternating field demagnetization characteristics of the Precambrian dyke swarms show a wide range of stability. Often it is difficult to determine the best cleaning field because of lack of a clear end point to the cleaning process. The stability index of Briden assists to some extent, but it is clear that this index is misnamed and should be termed an optimum cleaning index. When this index is multiplied by a new index (the coercive force index) that describes the range of coercive forces over which the directional properties are stable, a new stability index is defined. Studies of low temperature recovery phenomena and the use of the Lowrie-Fuller single-multidomain test show that the properties of these rocks are directly related to the predominance of single or multidomain magnetic grains. The margin between stable and unstable rocks seems to occur when the contributions of multi-domain and single-domain remanence are about equal.

1.12 Geomagnetic field characteristics (M.W. McElhinny, B.J.J. Embleton)

A world wide synthesis of Late Tertiary and Quaternary palaeomagnetic results has revealed that the offset dipole model of the geomagnetic field is very much a reality. Results cannot be explained away in terms of northward drifting continents. It is shown that the amount of offset has decreased during the past 25 million years until over the past 2 m.y. it is not significantly different from zero.

A synthesis of Cenozoic palaeomagnetic results from Australia shows there are many more intermediate directions of magnetization observed in mid-Tertiary lavas than one would expect from the reversal frequency deduced from magnetic anomaly profiles at sea. This suggests that there are more short events in this time range than has been suspected previously.

2. GEOMAGNETISM

2.1 Theoretical (F.E.M. Lilley, D.J. Bennett)

The phenomenon of electromagnetic induction in the earth depends greatly on whether the geologic structure is one, two or three dimensional, and it should be possible to thus classify local geologic structure from appropriate geomagnetic observations. A major problem investigated this year has been the definition of the most basic form to which geomagnetic observations can be reduced, and a "geomagnetic induction tensor" for each observing site has been proposed as meeting this requirement. The general geomagnetic induction tensor has then been examined exhaustively to determine what special characteristics it has under conditions of one, two and three dimensional geologic structure; and various ways of diagrammatically depicting such a tensor have been explored. One effective way appears to be in terms of two ellipses and two arrows, which can be drawn all together for the observing site in question on a map. This work has naturally led into the problem of determining the actual values of the tensor elements given real geomagnetic array data, and in particular estimating the errors in such values. This is a considerable problem in time-series analysis, and will be addressed in the future.

2.2 Instrumental (F.E.M. Lilley, G.W. Boyd)

The year 1973 has seen the final assembly and commissioning of the Research School's array of 21 protable magnetic variometers of the Gough-Reitzel design. (A planned set of 20 instruments with a full set of spare parts gradually became a set of 21 instruments with a less-full set of spare parts). This has involved attention to a host of technical and scientific design problems, not only in the development of the instruments themselves but also in the development of the peripheral equipment necessary for their efficient installation and operation.

Early prototypes were tested at the Black Mountain Laboratory, and installed in a hole by Lake Burley Griffin. By July the construction of all instruments was finished, and a field-test of the complete array was commenced at Toolangi Victoria, within 100 yards of the permanent magnetic observatory of the Bureau of Mineral Resources. The operation of 21 recording magnetometers all within the same paddock is perhaps a unique event in the history of geophysics,

(the few other owners of magnetometer arrays are not understood to have ever tested all their instruments together). The Toolangi tests continued until October, and very thoroughly proved the sensitivity of the instruments, the linearity of their response, and the accuracy of their calibration process. The data is still under examination, but it appears that the instruments are more sensitive than had been expected, with magnetic variations in all three H, D and Z components being readable to perhaps better than 1 nanoTesla, (1 nanoTesla = 1 gamma).

Of the very many design problems which had initially been faced, by the end of the Toolangi tests only a few minor ones remained, and the reliability and performance of the instruments is a considerable credit to the skilled workshop staff who made them.

2.3 Experimental (F.E.M. Lilley, G.W. Boyd)

The first field experiment with the new array of variometers commenced in October, with the installation of the instruments at 21 sites across southern Victoria, northern Tasmania, Flinders Island, Cape Barren Island and King Island in the Bass Strait. The sites were chosen to augment the information from the 1971 array operation, (which took place, with instruments on loan from Canada, across Victoria and southern N.S.W.). Particular objectives of the present array operation are the better delineation of the anomalous effects suspected from the 1971 operation in western Victoria, and the mapping of the southern part of a curious effect suspected in the region of the Bass Strait. The instruments are expected to be retrieved from their present sites in early 1974.

3. SEISMOLOGY

3.1 Velocity-density systematics within the Earth from free oscillation data

It is generally assumed that the bulk sound velocities of the rocks and minerals which constitute the Earth are linearly related to their densities and mean atomic weights. From analyses of velocity and density models obtained from inversions of free oscillation data, several workers have inferred a change in mean atomic weight between the transition zone and lower mantle. This conclusion has been disputed by Wang, who claims that the gross Earth data are compatible with a mantle of constant atomic weight.

Extremal models derived from a linear programming inversion of recently published free oscillation data confirm the presence of an offset in the bulk sound velocity vs. density profile corresponding to the depth range 600 to 1000 km. It has been shown that the Wang model also implies an offset in this region. However, on the basis of recent data of Liebermann and Ringwood concerning velocity derivatives with respect to pressure and temperature for various substances and the velocity-density systematics of materials undergoing polymorphic phase transitions, it appears that an interpretation of these results in terms of a change in mean atomic weight within the mantle may be premature.

3.2 Torsional free oscillations of the Earth

Current Monte Carlo and linear programming methods for the inversion of free oscillation data require linear approximations for the rapid calculation of eigenfrequencies from gross Earth models, and these approximations necessarily result in distortions of the derived uncertainty bounds. Methods are being investigated for fast determination of torsional eigenfrequencies without using linear approximations in the expectation that these may be used as a "first filter" in the selection of acceptable models.

The asymptotic structure of torsional eigenfrequencies is also being studied as a source of information about the shear velocities in the mantle and the radius of the core.

3.3 Seismic wave scattering

The hypothesis of scattering of PKP waves near the core-mantle boundary provides a comprehensive interpretation of features associated with the observed precursors to PK1KP, including the variation with distance of the times and slownesses of precursor onsets and the variations in amplitude,

azimuth and slowness of the precursor wave-trains. Previous observations have been supplemented by computer analysis of precursors recorded at the Warramunga seismic array, and the results indicate that observable scattering of the PKP waves occurs both before entry into and after exit from the core. The amplitudes and slownesses of the precursors can be theoretically accounted for by random variations of about one percent in density and elastic parameters in a layer 200km thick at the base of the mantle.

Analysis of Warramunga array records has also shown that the slownesses along the wave train between P and PP are consistent with a hypothesis of scattering in the crust and upper mantle. In addition to the features listed in the previous report, this hypothesis also accounts for the existence of some of the precursors to PKPPKP.

3.4 The D" region

Two very different types of models are currently being proposed for the lowest region of the Earth's mantle: (a) those in which P and S velocities increase uniformly to the core-mantle boundary, without any extreme change in gradien (b) those in which the velocity gradients decrease fairly abruptly at a height of 100km or so above the core-mantle boundary, and maintain a value close to the critical gradient down to the boundary. At present the free oscillation data are unable to distinguish between the two types of models, and it has been suggested that travel-time data which appear to support models of type (b) can be accounted for by invoking distortion phenomena at the core-mantle boundary.

On the other hand, slowness and amplitude data from short period P waves indicate a fairly rapid decrease in velocity gradient at a depth corresponding to an epicentral distance of about 92°, and it is very unlikely that these data can be interpreted as interface phenomena. The measured P and S times at distances beyond about 96° also indicate reduced velocities in D". The suggestion that the measured velocities are in error as a result of interface effects is weakened by the fact that the results are apparently not wavelength-dependent.

3.5 Seismicity and tectonics

Application of a master earthquake relocation procedure to a wide range of tectonic problems are being explored. In a study already completed, relocations of the larger reservoir-related earthquakes show that most of this activity is at mid-crustal depths, and thus is difficult to explain as a direct consequence of loading stress. Standard relocation

techniques based on a mean velocity structure have three to four times less resolving power than the master earthquake technique used by us. The technique has also successfully revealed features of the 1973 Picton earthquake aftershock sequence that would otherwise be undetected. For example, aftershocks within 4 hours of the main shock define a trend that may correspond to the strike of a buried fault. Central Asian earthquakes are also being relocated in the hope of identifying active faults. Trends shown by active and geologically recognizable faults in conjunction with focal mechanism studies will allow more meaningful comparisons between tectonics in oceanic and continental regions. The relocation technique is being refined for studies of mantle seismic zones. In particular, earthquakes at depths of 600 to 700km beneath the basin separating the New Hebrides and Tonga arcs are being relocated. It is hoped that a more detailed configuration of this seismic zone will provide clues to the generating mechanism of deep shocks.

3.6 Reservoir filling

Further field work was carried out this year on the Talbingo dam earthquakes. Nine portable instruments were placed around the reservoir for a period of six weeks. During this time, two small explosions were fired in the reservoir. These established the local crustal velocities and verified that the seismic events were taking place at shallow depths along the northern edge of the lake and in the vicinity of the dam and power station. Although seismic activity is still taking place around the reservoir it is now at a very much reduced level.

3.7 Crustal studies

Towards the end of 1973 a crustal seismic experiment was carried out in East Papua in conjunction with the Bureau of Mineral Resources. Nine portable instruments were installed and operated for seven weeks at various sites in East Papua to record the 113 shots exploded in the sea along the northern and southem coasts of East Papua.

3.8 Instrumentation

A new portable three component instrument has been designed for the study of shear wave velocities in the upper mantle. Eleven of these instruments are at present in construction and are expected to be completed in the first quarter of 1974. Considerably reduced power consumption, larger tape reels and improved mechanical construction will allow these instruments to record unattended for periods up to three months.

4. GEOTHERMY

4.1 Australia-wide survey (J.C. Jaeger, J.H. Sass)

The collaborative project between the A.N.U. and the U.S. Geological Survey to upgrade the knowledge of heat flow in Australia has reached the stage where a major paper is now in preparation reporting on the many heat flow measurements made in 1971 and 1972. During 1973 further suitable holes continued to be logged for temperature as they became available, and some holes were re-logged to check for stability after drilling. One hole in an important position in South Australia was deepened and then re-logged. The interpretation of all data obtained over the last few years should be completed in 1974.

4.2 Particular local problems (F.E.M. Lilley, G.W. Boyd)

With the commissioning of the Research School's new array of magnetic variometers, and the first field operation with them in 1973, a new phase in heat flow studies has been commenced which seeks detailed knowledge of the heat flow in areas under study by magnetometer array. The physical connection between the two different geophysical phenomena of electromagnetic induction and heat flow occurs through the strong dependence of rock electrical conductivity on temperature.

New personnel have recently become involved in this project, and a start has been made with the logging of three holes in south-west Victoria. These show thermal gradients as high as $44^{\circ}C\ km^{-1}$, and when core samples have been measured for thermal conductivity they appear likely to augment the other known high heat flow values in the area.

5. ROCK DEFORMATION

5.1 Quartz (D.J. Morrison-Smith, M.S. Paterson)

Infra-red measurements have confirmed that heterogeneous deformation in synthetic quartz crystals is correlated with non-uniformity in OH content, which is not homogenized even at 900°C. However, raising the temperature does have a strong influence on the nature of the deformation, as reflected in the dislocation structures. Electron microscope studies show an increasing tendency for tangled arrays of disclocations to develop at higher temperatures, while recovery processes are also indicated above 600°C. Many slip systems have been identified. These advances in our knowledge of the fundamental deformation processes in quartz are especially important in structural geology because of the widespread occurrence of deformed quartz-rich rocks.

5.2 Olivine (M.S. Paterson)

Preliminary deformation experiments have been done on specimens of synthetic forsterite at 1000° and 1200°C at 3kb confining pressure. This project has involved considerable modification of the high temperature, high pressure deformation apparatus, which can now use smaller specimens as well as reach the higher temperatures. It is planned to continue with a detailed study of the constant strain rate and creep behaviour of the forsterite and to make electron microscope observations on the dislocation structures. It is hoped thereby to contribute significantly to our understanding of flow processes in upper mantle rocks.

5.3 Nickel sulphide ore and associated rocks (J.A. MacDonald, M.S.Paterson)

Massive sulphide units within deformed rock sequences commonly show features suggesting movement relative to the enclosing rocks or representing the general effects of deformation. The Lunnon Shoot, Kambalda, is a relatively simple, well-documented case in which the rocks show abundant evidence of response to directional stress and in which the relatively low grade of regional metamorphism, namely upper greenschist facies, permits recognition of the primary rock types; also the massive sulphides can be closely described by reference to the Cu-Fe-Ni-S system, a well-known complex sulphide system. Therefore a study has been initiated to determine the relationship between the behaviour of the massive sulphide and that of the enclosing rocks of the Lunnon Shoot, and to determine the textural, chemical and mineralogical changes induced as a function of temperature and strain rate.

