INTERNATIONAL DICTIONARY OF GEOPHYSICS

SEISMOLOGY, GEOMAGNETISM, AERONOMY, OCEANOGRAPHY, GEODESY, GRAVITY, MARINE GEOPHYSICS, METEOROLOGY THE EARTH AS A PLANET AND ITS EVOLUTION

EDITORS

S.K. RUNCORN F.R.S.

INTERNATIONAL DICTIONARY OF GEOPHYSICS

SEISMOLOGY, GEOMAGNETISM, AERONOMY, OCEANOGRAPHY, GEODESY, GRAVITY, MARINE GEOPHYSICS, METEOROLOGY, THE EARTH AS A PLANET AND ITS EVOLUTION

EDITORS

S. K. RUNCORN F. R. S.
NEWCASTLE UPON TYNE U. K.

SIR EDWARD BULLARD, F. R. S.
CAMBRIDGE, U. K.

K. E. BULLEN, F. R. S.
SYDNEY, AUSTRALIA

W. A. HEISKANEN
HELSINKI, FINLAND

SIR HAROLD JEFFREYS, F. R. S.
CAMBRIDGE, U. K.

H. MOSBY
BERGEN, NORWAY

T. NAGATA
TOKYO, JAPAN

M. NICOLET
BRUSSELS, BELGIUM

K. R. RAMANATHAN
AHMEDABAD, INDIA

H. C. UREY, For. Mem. R. S.
LA JOLLA, CALIFORNIA, U. S. A.

F. A. VENING MEINESZ, For. Mem. R. S.
(deceased)
AMERSFOORT, NETHERLANDS

WITH THE EDITORIAL ASSISTANCE OF D. B. STONE NEWCASTLE UPON TYNE, U. K.

PERGAMON PRESS
OXFORD · LONDON · EDINBURGH · NEW YORK
TORONTO · SYDNEY · PARIS · BRAUNSCHWEIG

Pergamon Press Ltd., Headington Hill Hall, Oxford
4 & 5 Fitzroy Square, London W. 1

Pergamon Press (Scotland) Ltd., 2 & 3 Teviot Place, Edinburgh 1

Pergamon Press Inc., 44-01 21st Street, Long Island City, New York 11101

Pergamon of Canada, Ltd., 6 Adelaide Street East, Toronto, Ontario

Pergamon Press (Aust.) Pty. Ltd., 20-22 Margaret Street, Sydney, New South Wales

Pergamon Press S.A.R.L., 24 rue des Écoles, Paris 5ᵉ

Vieweg & Sohn GmbH, Burgplatz 1, Braunschweig

First published 1967

Library of Congress Catalog Card No. 66-16369

2802/67

FOREWORD

This International Dictionary of Geophysics is planned to serve a number of purposes. At a time when many of those trained in geology, physics and mathematics are entering geophysical work it seems timely to supply them with concise authoritative articles in the various fields. In addition many of those working in other branches of science and in engineering need access to clear explanations of geophysical terms and arguments.

During the International Union of Geodesy and Geophysics held at Berkeley in 1963, a number of the editors met informally to plan the work. At such a meeting they were very conscious of the long record of international collaboration in geophysics starting with the formation of the International Union of Geodesy and Geophysics, in 1919 and its various forerunners, and the succession in recent years of highly successful examples of international collaborative programmes, the International Geophysical Year, the International Year of the Quiet Sun, and the Upper Mantle Project. The editors therefore have striven to provide, as far as possible, a work not only covering the field but also having a truly international spectrum of contributions.

The Editors wish to express their gratitude to all who have contributed to this work and to Mr. S. Crimmin of Pergamon Press who has handled the project from the beginning.

LIST OF CONTRIBUTORS

AGAPOVA G.P. *(Moscow)*
AIKIN A.C. *(Greenbelt, Maryland)*
AITCHISON J. *(Glasgow)*
AITKEN M.J. *(Oxford)*
AKIMOTO S. *(Tokyo)*
ALLEN C.W. *(London)*
ALLER L. *(Los Angeles, Calif.)*
ANDERSON D.L. *(Pasadena, Calif.)*
ARGUE A.N. *(Cambridge)*
ARNOLD K. *(Potsdam)*
ARSCOTT F.M. *(London)*
ATLAS D. *(Bedford, Mass.)*

BALSLEY J.R. *(Middletown, Conn.)*
BANERJEE S.K. *(Newcastle upon Tyne)*
BARBER N.F. *(New Zealand)*
BARBIER D. *(Paris)*
BARNES V.E. *(Austin, Texas)*
BARSUKOV O.M. *(Moscow)*
BARTH C.A. *(Pasadena, Calif.)*
BATH M. *(Uppsala)*
BAUER S.J. *(Greenbelt, Maryland)*
BE A.W.H. *(New York)*
BEALS C.S. *(Ottawa)*
BEER A. *(Cambridge)*
BEYNON W.J.G. *(Aberystwyth)*
BJERHAMMAR A. *(Stockholm)*
BLACKWELL D.E. *(Oxford)*
BOLT B.A. *(Berkeley, Calif.)*
BOMFORD G. *(Oxford)*
BOURDEAU R. *(Greenbelt, Maryland)*
BOWDEN K.F. *(Liverpool)*
BOWIN C. *(Woods Hole, Mass.)*
BOYDEN C.J. *(Bracknell, Berks.)*
BRANDENBURGER A.J. *(Quebec)*
BREWER A.W. *(Toronto)*
BROUWER D. *(Newhaven, Conn.)*†
BROWN D. *(Melbourne, Fla.)*
BUCHWALD T.V. *(Sydney)*
BUDYKO M.I. *(Leningrad)*
BULLEN K.E. *(Sydney)*
BUXTON J.N. *(London)*
BYERS H.R. *(Chicago)*

CAGNIARD L. *(Paris)*
CAMERON A. *(New York)*
CHADWICK P. *(Norwich)*
CHAMBERLAIN J.W. *(Tucson, Arizona)*
COHEN L. *(Southampton)*
COOK A.H. *(Teddington)*
COULOMB J.M.F. *(Paris)*
COX A. *(Menlo Park, Calif.)*
CREER K.M. *(Newcastle upon Tyne)*
CROOM D.L. *(Maidenhead, Berks.)*
CULKIN F. *(Godalming, Surrey)*

DAHL O. *(Bergen, Norway)*
DALGARNO A. *(Belfast)*
DARBYSHIRE J. *(Anglesey)*
DEACON E.L. *(Victoria, Australia)*
DERRINGTON M.G. *(Manchester)*
DESSLER A. *(Houston, Texas)*
DIETZ R. *(Washington)*
DIX C.H. *(Pasadena, Calif.)*
DOBSON G.M.B. *(Oxford)*
DOELL R.R. *(Menlo Park, Calif.)*
DONAHUE T.M. *(Pittsburgh, Pa.)*
DONN W.L. *(New York)*
DONELLY T.W. *(Houston, Texas)*
DUTSCH H.U. *(Zurich)*

EASTHOPE C.E. *(Aberystwyth)*
EBDON R.A. *(Bracknell, Berks.)*
EMELYANOV E.M. *(Moscow)*
ENGELSEN I. *(Horten, Norway)*

FANSELAU G. *(Potsdam)*
FARQUHAR R.M. *(Toronto)*
FERRIS G.A.J. *(Leeds)*
FINCH H.F. *(Herstmonceux Sussex)*
FINLAY FREUNDLICH E. *(Germany)*
FRANK N.H. *(Cambridge, Mass.)*
FREEMAN M.H. *(Bracknell, Berks.)*
FU C.Y. *(Peking)*

GADE H.G. *(Bergen, Norway)*
GADSDEN M. *(Boulder, Colorado)*
GAKKEL YA.YA. *(Leningrad)*
GARLAND G.D. *(Toronto)*
GASKELL T.F. *(London)*
GILLES D.C. *(Glasgow)*
GIRDLER R.W. *(Newcastle upon Tyne)*
GLEN J.W. *(Birmingham)*
GLIDDON J.E.C. *(London)*

GODSON W.L. *(Toronto)*
GONCHAROV V.P. *(Moscow)*
GRIFFITHS D.H. *(Birmingham)*
GROSSMAN W. *(Hanover, Germany)*
GROVES G.V. *(London)*
GUILCHER A. *(Paris)*

HAHN A. *(Hanover, Germany)*
HALES A.L. *(Dallas, Texas)*
HANSEN W. *(Hamburg)*
HANSON W.B. *(Dallas, Texas)*
HARGREAVES J.K. *(Boulder, Colorado)*
HARRIS P.G. *(Leeds)*
HARRISON C.G.A. *(La Jolla, Calif.)*
HARRISON J.C. *(Boulder, Colorado)*
HAUBRICH R.A. *(La Jolla, Calif.)*
HAURWITZ B. *(New York)*
HEALY J.H. *(Lakewood, Colorado)*
HEDBERG H.D. *(Princeton, N.J.)*
HEDDLE T.A. *(London)*
HEEZEN B.C. *(New York)*
HEISKANEN W.A. *(Helsinki)*
HENRIKSEN S. *(Washington)*
HERSEY J.B. *(Wood's Hole, Mass.)*
HIDE R. *(Cambridge, Mass.)*
HINDLEY H.R. *(Buntingford, Herts.)*
HINES C.O. *(Ottawa)*
HIRVONEN R.A. *(Helsinki)*
HODGSON J.H. *(Ottawa)*
HONKASALO T. *(Helsinki)*
HOTINE M. *(Washington)*
HOUGHTON T. *(Oxford)*
HOUSNER G.W. *(Pasadena, Calif.)*
HUNKINS K. *(New York)*

HUNTEN D.M. *(Tucson, Arizona)*

ISHIGURO S. *(Godalming, Surrey)*

JACCHIA L.G. *(Cambridge, Mass.)*
JACOBS W.C. *(Washington)*
JEFFREYS H. *(Cambridge)*
JENSEN H. *(Copenhagen)*
JERLOV N. *(Gothenburg, Sweden)*
JOHNSON C.Y. *(Washington)*
JONES R.F. *(Bracknell, Berks.)*
JUNG K. *(Columbus, Ohio)*

KAISER T.R. *(Sheffield)*
KAULA W. *(Greenbelt, Maryland)*
KHAN M.A. *(Leicester)*
KING-HELE D.G. *(Farnborough, Hants.)*
KNAPP D.G. *(Washington)*
KNIGHTING E. *(Bracknell, Berks.)*
KNOPOFF L. *(Los Angeles, Calif.)*
KOCZY F.F. *(Miami, Fla.)*
KUENEN P.H. *(Groningen, Holland)*
KUKKAMAKI T.J. *(Helsinki)*

LAL D. *(Bombay)*
LANGLEBEN M.P. *(Montreal)*
LANGSETH M. *(New York)*
LAUGHTON A.S. *(Godalming, Surrey)*
LAURILA S. *(Columbus, Ohio)*
LAVERGNE M. *(France)*
LEE W.H.K. *(La Jolla, Calif.)*
LEHMANN I. *(Copenhagen)*
LEIBY J. *(Wood's Hole, Mass.)*
LENNON G.W. *(Birkenhead, Cheshire)*