A number of measurements have been made on gold-jacketed massive ore and matrix ore samples (approximately 50% sulphides and 50% talc plus carbonate) at 3 kilobars confining pressure and temperatures from room temperature to 900°C, and at strain rates of 10^{-4} and 10^{-5} sec^{-1}.

Massive ore is much weaker than matrix ore under all conditions tested. Twinning is conspicuous in pyrrhotite at the lower temperatures, while there is extensive recrystallization of the sulphides at higher temperatures, especially in grains that were originally pentlandite and which remain texturally distinguishable from the original pyrrhotite grains although the pentlandite stability limit (ca. 325°C) is exceeded. Electron microprobe measurements show that, although conversion of pentlandite to a monosulphide-like phase proceeds above 300°C, chemical equilibrium between grains formerly consisting of pentlandite and pyrrhotite is not attained under these experimental conditions until about 700°C, and even then textural difference persists. Deformation experiments have also been begun on the talc-carbonate rock associated with the orebody.

5.4 Theoretical Fabric Studies (G.S. Lister, M.S. Paterson, B.E. Hobbs)

The crystallographic preferred orientations to be expected from the homogeneous plastic deformation of polycrystalline aggregates of quartz, face-centred cubic metals, galena and sphalerite can now be calculated on the Taylor-Bishop-Hill model taking into account known possible slip systems. As the relative strength of the various slip systems is varied, transitions in the type of predicted fabric pattern occur. The fabrics resulting from various strain paths, both coaxial and non-coaxial, have also been calculated. As a result, nearly all the observed types of quartz fabric can be simulated, including some reported as having arisen from recrystallization. In some cases the fabric type has proved to be surprisingly sensitive to relatively small changes in the assumed relative resistances to slip on different systems. This type of analysis may therefore have important application in determining the environmental regime of past deformations, although further work is needed on the influence of factors such as heterogeneity of strain, climb of dislocations, and Dauphiné twinning; the effect of the latter is already being examined.

In the course of this work, a method has been developed for contouring on the surface of a sphere, using picture processing methods to represent the results.

5.5 Studies pertaining to earthquake mechanisms (M.S.Paterson, T. Fitch)

Preliminary experiments have been done on two aspects of mechanical behaviour in rocks that have been considered of possible relevance in understanding earthquake mechanisms, namely, stick-slip at sliding rock interfaces and the interaction of dilatancy, pore pressure and stability of sliding. In relation to the first topic, considerable efforts have been made to devise an arrangement for sliding on an interface parallel to the axis of differential loading in the pressure vessel, in order to avoid the disadvantages of developing eccentricity of loading and severe restriction in distance of sliding inherent in obliquely-cut specimens and to facilitate experiments at elevated temparatures. However, little success has so far been achieved.

The other experimental project aims to make simultaneous measurements of strain, dilatancy and longitudinal and shear wave velocities on stressed rock specimens subjected to high temperature, pressure and pore pressure. This should contribute fundamental data for testing the Nur, Scholz et al. hypotheses on the mechanism of earthquakes. A start has been made on adapting acoustic techniques for this purpose, with the collaboration of the Mineral Physics group, and on building the necessary auxiliary devices for the high temperature, high pressure deformation apparatus.

5.6 Room temperature rock mechanics (J.C. Jaeger N.C. Gay, M.S. Paterson)

As part of a programme of work on the deformation of granular media, experiments have been done on the formation of Riedel and thrust shears in shear zones, the deformation of conglomerates and the formation of boudinage. Measurements have also been made on volume changes in kinking using a dilatometer developed in earlier work.

6. MINERAL PHYSICS

6.1 Elastic properties of minerals synthesized at high pressures and temperatures (R.C. Liebermann, A.E.Ringwood)

Polycrystalline aggregates of low- and high-pressure polymorphs of various oxides, silicates, germanates and titanates have been hot-pressed at temperatures $T \leq 1200^{o}C$ and pressures $P \leq 70$ kbar. These specimens are less than 3% porous, less than 100 micron grain size, and are elastically isotropic. Compressional (v_p) and shear (v_s) velocities of the recovered specimens are determined as a function of pressure to 10 kbar at room temperature by the ultrasonic pulse superposition or pulse transmission techniques. These data combined with the X-ray density enable a complete characterization of the isotropic elasticity of these minerals.

Considerable effort in solid-state geophysics has been devoted to the search for systematic relationships between the elastic properties and the crystallographic structure and composition for oxides and silicates. Many of the empirical laws proposed imply a unique dependence of elastic wave velocity v on density ρ for materials of common mean atomic weight $\bar{M}$, irrespective of whether the density changes are due to variations in crystallographic structure, pressure or temperature.

Implicit in all of these geophysical discussions has been the assumption that the velocity-density laws are immutable to pressure, temperature, and crystallographic phase at constant $\bar{M}$; and, therefore, that any deviation from such laws observed in the Earth may be ascribed to changes in chemical composition (specifically, the iron content or FeO/(FeO+MgO) molecular ratio). In particular, it has often been assumed that these laws adequately described changes in velocity and density across polymorphic phase transformations. New data from the ANU have been presented for the olivine-spinel, olivine-beta phase, pyroxene-garnet, quartz-rutile, pyroxene-ilmenite, ilmenite-perovskite, and felspar-hollandite phase transformations. These data indicate that v-ρ relationships across such polymorphic transformations are not always equivalent to v-ρ changes caused by varying pressure, temperature, or composition at constant mean atomic weight. For the Earth, these data imply that previous discussions of the composition (specifically the iron content) of the upper and lower mantle based on v-ρ systematics may have to be re-evaluated.

These new velocity data for polymorphic phase transformations thought to be relevant to discussions of the Earth's interior enable examinations of velocity and density discontinuities in Earth models. In particular, the phase

transformation of olivine (α) to the spinel (γ) or β phase structures is now widely accepted as the cause of the velocity and density discontinuities observed in the Earth's mantle in the neighborhood of 400km depth. A comparative study indicates that the B1 and UTD Earth models are not consistent with the experimental elasticity data for the α-γ and α-β phase transformations in germanate and silicate compounds; this conclusion is based on the relationships of the density jumps to the velocity jumps and especially on the change of the v_p/v_s ratio across the 400km discontinuity in the Earth and the transformations in the laboratory. Alternatively, these laboratory data could provide useful constraints in future attempts to derive Earth models from inversion of gross Earth geophysical data.

6.2 Fluoride and oxide model systems (Ms Jones, I.N.S.Jackson, R. Liebermann)

Crystal chemical similarities between the fluorine and oxygen ions have led to the suggestion that fluorides and fluoroberyllates may be "weakened" models of oxides and silicates and thus reflect high-temperature behavior at lower absolute temperatures. This proposition is currently being employed to study the fluorides as models for the high-temperature elasticity of their oxide analogues. The limited data in the literature indicate that the fluorides exhibit "high-temperature" elastic behaviour at lower temperatures (by $\approx$ 100°K) than their oxide analogues.

6.3 Melting of solids at high pressures (I.N.S. Jackson, R.C. Liebermann, A.E.Ringwood)

Goldschmidt's suggestion of fluoride-oxide modelling has also been used to study the melting of solids at elevated pressures by DTA methods. Investigations are directed towards crystallographic structures of importance in models of the Earth's mantle: e.g., rocksalt, rutile, perovskite, strontium plumbate, spinel.

Studies are also directed towards the relationship of elastic shear instabilities to the melting of solids under pressure. Ultrasonic data for the elastic moduli c_{ij} as a function of pressure and temperature are used to calculate critical temperatures $T_{cr}(P=0)$ tne their initial pressure derivatives $(\partial T_{cr}/\partial P)_{P=0}$ for the elastic stability of the alkali halides with the rocksalt and CsCl structures. The stability criteria used for the two structures are $c'=\frac{1}{2}(c_{11}-c_{12}) = 0$ and $c_{44}=0$, respectively. These parameters of the critical curves exhibit remarkable correlations with corresponding parameters of the observed melting curves, $T_m(P=0)$ and $(\partial T_m/\partial P)_{P=0}$, offering strong support to the existence of a connexion between shear instability and melting postulated by previous investigators.

Comparison of the critical and melting curves for LiF, NaF, and KF with those for MgO, CaO and SrO suggests that fluorides which have been proposed as weakened crystal-chemical models for oxides may also be important models for the high P, high T melting behavior of their oxide analogues.

6.4 Dilatancy and earthquake prediction (I.N.S. Jackson, R.C. Liebermann, T.J.Fitch)

An interdisciplinary program has been started with the rock mechanics group to study velocity anomalies in rocks undergoing dilatancy during triaxial deformation at high temperatures. These studies have an important bearing on premonitory effects prior to large shallow earthquakes.

6.5 Diamond-anvil laboratory

A new laboratory has been established to study phase transformations, static compression and melting of materials in situ at high pressure utilizing X-ray diffraction methods in diamond-anvil systems.

7. EXPERIMENTAL PETROLOGY

7.1 Phase transformations at ultra-high pressures

(A.E. Ringwood)

Transformations of the mineral "thortveitite" ($Sc_2Si_2O_7$) and also $Y_2Si_2O_7$ into new, dense polymorphs possessing the pyrochlore structure were achieved at pressures exceeding 100,000 atmospheres. These transformations are of particular interest since they involve a change of coordination of silicon from fourfold to sixfold. Related transformations caused by this change of silicon coordination are believed to occur in the mantle at a depth of about 700km and to be responsible for the occurrence of a major seismic discontinuity. Crystallographic studies of these transformations continue in association with CSIRO (Mineral Chemistry Division).

A new member of the perovskite family of structures, $ScAlO_3$, was also synthesized at very high pressures. This phase is significant since it possesses by far the smallest unit cell volume of any known perovskite isomorph. The demonstration that relatively small cations such as Sc^{3} and Al^{3} can form perovskites under high pressure suggests that the phases $MgSiO_3$ and $FeSiO_3$ (Mg and Fe having similar radii to Sc, likewise Si to Al) may be capable of crystallizing in the perovskite structure in the deep mantle. This possibility is further supported by an analysis of shock wave data on $MgSiO_3$ and by the previous syntheses in our laboratory of $CaSiO_3$ perovskite. If $MgSiO_3$ and $FeSiO_3$ indeed adopt this structure, it would be of considerable significance to the constitution of the deep mantle, since the perovskite structure is one of the most closely packed oxide structures known and possesses some interesting physical and thermodynamic properties. A detailed crystallographic study of $ScAlO_3$ is in progress (in association with CSIRO, Mineral Chemistry Division).

7.2 Melting of upper mantle peridotite (D.H. Green)

The systematic study of the melting behaviour of pyrolite model upper mantle composition has continued with emphasis on the determination of melting behaviour with varying water-content(6%, 1.4%, 0.2%), ranging from water saturated to water-undersaturated conditions. The delineation of the stability fields of olivine, pyroxenes, garnet, amphibole, phlogopite and ilmenite establishes major boundary constraints which must be satisfied by models of magma genesis postulating conditions of partial melting, source rock composition and residual mineralogy for given magmas. In these studies the recognition of a stability field for the mineral titano-clinohumite at 30-40kb, 900-1050°C, may prove to have important petrogenetic implications. The determination of the water-saturated solidus for pyrolite composition places an important constraint on the minimum melting temperatures for the pyrolite model mantle and has been very carefully checked using the determination of amphibole composition change at the solidus. Melting begins at 985±10°C at 10kb, 960°±10°C at 20kb and 1035°+10°C at 30kb.

7.3 Compositions of glasses and liquids formed in experimental melting of pyrolite. (D.H. Green)

Further studies of quenched partial melting runs on water-saturated pyrolite at pressures >10kb have confirmed the non-equilibrium character of quenched glasses and demonstrated the rapid growth, during quenching, of zoned rims on primary phases and of quench phases such as amphibole and mica. It has been possible to use some experimental data to calculate equilibrium liquid compositions from known mineral composition, bulk composition and crystal/liquid partition relationships. To check the validity of this approach, bulk compositions matching the calculated composition have been prepared and run at the appropriate P,T conditions to establish that these liquids have the correct liquidus temperature and liquidus phases. The approach confirmed that at 10kb, 30-35% melting of pyrolite under water-saturated conditions, produces Mg-rich quartz tholeiite liquid (1100-1200°C) passing to olivine tholeiite at higher temperature. At 20kb, ~1100°C liquids are of olivine tholeiite character with ~30% melting but become increasingly undersaturated at lower temperatures, with lower degrees of melting.

7.4 Genesis of highly undersaturated magmas (G. Brey, D.H. Green)

Reconnaissance melting studies as functions of P,T, and water-content have been carried out on an olivine melilitite from central Tasmania and on an olivine leucitite from Buell Park, Arizona. The olivine melilitite has 38% SiO_2 and is thus the lowest SiO_2 magma yet studied in an attempt to determine conditions of origin. The

melilitite contains lherzolite inclusions of mantle origin and is sufficiently Mg-rich to have been in equilibrium with olivine ($\sim Fo_{89}$) of the upper mantle. The reconnaissance studies have shown that olivine persists as the liquidus phase to pressures of >35kb but that clinopyroxene and garnet are near liquidus phases at 35-40kb. Orthopyroxene has not been observed at any pressure on or near the liquidus and current experiments are underway to evaluate the role of CO_2 in affecting liquidus temperature and phases. In the olivine leucitite composition, olivine, clinopyroxene and phlogopite are liquidus or near-liquidus phases over a range of P,T and water contents. The reconnaissance study is consistent with hypotheses that such olivine leucitite magmas originate by partial melting of local phlogopite bearing wehrlite rather than garnet peridotite.