LEVIN B.J. *(Moscow)*
LONCAREVIC B.D. *(Dartmouth, N.S.)*
LORENZ E.N. *(Cambridge, Mass.)*
LOWES F.J. *(Newcastle upon Tyne)*
LUBIMOVA E. *(Moscow)*
LYTTLETON R.A. *(Cambridge)*

MACKENZIE D. *(Cambridge)*
MARTIN D.H. *(London)*
MARUSSI A. *(Trieste)*
MASON B.H. *(New York)*
MASON R.G. *(London)*
MATHEWS D. *(Cambridge)*
MCCLAIN E.P. *(Washington)*
MCFARLANE W.M. *(Washington)*
MEHNERT K.R. *(Berlin)*
MILLER J. *(Cambridge)*
MIYAKE Y. *(Tokyo)*
MOORE C.B. *(Tempe, Arizona)*
MOORE L.W. *(Bromley, Kent)*
MORITZ H. *(Berlin)*
MORSE R.M. *(Portland, Maine)*
MOSBY H. *(Bergen, Norway)*
MUELLER I.I. *(Columbus, Ohio)*

NAGATA T. *(Tokyo)*
NAGY B. *(La Jolla, Calif.)*
NASH W.B. *(Bournemouth, Hants.)*
NAYLER J.L. *(Claygate, Surrey)*
NESTEROFF W.D. *(Paris)*
NEWSTEAD G. *(Canberra, Australia)*
NIBLETT E.R. *(Ottawa)*
NICHOLLS G.D. *(Manchester)*
NICHOLSON R. *(Manchester)*
NICOLET M. *(Brussels)*
NODTVEDT H. *(La Spezia, Italy)*

O'BRIEN B. J. *(Houston, Texas)*
OMHOLT A. *(Oslo)*
OPIK E. J. *(Armagh)*
OROWAN E. *(Cambridge, Mass.)*
ORR C. *(Atlanta, Georgia)*
OVENDEN M. W. *(Glasgow)*

PACKER D. M. *(Washington)*
PAGEL B. E. J. *(Hailsham, Sussex)*
PALMEN E. *(Helsinki)*
PANOFSKY H. A. *(Pennsylvania)*
PARASNIS D. S. *(Boliden, Sweden)*
PARKER R. *(Portsmouth)*
PARRY J. H. *(Newcastle upon Tyne)*
PETROVA G. N. *(Moscow)*
PHILLIPS R. *(La Jolla, Calif.)*
PONNAMPERUMA C. *(Moffatt Field, Calif.)*
POOLE J. H. *(Dublin)*
PRICE A. T. *(Exeter)*

RAMANATHAN K. R. *(Ahmedabad, India)*
RAO K. N. *(Bombay)*
REID J. L. Jr. *(La Jolla, Calif.)*
RIKITAKE T. *(Tokyo)*
RINGWOOD A. E. *(Canberra, Australia)*
RINNER K. *(Graz, Austria)*
RITTMANN A. *(Catania, Sicily)*
ROBBINS A. R. *(Oxford)*
ROBERTS P.H. *(Newcastle upon Tyne)*
ROBIN G. DE Q. *(Cambridge)*
ROELOFS R. *(Delft, Holland)*
ROSSITER J. R. *(Liverpool)*
ROTHE J. *(Strasbourg, France)*
ROY A. E. *(Glasgow)*
RUNCIMAN W. A. *(Christchurch, N.Z.)*
RUNCORN S. K. *(Newcastle upon Tyne)*

SAELEN O. H. *(Bergen, Norway)*
SAGAN C. *(Cambridge, Mass.)*
SAITO T. *(New York)*
SATTERTHWAITE G. E. *(Oxford)*
SAVAGE J. C. *(Toronto)*
SAVERENSKY E. F. *(Moscow)*
SAWYER J. S. *(Bracknell, Berks.)*
SCHERHAG R. *(Berlin)*
SCHMERLING E. *(Washington)*
SCORER R. S. *(London)*
SCRUTTON C. T. *(London)*
SEKERA Z. *(Los Angeles, Calif.)*
SHEPARD F. P. *(La Jolla, Calif.)*
SHEPPARD P. A. *(London)*
SHOR G. *(La Jolla, Calif.)*
SLICHTER L. B. *(Los Angeles, Calif.)*
SMITH H. M. *(Hailsham, Sussex)*
SMITH S. W. *(Pasadena, Calif.)*
SMITH T. J. *(Washington)*
SNEDDON I. N. *(Glasgow)*
SQUIRES G. L. *(Cambridge)*
STACEY F. D. *(Brisbane, Australia)*
STANDLEY K. J. *(Dundee)*
STEINHART J. S. *(Washington)*
STEWART R. W. *(Vancouver)*
STONELEY R. *(Cambridge)*
SUTTON O. G. *(Bracknell, Berks.)*

TARDI P. *(Paris)*
THELLIER E. *(Paris)*
THOMAS P. D. *(Washington)*
THOMAS W. J. *(Swansea)*
THOMPSON LL. G. D. *(Columbus, Ohio)*
THORLEY N. *(Newcastle upon Tyne)*
TOKSOZ N. *(Pasadena, Calif.)*
TOZER D. C. *(Newcastle upon Tyne)*
TSUBOI C. *(Tokyo)*
TURNER F. J. *(Berkeley, Calif.)*

UDINTSEV G. B. *(Moscow)*
UOTILA U. A. *(Columbus, Ohio)*
UREY H. C. *(La Jolla, Calif.)*

VALLANCE JONES A. *(Saskatoon, Saskatchewan)*
VEIS G. *(Athens)*
VENING MEINESZ F. A. *(Amersfoort, Netherlands)*
VESTINE E. H. *(Santa Monica, Calif.)*

WADATI K. *(Tokyo)*
WALKER R. M. *(New York)*
WALLACE L. *(Tucson, Arizona)*
WARNER B. *(London)*
WEIDEMANN H. *(Hamburg)*
WHITHAM K. *(Ottawa)*
WHITMORE G. D. *(Washington)*
WHITTEN C. *(Washington)*
WILSON JAMES T. *(Ann Arbor, Michigan)*
WILSON R. L. *(Liverpool)*
WISE D. *(Lancaster, Pa.)*
WOLF H. *(Bonn)*
WOOLAND G. P. *(Hawaii, Honolulu)*
WYRTKI K. *(Hawaii)*

ZEIGLER J. *(Wood's Hole, Mass.)*
ZHIVAGO A. V. *(Moscow)*
ZUCKER I. J. *(London)*

† deceased

LIST OF CONTRIBUTORS

AGAPOVA G.P. *(Moscow)*
AIKIN A.C. *(Greenbelt, Maryland)*
AITCHISON J. *(Glasgow)*
AITKEN M.J. *(Oxford)*
AKIMOTO S. *(Tokyo)*
ALLEN C.W. *(London)*
ALLER L. *(Los Angeles, Calif.)*
ANDERSON D.L. *(Pasadena, Calif.)*
ARGUE A.N. *(Cambridge)*
ARNOLD K. *(Potsdam)*
ARSCOTT F.M. *(London)*
ATLAS D. *(Bedford, Mass.)*

BALSLEY J.R. *(Middletown, Conn.)*
BANERJEE S.K. *(Newcastle upon Tyne)*
BARBER N.F. *(New Zealand)*
BARBIER D. *(Paris)*
BARNES V.E. *(Austin, Texas)*
BARSUKOV O.M. *(Moscow)*
BARTH C.A. *(Pasadena, Calif.)*
BATH M. *(Uppsala)*
BAUER S.J. *(Greenbelt, Maryland)*
BE A.W.H. *(New York)*
BEALS C.S. *(Ottawa)*
BEER A. *(Cambridge)*
BEYNON W.J.G. *(Aberystwyth)*
BJERHAMMAR A. *(Stockholm)*
BLACKWELL D.E. *(Oxford)*
BOLT B.A. *(Berkeley, Calif.)*
BOMFORD G. *(Oxford)*
BOURDEAU R. *(Greenbelt, Maryland)*
BOWDEN K.F. *(Liverpool)*
BOWIN C. *(Woods Hole, Mass.)*
BOYDEN C.J. *(Bracknell, Berks.)*
BRANDENBURGER A.J. *(Quebec)*
BREWER A.W. *(Toronto)*
BROUWER D. *(Newhaven, Conn.)*†
BROWN D. *(Melbourne, Fla.)*
BUCHWALD T.V̂. *(Sydney)*
BUDYKO M.I. *(Leningrad)*
BULLEN K.E. *(Sydney)*
BUXTON J.N. *(London)*
BYERS H.R. *(Chicago)*

CAGNIARD L. *(Paris)*
CAMERON A. *(New York)*
CHADWICK P. *(Norwich)*
CHAMBERLAIN J.W. *(Tucson, Arizona)*
COHEN L. *(Southampton)*
COOK A.H. *(Teddington)*
COULOMB J.M.F. *(Paris)*
COX A. *(Menlo Park, Calif.)*
CREER K.M. *(Newcastle upon Tyne)*
CROOM D.L. *(Maidenhead, Berks.)*
CULKIN F. *(Godalming, Surrey)*

DAHL O. *(Bergen, Norway)*
DALGARNO A. *(Belfast)*
DARBYSHIRE J. *(Anglesey)*
DEACON E.L. *(Victoria, Australia)*
DERRINGTON M.G. *(Manchester)*
DESSLER A. *(Houston, Texas)*
DIETZ R. *(Washington)*
DIX C.H. *(Pasadena, Calif.)*
DOBSON G.M.B. *(Oxford)*
DOELL R.R. *(Menlo Park, Calif.)*
DONAHUE T.M. *(Pittsburgh, Pa.)*
DONN W.L. *(New York)*
DONELLY T.W. *(Houston, Texas)*
DUTSCH H.U. *(Zurich)*

EASTHOPE C.E. *(Aberystwyth)*
EBDON R.A. *(Bracknell, Berks.)*
EMELYANOV E.M. *(Moscow)*
ENGELSEN I. *(Horten, Norway)*

FANSELAU G. *(Potsdam)*
FARQUHAR R.M. *(Toronto)*
FERRIS G.A.J. *(Leeds)*
FINCH H.F. *(Herstmonceux Sussex)*
FINLAY FREUNDLICH E. *(Germany)*
FRANK N.H. *(Cambridge, Mass.)*
FREEMAN M.H. *(Bracknell, Berks.)*
FU C.Y. *(Peking)*

GADE H.G. *(Bergen, Norway)*
GADSDEN M. *(Boulder, Colorado)*
GAKKEL YA.YA. *(Leningrad)*
GARLAND G.D. *(Toronto)*
GASKELL T. F. *(London)*
GILLES D.C. *(Glasgow)*
GIRDLER R.W. *(Newcastle upon Tyne)*
GLEN J.W. *(Birmingham)*
GLIDDON J.E.C. *(London)*

GODSON W. L. *(Toronto)*
GONCHAROV V. P. *(Moscow)*
GRIFFITHS D. H. *(Birmingham)*
GROSSMAN W. *(Hanover, Germany)*
GROVES G. V. *(London)*
GUILCHER A. *(Paris)*