7.5 Mg/Fe partition between garnet and clinopyroxene as a geothermometer and geobarometer. (A. Råheim, D.H. Green)

In natural eclogites coexisting garnet and clinopyroxene demonstrate a wide range of the distribution coefficient

$$K_D = \frac{(Fe/Mg)_{ga}}{(Fe/Mg)_{cpx}}$$

from values of >50 to values of <2. Those eclogites with lower K_D values have formed at higher temperatures but no calibration of this potential geothermometer has hitherto been available. An experimental study has yielded high quality data showing the variation of K_D as a function of temperature from 600°C to 1400°C at 30kb, as a function of pressure from 20kb to 40 kb at 1100°C and as a function of Mg/Mg+Fe$_{total\ rock}$ from .05 to .95 in a natural basaltic composition. It has been shown that for $.05 < Mg/Mg+Fe_{t/rock} < .85$ the bulkchemical composition does not perceptibly affect the K_D value. At 30kb, the K_D value ranges from ~18.0 at 600°C to 1.45 at 1400°C defining the linear relationship $\ln K_D = 4639/T(°K) - 2.418$ (P=30kb). The pressure dependence of the K_D value has been shown to be greater than previously predicted. The data establish the validity of the experimental and microprobe method of calibrating P,T sensitive mineral equilibria to provide pressure, temperature determinants applicable with little or no extrapolation to natural mineral assemblages. Applying the calibration data to natural rocks shows that some eclogites in blueschist terranes have formed at 300°C, other eclogites from diamond pipes have formed at 1000°C.

7.6 Chemical compositions of coexisting olivine, ortho- and clinopyroxenes and garnet as a function of pressure and temperature. (T. Mori, D.H. Green)

The extent of solid solutions of coexisting olivine, ortho- and clinopyroxenes and garnet are stongly

temperature and pressure dependent. In other words, the partitioning of elements among these phases is a function of temperature and pressure.

The compositions of the four phases in pyrolite and natural garnet lherzolite compositions have been determined at 30 and 40 kb between 800 and 1500°C. Results show a remarkable P-T dependence. The pyroxene miscibility gap widens with decreasing temperature and the Al_2O_3 contents of two pyroxenes are directly proportional to temperature and inversely proportional to pressure. The grossular component in garnet is proportional to temperature and inversely proportional to pressure.

In addition, relationships between distribution coefficients and temperature were obtained, especially for Fe-Mg partition among ortho- and clinopyroxenes and garnet.

As the pressure dependence of the pyroxene miscibility gap is not yet well defined for the complex character of the pyrolite bulk composition, experiments were also done on the $MgSiO_3$-$CaMgSi_2O_6$ simple system at 1200°C from 5 to 40 kb. In contrast to prior evidence and assumptions in the literature on the pyroxene miscibility gap, i.e. that there is little pressure dependence, the data obtained show a distinct pressure dependence, e.g. neglect of 30kb pressure difference causes an error of temperature estimation of about 150°C.

7.7 Silicate chemistry laboratory

The analytical activities of the silicate chemistry laboratory have largely been integrated on complementary basis with the program of X-ray fluorescence and electron microprobe laboratories. Approximately 200 rock analysis for ferrous-iron, alkalies, water and carbon dioxide and loss-on-ignition were carried out. In addition, 50 rocks and minerals were analysed for nickel, cobalt, chromium and vanadium, also spectrophotometric microdeterminations of iron oxidation state were made for experimental petrology samples.

In the area of analytical developments, a series of new reagents were prepared, tested and the data published for the spectrophotometric determination of cobalt with a tenfold increase in sensitivity over current reagents. Selective spectrophotometric determination of traces of vanadium was also developed and a method is available for routine analysis. Another area of developmental work concerned further reduction in sample requirements for micro-iron analysis. The established reagent systems require approximately 5 mg sample per analysis, whereas a

more sensitive reagent assessed and used throughout the year requires only 2.5-3 mg sample. Another iron reagent was synthesized and thoroughly evaluated with most promising results. Being one of the most sensitive reagents of its kind, less than 1 mg samples can be analysed on a routine basis. The reagent is unavailable commercially but a substantial amount was secured through a complex series of syntheses. The results are being prepared for publication.

7.8 Liquids in equilibrium with peridotitic mineral assemblages at high water pressures (I.A. Nicholls)

The suggestion, based on crystallization experiments on natural basaltic andesites (Annual Report, 1972) that andesitic liquid compositions may be derived directly by melting of hydrous peridotite only at pressures <10kb, and temperatures <1000°C, has been tested by detailed examination of the assemblage obtained in an experimental run on pyrolite at 5kb ($P_{H_2O} = P_{Total}$), 1050°C. The water-saturated liquidus temperature of "andesitic" glass (~60% SiO_2, 20% normative quartz) in this run lies 80°C below the liquidus temperature (1050°C) required for equilibrium liquid compositions. This glass was apparently produced from a more mafic equilibrium liquid by the outgrowth of primary olivine and clinopyroxene during quenching of the run. The true equilibrium liquid composition was therefore estimated by the addition of olivine and clinopyroxene to a synthetic equivalent of the glass until a composition with liquidus close to 1050°C was obtained. This composition was of magnesian basaltic andesite to andesite type (58% SiO_2, 10% normative quartz).

Further investigations, aimed at determination of the most silicic, liquids capable of equilibrium with olivine at 5-15kb ($P_{H_2O} = P_{Total}$), 1000°C, made use of an olivine-addition technique. Reaction relationships between olivine and water-saturated andesitic liquids (56-60% SiO_2, 3-20% normative quartz) were made to proceed to completion by the addition of synthetic olivine (Fo_{85}) to equivalent glasses at a constant temperature of 1000°C, until olivine persisted. The nature of the liquids produced was studied by electron microprobe analysis of their quench products, chiefly glass and sheet silicate, followed by testing for equilibrium between the compositions obtained and coexisting primary crystals. Possible equilibrium compositions were derived using mass balance calculations, experimentally derived partition coefficients for olivine-liquid equilibrium (see below) and tests for correspondence between the liquidus temperatures and liquidus phases of these compositions and the temperature (1000°C) and crystalline phase assemblage of the original olivine-addition runs. The preferred compositions were "andesitic" (58-60% SiO_2, 3-14% normative quartz) at 5 and 10kb, 1000°C. However, at 15 kb a more alkaline, olivine-normative composition was obtained. These results therefore

reinforce earlier conclusions that strongly quartz-normative liquids may be produced by the melting of hydrous peridotitic compositions only at relatively low pressures (<10kb) and temperatures (<1000°C).

7.9 Partitioning of Fe and Mg between coexisting olivine and quartz-normative liquid at high water pressures

(I.A. Nicholls)

The partition coefficient $K_D = (X_{Fe^{2+}}/X_{mg})_{Olivine}/(X_{Fe^{2+}}/X_{Mg})_{Liquid}$ for equilibrium between olivine and quartz tholeiite to andesite liquids under conditions of P_{Total} = 2-10kb T = 1000°-1200°C and water-saturated and water undersaturated conditions (2-15% H_2O) has been determined by microprobe analysis of experimental olivine/glass pairs. For the range of liquids studied, and the conditions imposed, the value of K_D appears to be almost independent of P_{Total}, T, X_{H_2O} and (X_{Fe}/X_{Mg}) for olivine and liquid, and averages 0.4. This value is to be compared with that (K_D = 0.3) previously published for equilibrium between olivine and olivine tholeiite liquids for P_{Total} = 1 atm., T = 1100°-1300°C and anhydrous conditions. The application of the revised partition coefficient indicates that liquid produced directly by partial melting of peridotitic mantle are more magnesian than previously thought, and underlines the observation that natural andesites are too iron-rich to have equilibrated with olivine of compositions (Fo_{86-94}) typical of peridotitic materials.

7.10 Chemical and experimental study of lavas from Indonesia

(I.A. Nicholls, D. Whitford)

Major element analysis of lavas from West and Central Java has been continued, chiefly by electron microprobe analysis of glasses prepared on an iridium-strip heater (see below). New results confirm the spatial variation previously observed for Pleistocene to Recent lavas, i.e. tholeiitic compositions (low K_2O/SiO_2) nearest the Java trench, ranging to high-K andesitic to shoshonitic compositions (high K_2O/SiO_2, $K_2O/Na_2O \sim 1$) nearest the Java Sea coast. Basalts to basaltic andesites from the (?) Miocene "Old Andesite Formation" of Central Java and Bali are thought to represent early volcanic products of the present day Sunda island arc system. However, they are considerably more potassic than lavas from the early stages of evolution of other island arcs of the south-western Pacific. Trace-element investigation of both Miocene and Pleistocene - Recent lavas is continuing (see, Trace element geochemistry).

Experimental crystallization of an olivine leucitite from the Pleistocene volcano Muriah, on the northern coast of Java, has commenced. The water-saturated liquidus lies at ~1100° within the pressure range 5-30kb. Olivine and

clinopyroxene are the near-liquidus phases at 5kb, but only clinopyroxene and phlogopite appear at higher pressures. This composition is therefore unlikely to represent a product of water-saturated melting of a pyrolite upper mantle.

7.11 Partitioning of rare earth elements between garnet, clinopyroxene, amphibole and coexisting liquids at high pressures and high water pressures.

(K. Harris, I.A. Nicholls)

Four similar andesite glasses, each containing 1000 ppm of a different rare element (La, Sm, Ho, Yb) have been experimentally crystallized at pressures of up to 30kb, under anhydrous conditions and with 10% added water. The concentrations of the rare earth elements in garnet, clinopyroxene or amphibole and coexisting glass in these charges has been determined by electron probe microanalyser, and diagrams illustrating the variation of partition coefficients (concentration of element in crystalline phase/concentration of element in liquid) for the four elements constructed.

Under hydrous conditions, partition coefficients for equilibrium between garnet and andesitic liquid range from ~0.01 for La, through 1.3 for Sm and >35 for Ho to >25 for Yb. Clinopyroxene and amphibole also concentrate the heavier rare earth elements, but partition coefficients are much smaller, reaching maxima of 1.2 for Ho in clinopyroxene, and 3.3 for Ho in amphibole.

In spite of a very pronounced difference in the relevant clinopyroxene compositions, partition coefficients for clinopyroxene/anhydrous andesite liquid equilibrium are similar to those obtained for hydrous conditions. However, partition coefficients for garnet/andesite liquid are significantly smaller under anhydrous conditions (and hence higher temperatures).

Application of the experimental partition coefficients to the estimation of rare earth abundance patterns of liquids produced by partial melting of peridotitic and eclogitic mineral assemblages is in progress. A study of the partitioning of the same four rare earth elements between garnet, clinopyroxene, amphibole and a liquid of oceanic tholeiite type has commenced.

7.12 Oxygen fugacities prevailing during experimental runs in the piston-cylinder high pressure apparatus.

(I.A. Nicholls)

Experimental charges of quartz tholeiite to basaltic andesite composition, enclosed in Ag-Pd alloy capsules and run in the piston-cylinder apparatus under hydrous conditions, have been analysed colourimetrically for Fe_2O_3 and FeO. For charges in which liquid quenched to glass, the molecular ratio Fe^{3+}/Fe^{2+} ranges between 0.05 and 0.18. Comparison with experimentally determined relationships between oxidation states of basaltic and andesitic liquids and imposed oxygen fugacities (fO_2) indicates that fO_2 values attained during the equilibration of the analysed changes lay close to those of the nickel-nickel oxide buffer assemblage ($fO_2 \sim 10^{-8}$ atm. at 1200°C). The restricted range of values estimated in this way indicates that fO_2 within sample capsules is quite closely controlled due to the influence of the graphite heating element of the furnace assembly. Charges in which extensive quench crystallization took place yield much higher values of Fe^{3+}/Fe^{2+} (0.30 - 0.55). During quench crystallization, water is exsolved from the liquid present during the run. Dissociation of this water followed by diffusion of hydrogen through the capsule walls leads to increase in fO_2 and subsequently to oxidation of the charge.

7.13 Preparation of bulk rock glasses for major element analysis by electron microprobe (I.A. Nicholls)

The technique of fusing rock powders on an iridium-strip heater has been improved to allow the preparation of glasses of basaltic to rhyolitic composition suitable for accurate major element analysis by electron microprobe (see Electron probe laboratory). Powders of refractory rock compositions (eg. quartz-rich granites) are prepared for fusion by careful grinding to pass 300 mesh. Liquids are homogenised while on the iridium strip by stirring with a platinum rod. The resulting glasses are highly uniform, and yield precise results when replicate microprobe analyses are performed.