HAHN A. *(Hanover, Germany)*
HALES A. L. *(Dallas, Texas)*
HANSEN W. *(Hamburg)*
HANSON W. B. *(Dallas, Texas)*
HARGREAVES J. K. *(Boulder, Colorado)*
HARRIS P. G. *(Leeds)*
HARRISON C. G. A. *(La Jolla, Calif.)*
HARRISON J. C. *(Boulder, Colorado)*
HAUBRICH R. A. *(La Jolla, Calif.)*
HAURWITZ B. *(New York)*
HEALY J. H. *(Lakewood, Colorado)*
HEDBERG H. D. *(Princeton, N.J.)*
HEDDLE T. A. *(London)*
HEEZEN B. C. *(New York)*
HEISKANEN W. A. *(Helsinki)*
HENRIKSEN S. *(Washington)*
HERSEY J. B. *(Wood's Hole, Mass.)*
HIDE R. *(Cambridge, Mass.)*
HINDLEY H. R. *(Buntingford, Herts.)*
HINES C. O. *(Ottawa)*
HIRVONEN R. A. *(Helsinki)*
HODGSON J. H. *(Ottawa)*
HONKASALO T. *(Helsinki)*
HOTINE M. *(Washington)*
HOUGHTON J. T. *(Oxford)*
HOUSNER G. W. *(Pasadena, Calif.)*
HUNKINS K. *(New York)*
HUNTEN D. M. *(Tucson, Arizona)*

ISHIGURO S. *(Godalming, Surrey)*

JACCHIA L.G. *(Cambridge, Mass.)*
JACOBS W. C. *(Washington)*
JEFFREYS H. *(Cambridge)*
JENSEN H. *(Copenhagen)*
JERLOV N. *(Gothenburg, Sweden)*
JOHNSON C. Y. *(Washington)*
JONES R. F. *(Bracknell, Berks.)*
JUNG K. *(Columbus, Ohio)*

KAISER T. R. *(Sheffield)*
KAULA W. *(Greenbelt, Maryland)*
KHAN M. A. *(Leicester)*
KING-HELE D. G. *(Farnborough, Hants.)*
KNAPP D. G. *(Washington)*
KNIGHTING E. *(Bracknell, Berks.)*
KNOPOFF L. *(Los Angeles, Calif.)*
KOCZY F. F. *(Miami, Fla.)*
KUENEN P. H. *(Groningen, Holland)*
KUKKAMAKI T. J. *(Helsinki)*

LAL D. *(Bombay)*
LANGLEBEN M. P. *(Montreal)*
LANGSETH M. *(New York)*
LAUGHTON A. S. *(Godalming, Surrey)*
LAURILA S. *(Columbus, Ohio)*
LAVERGNE M. *(France)*
LEE W. H. K. *(La Jolla, Calif.)*
LEHMANN I. *(Copenhagen)*
LEIBY J. *(Wood's Hole, Mass.)*
LENNON G. W. *(Birkenhead, Cheshire)*
LEVIN B. J. *(Moscow)*
LONCAREVIC B. D. *(Dartmouth, N.S.)*
LORENZ E. N. *(Cambridge, Mass.)*
LOWES F. J. *(Newcastle upon Tyne)*
LUBIMOVA E. *(Moscow)*
LYTTLETON R. A. *(Cambridge)*

MACKENZIE D. *(Cambridge)*
MARTIN D. H. *(London)*
MARUSSI A. *(Trieste)*
MASON B. H. *(New York)*
MASON R. G. *(London)*
MATHEWS D. *(Cambridge)*
MCCLAIN E. P. *(Washington)*
MCFARLANE W. M. *(Washington)*
MEHNERT K. R. *(Berlin)*
MILLER J. *(Cambridge)*
MIYAKE Y. *(Tokyo)*
MOORE C. B. *(Tempe, Arizona)*
MOORE L. W. *(Bromley, Kent)*
MORITZ H. *(Berlin)*
MORSE R. M. *(Portland, Maine)*
MOSBY H. *(Bergen, Norway)*
MUELLER I. I. *(Columbus, Ohio)*

NAGATA T. *(Tokyo)*
NAGY B. *(La Jolla, Calif.)*
NASH W. B. *(Bournemouth, Hants.)*
NAYLER J. L. *(Claygate, Surrey)*
NESTEROFF W. D. *(Paris)*
NEWSTEAD G. *(Canberra, Australia)*
NIBLETT E. R. *(Ottawa)*
NICHOLLS G. D. *(Manchester)*
NICHOLSON R. *(Manchester)*
NICOLET M. *(Brussels)*
NODTVEDT H. *(La Spezia, Italy)*

O'BRIEN B.J. *(Houston, Texas)*
OMHOLT A. *(Oslo)*
OPIK E.J. *(Armagh)*
OROWAN E. *(Cambridge, Mass.)*
ORR C. *(Atlanta, Georgia)*
OVENDEN M.W. *(Glasgow)*

PACKER D.M. *(Washington)*
PAGEL B.E.J. *(Hailsham, Sussex)*
PALMEN E. *(Helsinki)*
PANOFSKY H.A. *(Pennsylvania)*
PARASNIS D.S. *(Boliden, Sweden)*
PARKER R. *(Portsmouth)*
PARRY J.H. *(Newcastle upon Tyne)*
PETROVA G.N. *(Moscow)*
PHILLIPS R. *(La Jolla, Calif.)*
PONNAMPERUMA C. *(Moffatt Field, Calif.)*
POOLE J.H. *(Dublin)*
PRICE A.T. *(Exeter)*