8. GEOCHRONOLOGY, GLOBAL GEOLOGY AND ISOTOPE GEOCHEMISTRY

8.1 Sr. Isotopes

8.1.1 The eastern margin of the Yilgarn Block, Western Australia (W. Compston, C. Roddick)

Isotopic work in this region seeks to obtain a complete and unambiguous time-record for the various rock units, including ore deposits, in typical Archaean greenstone sequences and their associated acidic rocks. It is part of the long term objective of tracing the origin and growth of the earliest crust.

Sr analyses have continued but emphasis this year has turned to Pb isotopic work on zircon, feldspars, sulphides and whole rocks, the results of which are described elsewhere. Attention has been focussed on:

(a) The Kambalda area, where Rb-Sr analyses of additional samples have detected two ages for intrusive felsites, with different initial $^{87}Sr/^{86}Sr$, which had been thought previously to be a single population that was not distinguishable in isotopic age from the Kambalda granits. The Rb-Sr age of the granite is not precise owing to its very limited range in Rb/Sr, and an apparent large discrepancy with its Pb-Pb and zircon U-Pb ages now disappears. Total rock samples of the metabasalts continue to show a range in apparent age because of later alkali metasomatism, but they can be placed as older than about 2800 m.y. from the Pb work on the intrusive granites.

(b) The Jones Creek Adamallite north of Agnew, Western Australia, which is overlain by a spectacular conconglomerate that is overlain in turn by another greenstone sequence. The total-rock age of the Jones Creek Adamellite has been precisely measured using its fortunately wide range in Rb/Sr, and corroborated by ages from mineral separates from the Adamellite and by ages of younger pegmatites. The result of 2695 ± 15 m.y. pins the age of the conglomerate and younger greenstone sequence as less than this fiture, so that for the first time we have conclusive radiometric evidence for at least two different periods of greenstone formation within the Yilgarn Block.

8.1.2 Origin and ages of granites in Eastern Australia

(W. Compston, P. Arriens, T. Shirahase, B.W. Chappell A.J.R. White*, J. Cocker+)

Detailed mapping and geochemistry by the Geology Department, A.N.U. on several large batholiths in south-

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\+ University of Tasmania

eastern Australia have identified the relative ages of many individual plutons and the chemical differences due to their different source materials. It has been proposed that the granites constitute partial melts of essentially crustal source materials, both igneous and sedimentary, and that the abundant xenoliths within the granites are cognate refractory fragments of their source.

The previous geochemical studies showed that, except for the volatile elements, the distribution of elements within plutons is controlled by mixing relationships between the xenoliths and a "pure granite" end-member. The isotopic relationship of the xenoliths to the melt is therefore critical to the interpretation of Rb-Sr isochrons. If the xenoliths are not cognate, their $^{87}Sr/^{86}Sr$ may be heterogeneous and different from that of the granitic end-member, and "isochrons" may be formed by mixing that have positive or negative starting slopes. Consequently, the first aim of our Sr isotope study was to examine the relationship between xenoliths and host rock.

Detailed total-rock work was carried out on:

(a) The Berridale Batholith ; and

(b) The New England Batholith

using samples prepared and analyzed for Rb and Sr by the Geology Department. Xenoliths and granitic matrix were always closely similar in their initial $^{87}Sr/^{86}Sr$ but both showed a detectable spread in values. Felsic bodies containing few xenoliths showed the least spread. Different plutons were often distinctive in their initial $^{87}Sr/^{86}Sr$. The initial $^{87}Sr/^{86}Sr$ of the so-called "S-type" granites (metasedimentary xenoliths) were distinctly higher in the case of the Berridale Batholith, reflecting their origin from sediments that were sufficiently older and high in Rb/Sr to accumulate appreciable radiogenic Sr. The New England S-type granites were not significantly high in initial $^{87}Sr/^{86}Sr$ reflecting much younger source rocks.

As a result of this work, the inherent population of initial $^{87}Sr/^{86}Sr$ values even within a single pluton is recognized as an important factor controlling the precision of a whole-rock Rb-Sr age determination. In general, perfectly-fitted isochrons are not to be expected, and the appropriate statistical method for line-fitting will be the McIntyre "Model III" solution (random y error independent of x).

Because of the above limitation, some of the plutons could not be adequately dated using total rock samples alone. Consequently, a programme of mica Rb-Sr ages has been started to check the ordering of intrusion within the batholiths seen in the field relationships. Instances of the resetting of mica ages have been found, and the need for zircon U-Pb work is evident.

Detailed work has also been done on

(c) The Murrumbidgee Batholoith, in which differences in age and the scatter of initial $^{87}Sr/^{86}Sr$ have been detected;

(d) The Kosciusko Batholith

and between indivual bodies.

(e) Blue Tier Batholith, north-east Tasmania.

Sr work on this batholith was undertaken principally to explore the possibility that localized changes of $^{87}Sr/^{86}Sr$ in the granites might occur during hydrothermal alteration that involved meteoric water from adjacent highly-radiogenic country rocks. Eleven major plutons and a selection of turbidite country rocks have been analyzed so far, to distinguish time differences and variations in initial $^{87}Sr/^{86}Sr$. Plutons associated with tin mineralization will be studied in particular, as these are altered hydrothermally and have high $^{87}Sr/^{86}Sr$ according to preliminary data.

8.1.3 Granitic rocks from New Zealand (*C. Adams)

Isochron studies of several plutons from New Zealand were made by a visiting scientist, and these data are relevant to a general survey of Palaeozoic and Mesozoic granites from the reassembled Gondwanaland.

8.1.4 Chronology of the Alligator River area, Northern Territory (W. Compston, B.W. Chappell)

In collaboration with Esso Minerals Ltd., and the Bureau of Mineral Resources, Rb-Sr work was carried out on Precambrian migmatites, granites and dolerite to specify the sequence of events related to uranium mineralization in this area. It was necessary to use the lunar laboratory for an internal age on the dolerites. Zones of hydrothermal alteration within all the above rocks were studied, and at least two such periods were identified. The uranium mineralization in its original and secondary form has been successfully placed within the radiometric time frame.

8.1.5 Cainozoic volcanics

Small differences in $^{87}Sr/^{86}Sr$ in young volcanics are relevant to the chemical history of their source regions

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in the upper mantle and/or the tracing of crustal contaminatio during passage of the lavas from their source to final emplacement. This application demands the highest-quality mass spectrometry and the use of a calibrated and minitored measurement system. The principal projects were:

(a) Volcanics from Java and Bali (D. Whitford, W. Compston

These Recent volcanics show a geographic pattern in $^{87}Sr/^{86}Sr$ possibly related to thickness of the underlying crust, and show correlations of high $^{87}Sr/^{86}Sr$ with cetain trace-elements that are indicative of crustal contamination. (These results are reported in more detail in this Report in the Trace Element section).

(b) Lamington volcanics (V.M. Oversby)

Samples from the northern flank of the Tweed Shield Volcano were analysed in connection with a Pb Isotopic study. The Beechmont basalt unit consist of olivine- quartz-normative tholeiites, with a uniform initial Sr^{87}/Sr^{86} ratio of 0.70385 ± 0.00004. The quartz-normative Hobwee basalts have initial ratios ranging from 0.70403 to 0.70426, clearly distinct from the Beechmont basalts. Springbrook rhyolites, with low Rb/Sr ratios, had initial Sr isotopic composition of 0.70486 significantly higher than both associated basalt units The Binna Burra rhyolites have extremely high Rb/Sr, making determination of initial Sr composition impossible. Rb-Sr ages of a Binna Burra rhyolite and an alkali rhyolite were measured as 22.8 ± 0.5 m.y. ($\lambda Rb = 1.405 \times 10^{-11}$ yr^{-1}).

8.1.6 Antarctic geochronology (P. Arriens)

(a) Prince Charles Mountains: Fieldwork during the 1972-73 summer was fully supported by helicopter operations in the Southern Prince Charles Mountains of MacRobertson Land, some 700km south of Mawson Station. During the withdrawal phase, geological work continued briefly in the Northern Prince Charles Mountains. Upon completion of inland operations, further fieldwork was done along the Mawson coast between Scullin Monolith and Campbell Head. Logistic support for the sea voyage to Antarctica and airborne operatio on the continent was provided entirely by the Antarctic Division of the Department of Science.

(b) Windmill Islands: Several distinct Rb-Sr isochrons are given by granitic gneisses in the Windmill Islands near Casey Station (Wilkes). The total-rock isochrons range from about 1400 m.y. to 1100 m.y., with initial $^{87}Sr/^{86}Sr$ ratios ranging from 0.7533 ±.0003 to 0.7030 ± .0012. Mica ages for both muscovite and biotite are close to 1100 m.y.

The gneisses have a complex history of injection and/or metasomatism, and it was only through the large number of samples analysed, with over 30 from a small area in Herring Island alone, that it was possible to resolve the data into separate isochrons. Our Herring Island isochron has a lower intercept and steeper gradient than two other isochrons. Had fewer samples been analysed, it would not have been possible to resolve these intersecting isochrons from a pattern of apparent scatter.

Rock samples were collected in clusters from a series of small sites. Some sites extended less than 4 metres across the layering of the gneisses, yet the rocks from any one site did not necessarily group into any one of the isochrons. The gneisses are now of upper amphibolite to granulite facies mineralogy, but the Rb-Sr system for the older isochrons probably predates the final metamorphism, and may have been set at the time of sedimentation. The younger isochrons could relate to episodes of later injection or metamorphism, which took place not long before the emplacement of a pegmatite which bears muscovite and biotite, and must post-date granulite facies conditions.

On models of continental re-assembly, the Windmill Islands lie opposite to Albany on the south coast of Western Australia. The geochronology of the Windmill Islands is closely comparable with what is known of the geochronology of the Albany-Esperance and Fraser Range areas of Western Australia.

(c) Vestfold Hills: Nearly all of the gneisses so far analyzed from the Vestfold Hills give an unequivocal Archaean age - e.g. 2548±42 m.y. with initial $^{87}Sr/^{86}Sr$ of 0.7018±.0003 for 38 samples. The discovery of Archaean rocks in the Vestfold Hills much lengthens the known span of geological time in the history of this region of Antarctica.

Total-rock measurements on a suite of dolerite dykes collected for palaeomagnetism suggests that many of the dykes have an age of over 1400 m.y. with initial ratio of about 0.703, rather than the 1030±220 m.y. with initial ratio of 0.705±.001 as reported by other workers in a previous study of six samples. Analysis of plagioclase concentrates will assist to resolve these differences. Although both ages may be correct, it can be noted that the majority of metamorphic rocks in Princess Elizabeth Land and MacRobertson Land give ages of less than 1100 m.y., and are not intruded by swarms of dolerite dykes as are the older gneisses of the Vestfold Hills.

(d) George V Land: Muscovite and biotite micas from samples collected at Cape Denison in Commonwealth Bay give ages of 1600-1700 m.y., and also near or less than 1300 m.y. The samples were collected by the Australasian Antarctic Expedition of 1911-13, led by Sir Douglas Mawson. On continental reassembly, the conjugate rocks in Australia are in Eyre Peninsula, which has a complex igneous and metamorphic history which probably begins before 2000 m.y., with younger events down to 1300 m.y. The existence of the older mica

ages from in situ samples as well as from erratic boulders at Cape Denison is consistent with re-assembly of George V Land adjacent to Eyre Peninsula, but far more intensive field sampling is required, both in Australia and Antarictica.

8.1.7 Basic dykes from Western and South Australia.

(A.R. Crawford, W. Compston)

Work on dyke swarms intruding the Yilgarn Block of Western Australia and the Gawler Block of South Australia has shown that dykes in Western Australia cover a greater range of ages than previously believed, from about 2700 m.y. at least, to about 750 m.y. Various metamorphic and contamination effects have led to considerable difficulties of interpretation, which are currrently being clarified through the use of complete chemical analyses. In South Australia, by contrast, the dykes examined are all approximately of the apparent age of the metamorphism of the Gawler Block, namely, 1700 m.y., and of granulite grade.

8.1.8 India and Iran (A.R. Crawford)

Reconnaissance geochronological work has shown the widespread existence of different apparent ages of rocks, known or strongly suspected to be Precambrian, particularly in northwestern and central Iran. In the north-western Alborz Mountains work supports the results of detailed mapping by a British group, with a Devonian metamorphism affecting Upper Precambrian rocks, Jurassic granite intrusion and less certain evidence of a Triassic event which is known in Azerbaijan.

Analysis of the Erinpura-Idar Granite suite of Rajasthan-Gujerat shows that these rocks, previously considered much older, are all of Malani Rhyolite age, namely, about 750 m.y. As in many other parts of India, biotite ages of about 500 m.y. are also found here.

Analysis of Himalayan samples from Simla (central Himalaya) shows that the total-rock ages of low-grade metamorphic rocks are Precambrian, though the latest deformation is Tertiary. Analysis of a suite from the Darjeeling Himalaya, collected at different levels through a zone of reversed metamorphism, gives total-rock apparent ages ranging from 1800 m.y. in the least-metamorphosed Daling Series at 3000 ft. to less than 500 m.y. at 7000 ft., muscovite ages from well over 2000 m.y. to less than 300 m.y., and biotite ages of less than 30 m.y.