RAMANATHAN K.R. *(Ahmedabad, India)*
RAO K.N. *(Bombay)*
REID J.L. Jr. *(La Jolla, Calif.)*
RIKITAKE T. *(Tokyo)*
RINGWOOD A.E. *(Canberra, Australia)*
RINNER K. *(Graz, Austria)*
RITTMANN A. *(Catania, Sicily)*
ROBBINS A.R. *(Oxford)*
ROBERTS P.H. *(Newcastle upon Tyne)*
ROBIN G. DE Q. *(Cambridge)*
ROELOFS R. *(Delft, Holland)*
ROSSITER J.R. *(Liverpool)*
ROTHE J. *(Strasbourg, France)*
ROY A.E. *(Glasgow)*

RUNCIMAN W.A. *(Christchurch, N.Z.)*
RUNCORN S.K. *(Newcastle upon Tyne)*

SAELEN O.H. *(Bergen, Norway)*
SAGAN C. *(Cambridge, Mass.)*
SAITO T. *(New York)*
SATTERTHWAITE G.E. *(Oxford)*
SAVAGE J.C. *(Toronto)*
SAVERENSKY E.F. *(Moscow)*
SAWYER J.S. *(Bracknell, Berks.)*
SCHERHAG R. *(Berlin)*
SCHMERLING E. *(Washington)*
SCORER R.S. *(London)*
SCRUTTON C.T. *(London)*
SEKERA Z. *(Los Angeles, Calif.)*
SHEPARD F.P. *(La Jolla, Calif.)*
SHEPPARD P.A. *(London)*
SHOR G. *(La Jolla, Calif.)*
SLICHTER L.B. *(Los Angeles, Calif.)*
SMITH H.M. *(Hailsham, Sussex)*
SMITH S.W. *(Pasadena, Calif.)*
SMITH T.J. *(Washington)*
SNEDDON I.N. *(Glasgow)*
SQUIRES G.L. *(Cambridge)*
STACEY F.D. *(Brisbane, Australia)*
STANDLEY K.J. *(Dundee)*
STEINHART J.S. *(Washington)*
STEWART R.W. *(Vancouver)*
STONELEY R. *(Cambridge)*
SUTTON O. G. *(Bracknell, Berks.)*

TARDI P. *(Paris)*
THELLIER E. *(Paris)*
THOMAS P.D. *(Washington)*
THOMAS W.J. *(Swansea)*
THOMPSON LL.G.D. *(Columbus, Ohio)*
THORLEY N. *(Newcastle upon Tyne)*
TOKSOZ N. *(Pasadena, Calif.)*
TOZER D.C. *(Newcastle upon Tyne)*
TSUBOI C. *(Tokyo)*
TURNER F.J. *(Berkeley, Calif.)*

UDINTSEV G.B. *(Moscow)*
UOTILA U.A. *(Columbus, Ohio)*
UREY H.C. *(La Jolla, Calif.)*

VALLANCE JONES A. *(Saskatoon, Saskatchewan)*
VEIS G. *(Athens)*
VENING MEINESZ F.A. *(Amersfoort, Netherlands)*
VESTINE E.H. *(Santa Monica, Calif.)*

WADATI K. *(Tokyo)*
WALKER R.M. *(New York)*
WALLACE L. *(Tucson, Arizona)*
WARNER B. *(London)*
WEIDEMANN H. *(Hamburg)*
WHITHAM K. *(Ottawa)*
WHITMORE G.D. *(Washington)*
WHITTEN C. *(Washington)*
WILSON JAMES T. *(Ann Arbor, Michigan)*
WILSON R.L. *(Liverpool)*
WISE D. *(Lancaster, Pa.)*
WOLF H. *(Bonn)*
WOOLAND G.P. *(Hawaii, Honolulu)*
WYRTKI K. *(Hawaii)*

ZEIGLER J. *(Wood's Hole, Mass.)*
ZHIVAGO A.V. *(Moscow)*
ZUCKER I.J. *(London)*

† deceased

A

ABSOLUTE TIME DATA FROM PALAEONTOLOGY. Recent work has suggested that palaeontology may provide a source of absolute time data for the past. The limited studies that have so far been made on the growth units of coral epithecae give estimates for the length of the Middle Devonian year and lunar month. Such determinations rely on the control exercised by natural rhythms on the metabolism of animals and plants being reflected in a well developed additive mode of hard tissue construction. These natural rhythms are also used by man to measure time. Thus the length of the day is based on one complete cycle of daylight and darkness and similarly, the Earth's rotation about the Sun results in the seasonal changes upon which the year was originally based. When these same cycles are preserved through observable variations in tissue construction, the organism is thus effectively recording the passage of time.

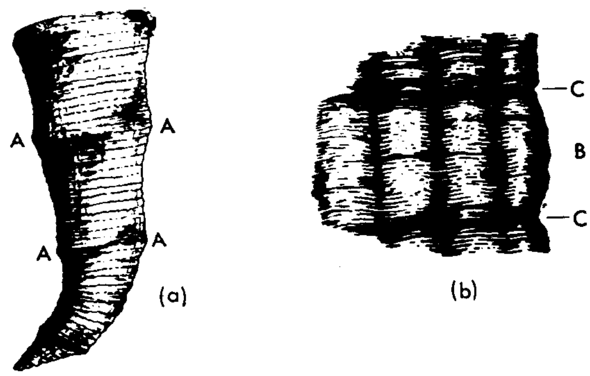
Annual growth cycles are widely known from living and fossil forms of life. Trees growing away from the equatorial zone frequently show well developed concentric rings of light and dark tissue representing summer and winter growth respectively. Sheep's horns also develop annual increments as do fish scales and the shells of some lamellibranchs. On a finer scale, daily variations in growth have recently been described from grasshopper exoskeletons.