Total-rock analysis of the Tusham Hill inlier in the Punjab, far from the rest of the Peninsular Shield, indicates an age of 950 m.y., neither Malani, as previously believed nor, Delhi, but in between.

8.1.9 History of Gondwanaland A.R. Crawford

Analysis of geological data has led to the following conclusions on aspects of Gondwanaland history; these are written up and published, submitted, or await diagrams:

(i) the Indo-Antarctic relationship was one with a joint granulite belt probably formed intra-continentally between 2100 m.y. and 1600 m.y., and distorted into a sinuous belt, now represented by the Eastern Ghats in India, between 750 and 450 m.y. ago, probably by relative movement between older crustal units beyond its margins.

(ii) the Indo-Malagasy relationship is indicated in detail by the extension of that distorted granulite belt, to which massive-type anorthosites are confined, into southern Madagascar, and the extension of the Narmada - Son lineament (between northern and southern Peninsular India) into northernmost Madagascar.

(iii) the Indo-Antarctic-Australian relationship involved also Tibet, which lay between Western Australia and India as a part of Gondwanaland, while the Tarim Basin Block lay off northern Western Australia with a part of north China. The Himalaya have a complex intra-continental origin post-dating the origin of the high hills of southern India and central Ceylon, but developed along fractures which opened first as thrusting developed in the latter areas when an Indian unit rotated relative to Tibet and Antarctica about a pole near Perth.

8.1.10 Bureau of Mineral Resources projects (R. Page and L.P. Black)

Substantial use of the Rb-Sr chemical and mass-spectrometric facilities continues by staff of the Bureau of Mineral Resources. Their dating projects this year have been located in the following regions:

(a) Arunta Complex (Northern Territory)
(b) Georgetown-Herberton-Mt. Garnet area,(Queensland)
(c) Mt. Isa-Cloncurry area (Queensland)
(d) Alligator River area (Northern Territory)
(e) Granites-Tanami area (Northern Territory)
(f) Papua-New Guinea

8.2 Lead isotope geochemistry and geochronology

8.2.1 Archaean plutonics of the Kalgoorlie-Norseman area,

(W. Compston, V.M. Oversby)

A study of the age and lead isotopic systematics in eight intrusive bodies of Archaean age from the Kalgoorlie-Norseman area, Western Australia, has been completed. The range of chemical composition of the intrusions was granodiorite to granite.

The youngest Pb-Pb age found was 2632±28 m.y., in contrast to the biotite Rb-Sr ages of 2590 m.y. (λ_{Rb}=1.405x 10^{-11} yr^{-1}) which are characteristic of the Kalgoorlie-Norseman area. The Pb-Pb ages were determined using whole rock, K-feldspar and plagioclase mineral separates. As such, one might have expected the Pb-Pb ages to agree with Rb-Sr mineral ages. The older ages found by Pb-Pb suggest that Pb and U in minerals may be less susceptible than Rb and Sr to diffusion under the P-T conditions of a cooling intrusion, and that some of the intrusions may have taken as much as 100 m.y. to cool below the blocking temperature for diffusion of Rb and Sr in biotite.

The oldest age determined was 2760±70 m.y. for an intrusion of granodioritic composition at Kambalda. The U/Pb ratio of the intrusion is very low, resulting in non-radiogenic whole rock lead isotopic compositions at the present day. This severely limits the precision of the Pb-Pb age determinations. A gneissic body, Stennet Rocks, located south of Norseman, gave an age of 2671±79 m.y. The chemical composition varies from granodiorite to adamellite; the U/Pb ratio is very low, but not quite as extreme as that of the Kambalda intrusion.

Buldania Rocks, a granodiorite-adamellite intrusion located east of Norseman, was dated at 2655±35 m.y. An aplite vein from this intrusion gave an age identical to that of the massive phase. A quarry of adamellite at Karonie (70 miles east of Kalgoorlie) gave an age of 2691± 74 m.y. Two parallel isochrons were found, indicating distinct heterogeneity in the initial isotopic composition of the pluton. The major element chemistry does not reflect the isotopic differences. The body is interpreted to be a multiple intrusion, representing sequential melting of a slightly heterogeneous source.

The Mungari Granite is a small adamellite intrusion, west of Kalgoorlie; the Pb-Pb age is 2640±35 m.y. Karramindie Soak is a small exposure of adamellite with chemical and isotopic characteristics which are virtually identical to the Mungari Granite. However, the age of Karramindie Soak is 2705±35 m.y. This suggests that magma was produced from a very homogeneous source over an extended period of time. A sample of adamellite from Menangina Rocks (approximately

80 miles north of Kalgoorlie) has a different chemical composition, and gives an age of 2640±53 m.y.

An extremely large area of intrusive rock (covering at least 250 sq. miles) occurs near Lake Johnston, west of Norseman. Samples collected from Wheeler Rocks in the NW portion of the intrusion were porphyritic adamellite to granite. An age of 2632±28 m.y. was obtained. The whole rock lead isotopic compositions were the most radiogenic found in this study.

Lead extracted from potassium feldspars was used to estimate the initial lead isotopic composition of the intrusions. This data places limits on the possible source materials for the magmas. All of the intrusions had source materials which had experienced at least one increase in U/Pb ratio prior to production of the intrusive magma. Plutons in the area near Norseman have initial lead compositions which require an anatectic origin from pre-existing acidic crustal rocks. Depending on the model chosen, the crustal rocks could have been as old as 4000 m.y. Intrusions in the Kalgoorlie area were either mantle-derived (considered improbable except possibly for Kambalda), anatectic from basic rocks, or anatectic from relatively young acidic crustal rocks.

8.2.2 Zircons from the Kambalda Granodiorite (W. Compston, *R.T. Pidgeon)

Zircons extracted from a section of drill core were analysed in an attempt to determine the age of intrusion of the granodiorite at Kambalda. The results gave an apparent age of approximately 2500 m.y., however, internal systematics of the data showed that this could not be interpreted as a real age. This apparent age was interpreted to be the result of mixing of zircons from the granodiorite with other zircons, possibly from felsites cutting the main granodiorite mass. Zircons from a surface exposure of the granodiorite gave an age of 2815±100 m.y., in good agreement with the Pb-Pb age of 2760±70 m.y. determined on whole rock and feldspar sample from the drill core.

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* Scottish Research Reactor Centre, East Kilbride, Scotland.

8.2.3 Kambalda felsites and sulphides (J.C. Roddick, V.M. Oversby, W. Compston)

Lead isotopic work has begun on rocks at Kambalda in order to extend and clarify the geochronology already undertaken using the Rb-Sr system. The sulphides at Kambalda contain very little lead, and the technique of silica gel solid source analysis has greatly reduced the labour and time required to carry out isotopic determinations. The lead in the sulphides is similar to, but distinct from, the initial lead in the Kambalda granodiorite (dated at 2760±70 m.y. by a Pb-Pb isochron). Lead in some felsites may be related to that in the sulphides, while other felsites appear to be distinct from the sulphides. A number of felsite samples are enriched in radiogenic lead and appear to confirm the Rb-Sr interpretation that there is a range in ages extending from possibly as old as 2800 m.y. to as young as 2500 m.y.

8.2.4 Lamington Volcanics, S.E. Queensland (V.M. Oversby, *A. Ewart)

A lead isotopic study was undertaken on the basalt-rhyolite-basalt sequence in Lamington National Park to determine whether the rhyolites were genetically related to either of the basalt units. Two olivine tholeiites from the lowermost basalt (Beechmont basalt) have lead compositions which are less radiogenic than mid-ocean ridge basalts ($^{206}/_{204}$ = 17.65; $^{207}/_{204}$ = 15.42). An olivine tholeiite and a quartz tholeiite from the Beechmont basalt have $^{206}/_{204}$ = 18.10, $^{207}/_{204}$ = 15.50. This bimodal distribution of lead compositions contrasts with the uniform strontium isotopic composition found for the Beechmont basalt. The Hobwee basalt (upper unit) has fairly uniform lead composition with $^{206}/_{204}$ between 18.13 and 18.22. The Binna Burra rhyolites have remarkably uniform lead composition and concentration. The composition ($^{206}/_{204}$ = 18.41) is much more radiogenic than that in the basalts, thus disproving a genetic relationship between the basalts and rhyolites. Springbrook rhyolites, which occur slightly east of the Binna Burra section, are even more radiogenic with $^{206}/_{204}$ = 18.53. The data suggest that the rhyolites were formed by local anatectic melts of crustal material. The basalts may have provided heat for anatexis, but did not contribute a significant amount of material in the formation of the rhyolites.

8.2.5 Lead evolution of the upper mantle and crust (V.M. Oversby)

Recently published results giving new precisely determined decay constants for U^{238} and U^{235} have caused substantial changes in the lead evolution model of the crust and upper mantle. Calculation of lead isotopic growth curves using the new decay constants shows that modern mantle-derived volcanic rocks, and galenas ranging in age from 3×10^9 yr. to the present can all be considered as part of the same evolving

* University of Queensland

system. Large scale heterogeneity in the U/Pb ratio of the mantle in Archaean times can be limited to a range of ±5% about the mean value. The mean U/Pb ratio of the upper mantle plus lower crust has increased by about 5% from 3x109 yr. ago to the present. The range of U/Pb ratios in the present mantle, however, is more than an order of magnitude greater than the range at 3x109 yr. ago.

8.2.6 Analytical procedures (V.M. Oversby, W. Compston)

During the year, a change-over was made from mass spectrometric analysis using PbI_2^+ in the gas source instrument (MS12) to analysis by solid source with a silica gel activator. Analyses of the NBS isotopic standard have shown that samples of 200ng Pb can be run with very little fractionation. Provided that the temperature of the run is between 1100 and 1250°C, fractionation is constant from one run to the next. Use of the silica gel method allowed a reduction in the size of sample taken for chemical processing by about a factor of ten, and resulted in a lowering of the chemical processing blank to 5 to 10ng per analysis.

The gas source mass spectrometer (MS12) was retired from active use at the end of May, 1973. Between November 1, 1972 and May 30, 1973, 181 runs were done on the MS12 by 2 users.

8.3 Apparatus and techniques

8.3.1 Thermal ionization mass spectrometers

A fast vibrating-reed electrometer, Cary Model 36, has been tested and calibrated on the MSZ for Sr and Pb isotopic work. Response was complete within one second using a 5x1010 ohm input resistor, compared with at least four seconds for the previous electrometers (Cary Model 31). The Cary 401electrometer has also been employed but is less satisfactory, having a higher dynamic zero and higher short-term noise.

This year there have been 16 different users, including 6 visitors and 3 Bureau of Mineral Resources staff. The number of runs on the MSZ machine, 1656, has doubled compared to last year, as a result of fast measuring techniques and round-the clock operation. Useage of the Nuclide machine, 1150 runs, was very similar to previous years and there was an increased use of MSX (554 runs) which reflects its linkage to the computer half-way through the year.

8.3.2 X-ray fluorescence laboratory

During the year the equipment was shifted from the first floor to the basement, which caused the loss of about five weeks of working time. Analyses carried out during the year were as follows:

Type	No. of Samples	Users
Precise Rb/Sr	255	5
Approx. Rb/Sr	720	8
Approx. Pb	10	1
Trace elements	123	2
Major elements	311	12
Diffractometer	53	7

8.3.3 Computer (P. Arriens)

The multi-access mode of operation of the Hewlett-Packard 2116B computer was described in the 1972 Annual Report. Since then additional code was added to the Hewlett Packard Real Time Executive software. This has enabled programs of the multi-user operating system to gain additional responses from RTE. In effect, programs are now able to submit messages to RTE which previously could be submitted only through the operator console, and the messages which normally appear on the operator console are optionally available to the program.

These changes required re-assembly of the RTE system programs, and a re-structuring of the multi-user system programs. The result was a more robust operating system capable of concurrently supporting three or more solid-source mass spectrometers as well as the electron probe and other users.

Software development of the multi-user system ceased in August 1973. The system inherently could be developed to support the operation at will of any of the local teletypes as remote consoles of the UNIVAC 1108, using the 2116B as a multiplexor. Software "interfaces" for full duplex communication to outside computer are written into the multi-user system programs.

8.4 Potassium-Argon Geochronology

Studies during the year have covered a wide spectrum of problems relating to time and the geological history of the Earth. Work has progressed on a number of major projects including the geomagnetic polarity time scale, the physical time scale for the Cenozoic, volcanic migration patterns in oceanic island chains, the evolution with time of the New Hebrides island arc and the Tasman Basin, and the determination of the age of Palaeozoic granitic rocks in Central and Western Victoria. Further development work was undertaken on the $^{40}Ar/^{39}Ar$ method of dating.

During the year about 430 isotopic analyses of argon and over 200 potassium measurements were made, resulting in about 220 new age determinations, approximately half of which were measured in duplicate. The balance of the argon runs consisted of numerous calibrations and a number of $^{40}Ar/^{39}Ar$ determinations. The substantially modified MS10 mass spectrometer was used for most of the argon analyses, and, apart from some resolution problems, is performing satisfactorily. A digitized read-out system has been built for the MS10, substantially improving precision of measurement and also decreasing the amount of labour involved in obtaining data. A peak switching device, now nearing completion, will further improve data acquisition and enable the mass spectrometer to be interfaced with the Hewlett-Packard computer.