In themselves, these examples are of purely relative use as they only allow the calculation of the age or growth rate of the tissue concerned. To provide absolute time data, the same structure in the same organism must reflect distinct growth increments dependent on natural cycles corresponding to two or more different time units. Up to the present, relationships of this nature have only been observed in corals, where the surface of the epitheca (see figure) displays three different morphological units corresponding, it appears, to daily, lunar monthly and yearly growth cycles.

Whitfield (1898) was the first to consider the significance of a periodicity in coral growth. On *Acropora palmata*, from the Bahamas, he described broad undulations in the epitheca of the outer fronds. The undulations, he suggested, were annual increments of growth formed in response to the differences in water temperature between winter and summer months observed in the area where the coral lived.

Subsequent work on coral growth has supported Whitfield's conclusions on the annual nature of these growth increments. Ma (1937) and Wells (1963) have compared measurements of annual growth on the annulations, as the undulations in the epitheca are usually termed, with direct observations of the growth rate on living corals. For the same species from the same locality the two figures thus obtained corresponded very closely in every case.

There has been some speculation on the nature of the yearly cycle responsible for these annulations. Both fluctuations in nutrient supplies and periodic reproductive activity have been put forward, but Ma has presented a great deal of evidence in favour of Whitfield's original suggestion. In a series of papers between 1933 and 1937,



Diagrammatic representations of a simple coral to show the relationships of the growth increments on the epitheca. The epitheca is the thin continuous wall of calcium carbonate surrounding the coral structure. 1(a) shows three complete annual growth cycles, each of which is divided by light constrictions into thirteen bands. 1(b) is an enlargement of one complete band comprising of the order of thirty growth-ridges. A = annulation; B = band; C = constriction.

Ma has described annulations and related internal growth cycles from recent and fossil corals. He has demonstrated (1934a) that the internal cycle is more distinctly developed in corals growing in areas of greater annual water temperature range, and also that the yearly growth increment is longer for the same species in areas of more uniformly warmer water. In recently killed specimens of *Favia speciosa*, he (Ma 1934b) was able to equate a short growth increment for a known year with abnormally low water temperature recorded in the locality of growth for that year.

Although Ma's circumstantial evidence is strong, direct experimental studies of living corals have not yet been made to determine precisely the factors responsible for the annual growth cycles. There nevertheless appears to be no doubt that they *are* yearly in nature.

The recognition of the significance of a second, distinct growth cycle in coral epithecae is very recent. Wells (1963) drew attention to the very fine growth-ridges developed on the epitheca parallel to the growing edge of the coral skeleton. He remarked that they clearly represent a regular variation in the amount of calcium carbonate secreted by the polyp. Such measurements as have been made show the ridges to be of the order of 0·05 mm thick (Scrutton 1964). Thus the slightest abrasion of the epitheca, either during life or after death, is sufficient to partially or completely obscure them.

Wells suggested that the growth-ridges represent a diurnal cycle of growth and he quotes in support of this two distinct lines of evidence. Physiological studies of calcium carbonate secretion in corals have shown that the uptake of this mineral in coral tissue is significantly greater in daylight than in darkness. In addition, Wells was able to count the ridges on recent corals, the annual growth rates of which had been satisfactorily established. His counts approximated to 360 in the space of a years growth. Thus there is good evidence that besides the broad yearly annulations, the coral epitheca records in its morphology the passage of days. In other words, a means is now available for counting the number of days in the year for any geological period in which corals are sufficiently well preserved to show the fine growth-ridges.

Wells has obtained data of this sort for the Devonian. He mentions some of the difficulties involved in obtaining counts from fossil material and Scrutton (1964) has further stressed the need of selecting for study of parts of the coral epitheca most likely to develop a full quota of growth-ridges. With the limited material at his disposal, Wells was able to show that the yearly annulations separated the growth-ridges into groups of about 400, which is thus interpreted as an estimate for the number of days in the Devonian year. He compared his results with those obtained from calculations relating astronomical estimates of the Earth's motion in the past to radioactive age determinations for the geological systems. The latter suggest that the number of days in the year decreased from 402 in basal Devonian times to 396 at the top of the system. Thus the results from physical calculations and those so far available from palaeontological methods show close correlation.

Scrutton (1964) suggested that the growth of the coral epitheca also responded to a third rhythm. On a small collection of well preserved Middle Devonian corals he was able to demonstrate a regular grouping of the growth-ridges up the length of the epitheca of much shorter period than a yearly cycle. These bands of ridges are separated by constrictions parallel to them, representing a periodic reduction in calcium carbonate secretion. Counting the number of ridges per band, the average of data for 112 bands from 10 corals showed that the constrictions occurred at about 30·5 day intervals, and thus thirteen times in the course of a Devonian year. Scrutton suggested that each band corresponded to a lunar cycle and quoted in support a report that similar constrictions, with a period of approximately 28 ridges or days, had been observed on *Lophelia pertusa*, a living coral from the Norwegian fjords.

The particular mechanism through which the lunar cycle could affect the growth of the epitheca is not known. Scrutton considered three main possibilities and concluded that a lunar breeding periodicity in these corals is the metabolic function most likely to be responsible for the constrictions. It is possible, however, that a combination of factors is involved and a more definite conclusion on the cause of the constrictions must await physiological studies of growth processes in living corals.