8.4.1 Geomagnetic polarity time scale

(I. McDougall, N.D. Watkins*

The polarity time scale was developed from combined palaeomagnetic and K-Ar dating studies and has been a major research project of this group for a number of year. Its importance lies in delineating the history of the geomagnetic field and it was an essential building block for the development of the plate tectonic model of Earth behaviour. The polarity time scale continues to be of great interest, particularly as it is used increasingly in stratigraphic and other studies.

In the current year one project has been completed and another commenced in relation to refinement of the polarity time scale. Palaeomagnetic studies on oriented samples from two sequences of olivine basalt lavas on the island of Reunion, Indian Ocean, together record the Reunion normal polarity event within the Matuyama reversed epoch. Detailed K-Ar dating of the lavas indicates that the Reunion event has a mean age of 2.02 $\pm$ 0.02 m.y., with a duration estimated to lie within the range 10,000 to 50,000 years. The short duration of the event may explain why it has been detected only rarely in deep sea sedimentary cores. These new results provide strong evidence that the Reunion event is distinct from, and older than, the Olduvai event.

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Comprehensive and systematic collections of oriented samples were made in Iceland during the year in an attempt to further refine the polarity time scale and to extend it beyond 3.5 m.y. ago, the present older limit to the accurately determined time scale. Because of the finite resolution of the K-Ar dating method it is essential for this purpose to collect from continuous sequences of lavas, such as are uniquely developed in Iceland. Despite the fact that Icelandic lavas are more altered than was expected it is hoped that the current work will provide some of the necessary data.

8.4.2 The Pliocene-Pleistocene boundary

(I. McDougall, O.P. Singleton, C.W. Mallett*)

The identification of this boundary in Australian sequences has been extremely difficult and the subject of much controversy. Previously the general approach has been to equate the onset of marked cooling in the Late Cenozoic as the beginning of the Pleistocene. However, studies made here and elsewhere have shown unequivocally that cooling and glaciation began much earlier than the beginning of the Pleistocene, defined stratigraphically as the base of the Calabrian stage in Italy. A detailed micropalaeontological study of sedimentary sequences in Western Victoria and K-Ar dating of associated basalts has now enabled us to locate the boundary, dated elsewhere at about 1.8 m.y., with much greater precision than previously. The importance of this work, apart from the stratigraphic implications, is that the study of former climates now can be made much more objectively than has been the case in the past.

Another separate, but related, study has been completed which shows that a low stand of the sea, presumably due to a regression during glaciation, occurred 0.30 m.y. ago as shown by the age of basalts at Port Fairy, Victoria, which fill a valley cut to a depth of at least 30 m below present sea level.

8.4.3 Volcanic Island Chains (R.A. Duncan, I. McDougall)

Interest in linear chains of volcanic activity, usually well removed from lithospheric plate margins, has grown recently with the suggestion that these sites of volcanism may be surface manifestations of fixed 'plumes' of upwelling mantle material. If this hypothesis is correct then the chains of igneous centres record the absolute motion of the lithospheric plates with respect to the mantle of the earth, providing an extremely

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* University of Melbourne

attractive method of unravelling plate motions. The model predicts that the members of these igneous scars exhibit a progressive increase in age away from the source and have a geometry consistent with plate motion as determined from palaeomagnetic evidence.

Previous work had been concentrated on the Hawaiian Island chain. In the current year studies have been extended to the linear volcanic island chains of French Polynesia, southeast Pacific Ocean. Extensive collections of samples from the Marquesas and Society Island chains are presently under detailed study. Samples from five islands of the Marquesas Island chain have been dated and yield ages ranging from 4.0 to 1.3 m.y. Results from individual volcanoes show a very limited range in age and indicate that each volcano was built over a very short period of time. Overall there is a regular decrease in age from northwest to southeast along the island chain, with a calculated rate of migration of the volcanism of 9.9 cm/year. These data are consistent with the model of rigid Pacific plate movement over a fixed "hot spot", taking into account the Hawaiian results, provided that the pole of rotation for the Pacific plate for the last 5 m.y. is located near 55°S, 170°E.

Geochronological and geochemical work is continuing on this island chain and on the Society Islands.

Ages also have been determined on a suite of volcanic rocks from Pitcairn Island which lies near the Gambier Islands - Duke of Gloucester Islands lineament in the southeast Pacific. The results show that Pitcairn was built subearially in less than 0.5 m.y. in Pleistocene times. Pitcairn therefore is much younger than the 5 to 7 m.y. ages reported for the Gambier Islands, and thus there is a suggestion of migration of volcanism from northwest to southeast along the lineament in the same direction and approximate rate as for the better developed island chains of the Pacific.

8.4.4 New Hebrides (M.P. Gorton)

Earlier K-Ar results from the islands of Epi and Aoba showed that widespread Late Cenozoic volcanism in the New Hebrides is of younger age than had been thought previously. These conclusions have been confirmed and extended by ages of less than 100,000 years obtained on rocks from the volcanic islands of Ambrym and Tongoa.

Ages of 5 to 6 m.y. were found for tholeiitic submarine basalts on Pentecost, which confirms the Miocene-Pliocene age expected from the palaeontological control that is available. These basalts may well date from the beginning of the present tectonic regime in the New Hebrides, an event which may be of more than local significance in view of the similar ages obtained previously on a suite of rocks from Fiji.

Discordant K-Ar ages of 56 to 25 m.y. have been published by other workers for andesites and diorites associated with a widespread group of Early Miocene rocks from the New Hebrides. More recent determinations in this laboratory gave ages of about 18 m.y., in accord with the stratigraphic control.

Most volcanic rocks in the New Hebrides fall into one of the three groups recognized from the geochronology. Volcanism in the intervening periods is rare. It seems possible that this episodic development of the island arc is related to periodic readjustment of the rather unstable lithospheric plate boundaries nearby.

8.4.5 Lord Howe Rise (I. McDougall, G. van der Lingen New Zealand Geological Survey)

The Lord Howe Rise is a major submarine feature of continental-type structure extending in a northwest to north direction from New Zealand and separated from Australia by the Tasman Basin. Drilling at site 207 (Deep Sea Drilling Project Leg 21), located on the summit of the Rise, bottomed in rhyolitic rocks. Sanidine concentrates from four samples of the rhyolite yielded concordant ages of 94 m.y., which is early Upper Cretaceous. These ages provide important information on the timing of the development of the Tasman Basin and the initiation of the large scale movements related to the breakup of this part of Gondwanaland. At the time of eruption of the rhyolites the Lord Howe Rise is thought to have been emergent and adjacent to the eastern margin of the Australian continent. Subsequent to 94 m.y. ago and prior to deposition of Maastrichtian (70 to 65 m.y. B.P.) marine sediments on top of the rhyolitic basement of the Lord Howe Rise, rifting occurred, and the formation of the Tasman Basin began by sea floor spreading, with rotation of the Rise away from the margin of Australia. Out data provide strong support for the interpreation that magnetic anomalies, recently found in the Tasman Basin, date from Late Cretaceous to Early Cenozoic.

8.4.6 $^{40}Ar/^{39}Ar$ dating method (I. McDougall)

Development of this method of measuring ages has continued. The technique involves conversion of a fraction of the ^{39}K atoms to ^{39}Ar by fast neutrons during irradiation of the samples in the AAEC reactor, HIFAR, at Lucas Heights, near Sydney. Subsequent isotopic analysis of the argon extracted from the irradiated samples enables ages to be determined. The total fusion method can now be applied on a nearly routine basis, although the precision attained is not as high as in the conventional K-Ar method, because of large neutron flux gradients in the reactor. Correction factors for interferences due to neutron interactions on other potassium isotopes and on calcium have been determined for HIFAR. The first incremental heating experiment was carried out successfully in this laboratory, yielding the classical plateau argon age pattern. When manpower becomes available the incremental heating technique will be applied to detailed studies on samples from simple and complex geological terrains to further elucidate thermal histories of these regions.

8.4.7 Central and Western Victoria (J.R. Richards)

Approximately 70 age measurements were completed during the year on biotite, muscovite and amphibole separated from Palaeozoic granitic rocks of Central and Western Victoria. The great majority of the ages are Devonian and further emphasize the importance of granitic magmatism of this age in the southern part of the Lachlan Geosyncline of the Tasman Orogenic Zone of Eastern Australia. In Western Victoria a number of Ordovician granitic rocks have been found, extending eastward the known area of Early Palaeozoic granites associated with deformation and metamorphism, and previously well documented in eastern South Australia.

Other Projects

Work has begun on the dating of basalts from Lord Howe Island in conjunction with palaeomagnetic investigations. Field work and the laboratory results indicate that previous ideas on the evolution of this volcanic island require considerable modification.

A small granitic stock just west of Tumut, N.S.W., has been dated by K-Ar on four muscovite concentrates, and by Rb-Sr on whole rock samples. The ages are essentially concordant at slightly greater than 400 m.y. This age is of some importance for the physical time scale as the granitic body intrudes mid-Silurian sediments and is overlain by mid-Lower Devonian sediments.

Ages have been measured on many other samples from Australia, Papua New Guinea (with the Bureau of Mineral Resources) and from a number of other regions in relation to several smaller cooperative projects.

8.5 Rock processing and mineral separation

Crushing of rock samples and mineral separations were carried out for geochronological and geochemical studies, a total of 687 samples being prepared. For the geochronology group some 510 terrestrial samples were prepared, 158 of which were high purity mineral separations. An additional 95 whole rock samples were crushed for major element analyses. In the lunar program 24 mineral separations and 29 whole rock samples were prepared in a high purity laboratory, involving a considerable amount of hand picking to obtain the good mineral concentrates required.

8.6 Carbon^{14} age determinations

8.6.1 Production and allocation of C^{14} age determinations

The radiocarbon dating laboratory has supported independent investigations undertaken by scholars and academic staff of the School of Earth Sciences, School of Pacific Studies and School of General Studies and has undertaken research activities of its own, it has also supported some of the dating activities of the Australian Institute of Aboriginal Studies.

The distribution of age determinations carried out is as follows:

School of Earth Sciences	8
Prehistory (IAS)	47
Biogeography and Geomorphology	54
Prehistory (SGS)	10
Asian Civilization	5
Geography (SGS)	15
Australian Institute of Aboriginal Studies	14
CSIRO	6
Radiocarbon laboratory	33
	192

8.6.2 Archaeomagnetism

A study was undertaken into the archaeomagnetic investigations of ancient aboriginal fireplaces at Lake Mungo and Willandra and associated sites at Western N.S.W., Australia. It established and dated precisely an excursion of the geomagnetic field about 30,000 years ago, lasting less than ca. 2,600 years. This provides a significant basis for further evaluation of the relationship between changes of the earth's geomagnetic field and production rate of C14. The study also established that Aboriginal man settled in the area some 32,000 years ago.

8.6.3 Age of paleosols and parent material (climatic implications).

Buried organomineral soil material near the base of slope deposits at 590 m, Black Mountain, Canberra, was dated at ca. 28,000 years ago. This age was not significantly different from the mean age of slope deposits near Lake George, dated at ca. 26,800 B.P., and correlated well with the previously reported mean age of slope deposits above 1000 m in the Snowy Mountains, N.S.W. dated at ca. 31,500 B.P. A method for comparing the C^{14} determinations has been proposed. On the basis of their similar ages it

is suggested that the Black Mountain deposits were formed under similar climatic conditions to the Snowy Mountains deposits, i.e. periglacial climate with mean annual temperatures at least 8°-10° lower than at present. If this was so, the synchronous slope deposits near Lake George must also have been developed during colder climate.

8.6.4 Royal Society and University of Queensland Expedition to the Great Barrier Reef.

The C^{14} laboratory is the principal investigator in an evaluation of the ages and chronology of formation of the Great Barrier Reef, Queensland, Australia. Samples for the C^{14} dating programme were collected during Phase I of the expedition, July-August 1973. Seventeen live specimens of corals and molluscs were collected to provide modern reference standards and in cooperation with the Geomorphic and drilling parties of the Expedition some 50 samples were collected for C^{14} dating

8.6.5 C^{14} ages of last high sea-level stand

The ANU C^{14} laboratory has undertaken a study to validate C^{14} age determinations from buried logs in high sea level beach deposits in northern N.S.W., Australia. The logs, if dated as submitted gave an indicated age of ca. 26,000 B.P., an age not acceptable on basis of past world wide high sea level studies, whilst chemical fractions isolated from these logs gave ages of ca. 13,000 years for resin extracts, ca. 26,000 years for humic extracts an greater than 40,000 years for cellulose. Clearly, several events are represented; one, the biological age of wood at time of deposition; two, the time of deposition of logs in present environment; three, the cementing of logs into the sand dunes by particulate and colloidal organic matter.

The separation of these events by careful dating of purified organic fractions is hampered by two factors: i) the isolation of datable organic fractions of 99.9% purity or better, and ii) the evaluation of residual C^{14} ccuntrates close to or within background error limits (45,000 to 50,000 years B.P.).

8.6.6 International radiocarbon dating standards

The 8th International Radiocarbon Dating Conference Wellington, New Zealand, has approved the Inter-laboratory Standards Cross-checking Programme coordinated by the ANU C^{14} laboratory. Nineteen C^{14} dating laboratories have accepted to participate and samples of 1850 Arizona Wood prepared by the Tree Ring Research Laboratory, University of Arizona, ANU-Sucrose, and NBS Oxalic Acid (the International Radiocarbon dating standard) have been distributed. Fifteen laboratories have now completed extensive determinations of these standards. The analysis of these results is now in progress.

9. TRACE ELEMENT GEOCHEMISTRY

9.1 Analytical techniques S.R. Taylor, M.P. Gorton

Further refinements to the computer program for data reduction from the spark source mass spectrograph have increased the precision of the analyses and speeded up the output of data. A Wright and Doherty type petrological mixing program has been developed to study the chemistry of the complex lunar highland breccias, which frequently contain several components.

The program (PETMIX III) is written in FORTRAN V as implemented on the UNIVAC 1108 computer. Provision has been made for up to 54 elements, including trace elements in ppm. Since many trace elements are present in numerically large concentrations, thus biasing the residuals, all elements are normalized to unity. To take account of the reliability of data or of the desirability of a good fit, it is necessary to superimpose a weighting system on the normalization.

When some components yield prohibited solutions PETMIX III will rerun the data in a series of runs omitting; each component in turn, with provision for omitting a second component within each of these runs.

9.2 Indonesian volcanic rocks (D. Whitford, S.R. Taylor, I. Nicholls)

The basic aim of the research is to study the spatial and temporal variations in the geochemistry of the volcanics of the East Sunda arc, with particular reference to Java and Bali, and to evaluate these data in the context of recent hypotheses concerning magma genesis in the island arc environment. Most of these theories have been developed on the basis of high pressure melting and crystallization studies and it is hoped that detailed geochemical investigations will serve to place additional constraints on them.

The rocks analyzed range from those with tholeiitic affinities close to the trench through lavas of calc-alkaline, high K calc-alkaline to shoshonitic affinities moving away from the trench. Samples so far analyzed from the Old Andesite Formation are generally richer in K than the tholeiitic rocks which characterize the early stages of several other island arcs of the Western Pacific region. Miocene basalts of Bali are also relatively potassic and display a distinctive trend of decreasing K_2O with increasing SiO_2.

The potassium rich Pleistocene lavas of G. Muriah in far northern Central Java have a compositional range similar to that found, for example, in the Roman Volcanic Province in Italy. Two compositionally distinct groups can be recognized, one showing a regular pattern of increasing K_2O content with increasing SiO_2, and the other being less well defined but showing generally lower K_2O contents for similar levels of SiO_2.

The strontium isotopic studies have highlighted several significant variations. The initial $^{87}Sr/^{86}Sr$ ratios in the recent volcanics of Bali are consistently lower (0.7039-0.7040) than those of West and Central Java (0.7045-0.7060). A similar, although less well defined, trend is also present in the "Old Andesites". The decrease in initial $^{87}Sr/^{86}Sr$ may be related to the observed decrease in crustal thickness from ∿30-35km under West and Central Java to ∿20-25km under Bali. The highly potassic lavas of G. Muriah have initial ratios of ∿0.7045, a value too low for crustal contamination to have played an important role in their genesis. The rocks from G. Papandajan and G.Merapi (Central Java) have initial $^{87}Sr/^{86}Sr$ ratios of ∿0.706. These relatively high values, in addition to anomalously high values of K, Rb, the light rare earths, etc., with respect to the distance of these volcanoes from the trench (and hence the Benioff Zone), suggest that crustal contaminati may have played a role in the formation of these particular rocks.

9.3 Caribbean igneous rock suites (T.W. Donelly*, S.R. Taylor)

One hundred and five igneous rock samples from the Caribbean were analyzed, 33 by MS7 spark-source mass spectrometry, 103 by emission spectroscopy, and 50 by X-Ray fluorescence.

The suite of samples had been previously studied by major-element, U, Th, Pb and Sr isotopic methods and the presence of two contrasting suites of magmas proposed. These appeared to correspond to the "island-arc tholeiite" and "calc-alkaline" plus "shoshonitic" suites of the southwest Pacific Island-arcs; thus the first goal of the project was to establish a correlation between the two areas. Such a correlation, based largely on rare-earth elements, as well as Zr, Sr, and other minor elements was made.

A further aim was to correlate plutonic and volcanic minor-element chemistry. The plutonic suites display far greater variability (dispersion) of minor element

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* S.U.N.Y., Binghampton

distribution, but are clearly co-magmatic. A high-cobalt plutonic suite was identified in the southern Caribbean.

A study of some ocean-floor basalts from the Caribbean was made. These amplified the earlier conclusion that these rocks are typical mid-ocean ridge basalts in composition, although erupted behind the arc.

In summary, the Caribbean igneous rocks project firmly established the correlation between the chemically contrasting suites within the Caribbean, and the southwest Pacific island-arc areas.

9.4 Deep sea basalts (D. Whitford, S.R. Taylor)

Because of the important role ascribed to the subducted oceanic crust in some theories of island arc calc-alkaline magma genesis, basalts from Christmas Island as well as from cores from the Deep Sea Drilling Project (DSDP) (Leg-27 - sites 259, 260, 261) in the eastern Indian Ocean have been analyzed for major and trace elements. Although there is quite a large variation between individual samples from the DSDP cores, almost all the spread in composition lies within the range of compositions of abyssal tholeiites from elsewhere in the world. The Christmas Island basalts are quite alkaline, typical of the so-called "oceanic island type basalts".

9.5 Trace elements in rutile and their significance for the origin of andesitic rocks (S.R. Taylor)

Rutiles separated from three eclogites are found to have high Zr, Hf and Nb contents. Zr/Hf ratios are comparable, but Zr/Nb much lower than in basalts. Sr, W, Mo vary systematically with Zr and are high. U is very high in one specimen, moderate but higher than thorium in another and in a third U and Th were not detected. The rutiles are enriched in light rare earth elements.

It has been suggested that andesitic rocks are produced by partial melting of ocean floor basalt in subduction zones and that eclogite is the residue. These observations suggest that the low Ti, Zr, Nb and high Zr/Nb ratio, all of which are characteristic of subduction zone rocks, can be explained if rutile is a refractory phase in the eclogite residuum.

9.6 Geochemistry of sedimentary rocks

9.6.1 Rare-earth abundances and continental evolution

(W. Nance, S.R. Taylor)

Analytical rare-earth element data for Precambrian sedimentary rocks show an Eu enrichment relative to Paleozoic and younger rocks. Young sedimentary rocks show an Eu depletion relative to the chondritic REE pattern. The Precambrian sediments show no Eu anomaly relative to the chondrite pattern. Precambrian sedimentary rocks and present-day volcanic rocks of island arcs have similar REE patterns, total REE abundances and excess Eu. This similarity, both in enrichment of Eu and in total REE content, between recent island arc rocks and Precambrian sedimentary rocks suggests that the latter may be derived from ancient equivalents of island arc rocks. It is proposed that (a) the Eu excess in the Precambrian sediments reflects that in the source material and is an artifact of early crustal formation via island arc volcanism and (b) that the europium depletion in modern upper crustal rocks is a consequence of partial melting, producing an upper crust of granodiorite composition, and a residual lower crust enriched in europium.

9.7 Pelagic marine sediments (T.W. Donelly, S.R. Taylor)

The principal aim of the project was to determine to what extent would minor-element chemistry elucidate the problem of provenance of detrital constituents in deep-sea sediments, and more specifically to distinguish between a terrigenous contribution and a calc-alkalic volcanic contribution. A further aim was to ascertain the sorts of information that rare-earth element distributions could provide for provenance and diagenesis of deep-sea sediments.

The first-row transition metals, as well as a number of heavier metals, are subject to secondary redistribution in the sediment so that their local abundance has no genetic significance.

The rare earths and Zr proved, however, to be fairly conservative and potentially useful. The distinctio between a terrigenous (shale) and a volcanic contribution would appear possible through the REE/Zr or Ce/Zr ratio, which is high for terrigenous and low for volcanic sources. Also, the terrigenous samples have a negative europium anomaly. Clays derived from diagenesis of basaltic ash retain the rare-earth pattern of the basalt.

9.8 New Hebrides (M.P. Gorton, S.R. Taylor)

Completion of a detailed geochemical study of the New Hebrides island arc has allowed the evolution of the arc to be divided into three main stages. An early, pre-mid Miocene stage of basaltic to andesitic calc-alkaline volcanism built the foundation of the arc and was followed after a long period of quiescence by an U. Miocene-Pliocene phase of tholeiitic volcanism located to the east of the old volcanic ridge. Dominantly basaltic volcanism which spans the last 2 m.y. is located between these two earlier ridges and ranges in character from tholeiitic to alkaline. Within this phase, basalts of two different types may be interbedded, and the chemistry and location of this phase of volcanism is interpreted as a result of rifting and of subsequent fragmentation of the arc in post-Pliocene times.

Recognition of rare earth element patterns typical of ocean ridge tholeiites from basalts of an ophiolite sequence on Pentecost island suggests that these rocks may be a slice of ocean floor. Local geology suggests over-thrusting from the east implying former eastward subduction in the New Hebrides, the reverse of the present day polarity.

Rare earth partition coefficients have been determined for a range of minerals, and recognition of the possibility of strong compositional control in amphiboles may preclude the use of amphibole in the generation of andesites.

10. COSMOCHEMISTRY

10.1 Lunar chronology (W. Compston, B. Chappell)

10.1.1 Apollo 16 soils

Rb-Sr model ages and chemical analyses by X-ray fluorescence were made of nine Apollo 16 soils, as part of a continuing program of lunar analyses jointly with the ANU Geology Department. Compared with other lunar sites, these soils are distinctive in their higher CaO and Al_2O_3. Interelement correlations indicate that the slight chemical heterogeneity within the suite is due to the mixing of two rock components that differ principally in their plagioclase content. The plagioclase-rich end member is concentrated near North Ray Crater. A well-fitted "4.6 b.y." Rb-Sr isochron was found which is interpreted as a mixing line without direct time significance. In contrast to the Apollo 14 soils, there was little "secondary" dispersion of the data along a 4.0 b.y. isochron even though this is the known mineral age of rocks from this site, so that the Apollo 16 data are evidently dominated by Rb-enriched rock fragments that have single-stage model ages greater than about 4.3 b.y.

10.1.2 Apollo 17 mare basalts

A Rb-Sr mineral age of 3.83±0.05 b.y. and initial $^{87}Sr/^{86}Sr$ of 0.69920±0.00003 were found for rock 70035 (an early release sample), using separates of plagioclase and ilmenite. These results are not distinguishable from the low-K Apollo 11 basalts but the age is slightly greater than the high K Apollo 11 basalts. Chemical analysis by X-ray fluorescence showed that 70035 is an Apollo 11 low-K type basalt, but in detail, it contains more Ti, Mg and lower Al,Ca than the Apollo 11 rocks.

Additional Apollo 17 basalts have now been received so that comparative isotopic work can be done.

10.1.3 Lunar breccias

The particular challenge in lunar geochronology lies in handling the dating problems of breccias. These are: (i) to measure the internal ages of clasts, which ought to be greater than the (latest) breccia-forming event; and (ii) to measure the age of the brecciation through mineral ages for the equilibrated matrix.

The principal technical limitation is the small volumes of the clasts and of clast-free recrystallized matrix available. It is essential that blank levels and machine sensitivity permit the use of milligram quantities of hand-picked minerals containing as little as 50x10-9g of strontium. With these requirements in mind, a considerable effort has been made this year with the housekeeping problems of reagent purity, fall-out level, hand picking procedures and the chemical procedures for low alkali Mg-rich samples. We believe we now have more constant blanks (0.06±.01 ng for Rb) and cleaner samples, which yield better runs on the mass spectromter.

A mineral age for the Apollo 16 breccia 68416, a gabbroic anorthosite, was obtained at 3.9±0.1 b.y., in good agreement with the published results for sample 68415 which was chipped by the astronauts from the same large boulder. The initial $^{87}Sr/^{86}Sr$ was also in good agreement with 68415, so that no contamination on the moon during emplacement of the anorthosite material bearing a 4.6 b.y. model age was detected.

Current work on another brecciated and equilibrated gabbroic anorthosite, 77017, is less successful owing to the very small dispersion in Rb/Sr between plagioclase and opaques.

10.2 Lunar geochemistry (S.R. Taylor, M.P. Gorton)

10.2.1 Establishment of overall highland composition by correlation of landing site samples with orbital chemical data.

Study of inter-element relationships (e.g. Zr/Mb/Hf etc., has revealed widespread inter-element correlations. Most of the refractory elements (REE, Th, U, Zr, Hf, Nb, Ba) show strong positive correlations, interpreted as resulting from mixing. Such correlations can be used in conjunction with the orbital gamma-ray Th and XRF Mg/Si and Al/Si values to model the overall composition of the highland crust.

An average highland composition is proposed, based on the Apollo 15 and 16 orbital data for Si, Al, Mg and Th. Abundances for most other elements are derived from the inter-element relationships and correlations, and checked by the mixing program.

The resulting composition consists of 69% highland basalt (gabbroic anorthosite) and 31% Low K Fra Mauro basalt. There is no significant Eu anomaly. The abundances are:

SiO_2:45.2%; TiO_2: 0.68%; Al_2O_3: 24.9%; FeO: 6.3%; MgO: 8.5%; CaO: 13.8%; Na_2O: 0.4%; K_2O: 0.11%; Cr_2O_3: 0.11%; Ba: 144 ppm; Th: 1.8 ppm; U: 0.46 ppm; Pb: 1.6 ppm; Zr: 156 ppm; Hf: 3.2 pp Nb: 10.8 ppm; Y: 32 ppm; Σ REE: 85 ppm.

10.2.2 Relation of highland crust to whole moon

Multielement models of overall highland composition can be related to various whole moon models, to establish geochemical element budgets and constraints on whole moon models.

An important chemical characteristic of lunar samples is the high concentration of refractory elements, coupled with depletion of volatile elements in comparison with primitive solar nebula element abundances. The concentration of many refractory elements (such as rare earths) in lunar samples frequently equals or exceeds those in terrestrial crustal samples. It is clear that such high abundances can not be typical of the whole Moon. For example, the contents of the heat-producing elements, K,U and Th in the surficial rocks are sufficient to generate the observed heat flow from a thin outer zone. Thus the concept of an outer zone of the Moon enriched in refractory elements has gained general acceptance. Two basic models have been proposed to account for these observations:

(i) The lunar uplands represent a primitive lunar "crust" derived by differentiation after accretion, from parent material which may have been either primitive or fractionated prior to accretion.

(ii) Primary accretion of an outer layer enriched in refractory elements (heterogeneous accretion model).

It is possible to distinguish between these alternatives by a study of the relative abundances of a wide spectrum of trace elements. Moreover, the role of volatilization and condensation processes can be assessed from the relative abundances of the abundances of the volatile elements relative to those of involatile elements.

Ratios of volatile to involatile elements (such as K/Zr, K/La) are constant for many elements both in mare and highland samples. It is particularly significant that many elements of varying volatility show good correlations. Such observations place constraints on heterogeneous accretion models, which accrete a highland crust more depleted in volatile elements than the deeper source regions of the mare basalts.

10.2.3 Crystal-liquid fractionation and the lunar crust

The role of liquid-solid fractionation can be studied through comparisons between abundances in the crust and the whole moon. The following relationships emerge:

Elements which are similar in size and valency to Fe^{2+} and Mg^{2+} are depleted in the crust. These cations are assumed to be major constituents on the lunar interior, and elements of similar chemical character are retained in crystal lattice sites occupied by them. As the size or valency of the elements differs from those of Fe^{2+} and Mg^{2+}, there is a progressive enrichment in the lunar crust. Such a pattern is consistent with crystal-liquid fractionation since the entry into or rejection of lithophile ions from silicate lattices is dependent on size and valency inter alia.

There is no simple correlation with volatility. Thus it is clear that the overriding influence in the partitioning of elements into the highlands has been that of solid-liquid, not solid-gaseous equilibria. The whole Moon, or at least the portion affected by melting, is depleted in volatile elements, relative to primordial solar nebula abundances.

10.2.4 The lunar highlands : Summary

In summary, it seems that the general features of lunar highland chemistry can be explained by melting and differentiation of a Moon (already depleted in volatiles). The lack of correlation with element volatility constitutes further evidence against the accretion of the outer layer of the Moon from more refractory material than that comprising the interior. This reinforces the evidence of uniformity of volatile/involatile element ratios between highland and mare samples, in favour of the homogeneous accretion model.

10.3 Meteorite geochemistry (P. Martin, B. Mason)

A group of 21 samples of various constituents of the Allende meteorite have been analyzed. These samples are important since they may represent primitive condensed solar nebula material.

The Allende samples can be grouped in various ways by using chemical, mineralogical, and textural parameters.

The largest group (I) can be characterized as melilite chondrules, which are spherical aggregates of melilite, Al-Ti pyroxene, and spinel, usually also a little anorthite. They have a coarsely crystalline igneous texture. Chemically they are characterized by high Al_2O_3 (27-33%), high CaO (23-33%), an unfractionated rare earth pattern averaging 10-15 times chondritic abundances (but with a slight positive europium anoamly - Eu/Eu* is 1.2-1.5).

Another well defined group (II) has low Eu (0.1-0.4 ppm) and a marked negative Eu anomaly (Eu/Eu* is 0.1-0.6), a fractionated rare earth pattern with light REE (La-Sm) relatively high, with rapidly diminishing relative abundances of the heavier REE, but with a positive Yb anomaly. Texturally they are fine-grained aggregates with an irregular form.

Group III samples are texturally similar to the preceding group and have similar low Eu concentration and a marked negative Eu anomaly. However, they have an unfractionated REE pattern like that of group I, but with a negative Yb anomaly. They have high Al_2O_3 (40.3, 43.3%) and moderate CaO (11.4%).

A fourth group is characterized by high MgO content (23-35%) and consists largely of olivine. Texturally they are fine-grained irregular aggregates. The REE concentrations are low and the pattern is relatively unfractionated.

10.4 Apollo 17 high titanium basalts (D.H. Green, A.E. Ringwood)

The Apollo 17 lunar landing returned numerous samples of fine-grained, rapidly quenched titanium-rich basalts differing significantly from the previous Apollo 11 Ti-rich basalts in the abundance of modal olivine and in higher MgO contents and Mg/Mg+Fe ratios, Several of the basalts have been studied by electron microprobe analysis and parallel melting studies on the compositions demonstrate that the olivine phenocrysts are not accumulative and that the bulk compositions of the samples may be taken as magma compositions at the lunar surface. These studies thus support the previous conclusions that the Ti-rich lunar basalts are close to primary magmas from the lunar interior and are not highly fractionated derivatives of near surface processes. Of particular interest are the samples of orange glass which have the composition of very magnesian and olivine-rich Ri-rich basalts. Experimental study of the melting relationships of this composition as a function of pressure have yielded the important result that orthopyroxene is a liquidus phase at 20kb - 25kb with olivine on the liquidus at lower pressure and clinopyroxene on the liquidus at higher pressure. There is no Ti-rich phase on or near the

liquidus at these pressures. Considered in relation to the studies on other lunar mare basalts, the results show that an internally consistent model of partial melting of an orthopyroxene + clinopyroxene + olivine + accessory minerals source rock can be presented yielding the Ti-rich basalts (8-10% TiO_2) as the smallest melt fraction, and the Ti-poor Apollo 15 Green Glass (0.4% TiO_2) as the largest melt fraction (30-60% melting) of the deep lunar interior.

10.5 Lunar experimental petrology (A. Ringwood, D.H. Green)

10.5.1 Evaluation of the significance of Ca, Al, rich lunar compositions in relation to the mean lunar composition

Some recent discussions of lunar chemistry and origin have suggested that the mean lunar composition is rich in Ca+Al and that the observed gabbroic anorthosite ('Lunar Highland Basalt') compositions from the Lunar Highland regions may either be representative of the mean lunar composition or are representative of a partial melt extracted from the deep lunar interior. The techniques of experimental petrology have been used to evaluate these hypotheses in terms of the mean density and coefficient of moment of inertia constraints, the internal consistency of the partial melting model, and the further constraint that the lunar interior composition must be capable of yielding mare basalts by a process of partial melting. It has been shown that the hypotheses fail when evaluated against all these constraints and there is no support for a mean Ca, Al-rich lunar composition, rather the gabbroic anorthosite rock types must be restricted to an outer layer derived in an early differentiation of the outermost 100-200km of the moon.

10.6 Origin of Earth and Moon

Dramatic advances in our understanding of the composition and constitution of the moon have been made during the last few years as a result of the Apollo project and the study of returned lunar samples. Likewise, over the past decade, major advances have been made in our knowledge of the nature of the earth's interior. The flood of new information provides many new boundary conditions for theories of the origin of earth and moon and has stimulated new enquiries into this venerable and controversial topic.

A detailed study of some of these questions was carried out during the year and some new perspectives were reached. A comprehensive hypothesis of the origin of the earth and moon has been proposed and will be further developed and subjected to critical scrutiny in the years to come.

10.7 Meteorite petrology (P. Martin, A.E. Ringwood)

It has been proposed that inclusions of high temperature, refractory minerals found in certain meteorites may represent the earliest condensates from the primitive cooling solar nebula. This proposition, currently popular in the U.S.A., is being tested via a detailed chemical, mineralogical and experimental petrological investigation of these samples. Preliminary indications are that they have cooled and crystallised much too rapidly to be consistent with the origin suggested above.

10.8 Meteorites (S.J.B. Reed)

Microprobe work on the following meteorites was carried out:

(i) Donnybrook I (in collaboration with Dr. R.A. Binns, University of W.A.), new mesosiderite.

(ii) Donnybrook II (with Dr. Binns), new iron meteorite.

(iii) Bencubbin (with Dr. Binns), new type of chondritic inclusions.

(iv) New stony meteorite from Winton area, Queensland (in collaboration with Professor A. Wilson, University of Q ueensland), H4 chondrite.

(v) New iron meteorite obrained from resident of Broken Hill, said to have been found in S.A. (octahedrite).

10.6.1 Fireball of July 25

A spectacular meteoritic fireball travelling approximately E-W was seen over a large area of N.S.W. Investigation of sighting reports suggested a landing site a few km W. of Deniliquin, but so far no pieces have been found.

10.6.2 Meteorite collection

Further acquisitions were made, and the collection now includes 165 chondrites, 21 achondrites, 104 irons, and 23 stony-irons.

10.6.3 Apollo 16 meteoritic metal particles

Microprobe analysis of about 100 metallic particles separated from five Apollo 16 rock and soil samples showed all but one to be meteoritic by the criterion of cobalt content. However, by comparison with known terrestrial

meteorites the lunar metal was nickel-poor and phosphorus-rich. This may indicate a significant difference between the early meteoritic component thought to predominate in the Apollo 16 samples and recent terrestrial meteorites. According to the Fe-Ni-P phase diagram the compositions of coexisting metal and phosphide represent temperatures in the range 550°-650°C.

10.8 Accurate analysis of bulk silicate rocks using the TPD microprobe (I.A. Nicholls)

Glasses prepared by fusion of bulk rock powders on an iridium-strip heater (see Experimental petrology) have been analysed for major elements using the TPD microprobe. Spectral overlap coefficients are calculated from the available range of mineral standards. Peak intensities for unknowns are converted to uncorrected concentrations using well-known standard rocks as substandards. Triplicate analyses are performed on duplicate glasses. Limits of precision and accuracy of determinations range from 1-2% relative for elements present in high concentration to ∿10% for elements present at the 1% level. Satisfactory analyses of sub-alkaline to alkaline basaltic compositions, andesites, dacites and rhyolites or granites have been obtained.

11. PETROLOGY

11.1 Mineral zoning as a record of P,T history of metamorphic rocks (A. Råheim)

As part of the combined geochronological and petrological study of eclogite and enclosing quartzite and schist in western Tasmania, detailed study has been made of the chemical zoning in the primary metamorphic minerals. The zoning is particularly well-developed in garnet with Fe, Ca-rich core and Mg-rich rim but in contrast to this co-existing clinopyroxene or micas have Mg-rich cores and Fe-rich rims. Various models of diffusion-controlled metamorphic growth have been evaluated and rejected in favour of growth during changing P,T conditions with failure of early-formed crystal nucleii to maintain equilibrium under the changing physical conditions. A similar conclusion follows from the study of zonal variation in Al-Si substitution in phengitic muscovite and parallel patterns of mineral zoning are found in all the rock types of the region. Experimental study of the P,T dependence of the Fe, Mg partition between garnet and clinopyroxene and known stability relationships of the minerals allow the inference that the region passed through a prograde metamorphism from 8-10kb, 450°C to a metamorphic maximum at >10kb, 600±20°C. Following waning of this metamorphic event, evidenced in very slight reversed zoning on the outermost margins of crystals, up to three later, largely tectonic events have produced variable and local growth of chlorite, amphibole and mica as secondary alteration at low P, low T conditions.

11.2. Talc+Garnet+Kyanite+Quartz schist from an eclogite-bearing terrane, western Tasmania. (A. Raheim, D.H. Green)

A previously undescribed metamorphic assemblage of talc+almandine-pyrope garnet+kyanite+quartz occurs in association with eclogite in western Tasmania. Detailed study of mineral chemistry and consideration of relevant alternative assemblages has shown that the thermal maximum during metamorphism was at 600±20°C, at a pressure of >10kb. Chemical zoning in the garnet and talc preserves evidence of increasing temperature, at high pressure, during growth of the major minerals. The rock types of the metamorphic sequence are dominantly meta-pelites and quartz-rich meta-sandstones and the petrological studies demonstrate that the sedimentary sequence was buried to depths of >30km during Precambrian orogeny but was then uplifted and cooled at much shallower crustal levels.

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