Thus the available evidence from growth cycles in fossil corals suggests that the Devonian year, which was approximately 400 days in length, was divided into 13 lunar months of about 30·5 days each. The amount of data is as yet small and, apart from two counts of the number of days in the year made on Carboniferous corals by Wells, is restricted to the Devonian. Nevertheless, despite the high quality of preservation required, it is possible that careful collecting will provide sufficient suitable coral material to give greater statistical reliability to the Devonian results and to furnish similar data for many other geological systems.

Before too much weight is placed on the coral results, however, it is important that the time-growth relationships so far suggested should be tested by a series of direct experiments on skeleton building in living corals. Neither should it be overlooked that not only corals, but other fossil groups, some of which are known to show annual growth increments, may provide the same sort of data from rhythms developed internally in their hard parts. It would greatly facilitate this work if the present necessity of high quality preservation could be circumvented.

Bibliography

MA T.Y.H. (1934a) *Proc. Imp. Acad. Tokyo*, **10**, 353.
MA T.Y.H. (1934b) *Sci. Rep. Tohoku Univ.*, **16** (3).
MA T.Y.H. (1937) *Palaeont. sinica* B, **16** (1).
SCRUTTON C.T. (1964) *Palaeontology*, **7** (4), 552.
WELLS J.W. (1963) *Nature, Lond.*, **197**, 948.
WHITFIELD R.P. (1898) *Bull. Amer. Mus. Nat. Hist.*, **10**, 463.

C.T. SCRUTTON

ABYSSAL PLAINS. Many of the enclosed basins of the deep ocean adjacent to sources of sediments have been found to have extremely flat bottoms. Precision echo sounding has shown that these areas often have gradients as small as 1:5000 over many tens of miles and that the local relief does not exceed a metre or two. An abyssal plain is defined (Heezen and Laughton 1963) as an area of the ocean basin floor in which the gradient is less than 1:1000 and which is characterized by a lack of relief greater than two metres.

Because of the way in which it is formed, the slope of an abyssal plain indicates the direction from which the sediments have arrived. Commonly the further from the sediment supply, the smaller the gradient so that at the outer limit of the plain, the sediments are ponded around abyssal hills in horizontal strata. Sometimes there is a small but discernable discontinuity in gradient between about 1:500 and 1:1000 which divides the region over which turbidity currents are travelling in a state of dynamic equilibrium, from the abyssal plain where the decay of turbidity currents leads to sediment deposition and ponding. The former region, typically with gradients of 1:500, is called by Heezen the continental rise since it leads up to the continental slope, but frequently it extends many hundreds of miles from the slope. The continental rise is also distinguishable by its small scale relief of a few tens of metres often in the form of shallow valleys, scarps and undulations.

Abyssal plains have been found in most of the ocean basins of the world. The best known are in the north Atlantic either side of the mid-Atlantic ridge and fed from the continental shelves of Europe, Africa, and America. The Biscay and Iberian abyssal plains are both about 30,000 sq. mi. and extend some 300 mi. from the continental shelf. The Sohm abyssal plain south of Newfoundland (Heezen *et al.* 1955) is 350,000 sq.mi., and extends 1000 mi. from the continental shelf and covers the foothills of the mid-Atlantic ridge.

Extensive plains have been found in the South Atlantic, the Indian ocean and the Arctic. In the Pacific abyssal plains are less common and this is related to the large ratio of area to perimeter, and to the sediment traps provided by the marginal trenches. However, some of the island groups are surrounded by flat areas where the older terrains of hills have been buried by ponding sediments derived from the island pedestals. These are known as archipelagic aprons or plains, according to the smoothness of their surface (Menard 1956). Volume calculations suggest that only the smooth archipelagic plains can be derived from erosion of the islands and that the somewhat rougher aprons may be due to basaltic flows.

Many small abyssal plains have been found in the adjacent seas such as the Mediterranean, the Gulf of Mexico (Ewing *et al.* 1962), the Carribean (Ewing *et al.* 1960), the Bering Sea (Udintsev *et al.* 1959), the Okhotsk Sea (Udintsev 1957) and in the California Borderland region. The relationship of the basins and their associated plains, aprons and channels off Southern California has been described by Emery (1960).

Many of the deep sea trenches have abyssal plains formed of sediments derived from the steep slopes and from the associated island areas. These plains are sometimes only a mile or two wide but may be many miles long. The extent of the plain in a trench is an indication of the age or activity of the trench. The best developed and most studied is that in the Puerto Rico Trench where shallow water benthonic foraminifera were found (Ewing and Heezen 1955).

A typical core taken from an abyssal plain shows that the normal pelagic column of oozes or clays is repeatedly interrupted by well defined layers of well sorted sands and silts. These turbidite layers are characterized by a sharp lower boundary where the passage of the turbidity current has removed the sloppy sediment normally found in the top few centimetres of a pelagic core, and by the gradation from a coarse material near the bottom to fine silts or clays near the top. The upper limit of a turbidite layer is hard to distinguish from the pelagic material since it consists of the fine clay material remaining longest in suspension after the decay of the turbidity current, but it is characteristically free from the foraminiferal tests which are found distributed in the pelagic ooze.

The thickness of turbidite layers varies from a fraction of a millimetre, often visible only after the core has dried out and split along a weak silt band, to several metres grading from coarse sand and gravel to clay. The difficulty of obtaining cores in an abyssal plain may be due to the incoherence of a well sorted sand which prevents it being retained in a core catcher.

A high degree of correlation of these turbidite strata has been observed between cores as much as 30 miles apart in the Madcap abyssal plain west of the Canary Islands (Belderson and Langton (in press)). Three graded layers of silt and clay about 15 centimetres thick were observed in six cores separated by increasing intervals. The correlation was established both by the colour, texture and carbonate content of the interbedded pelagic material which was unusually variable and by the palaeoclimatic record indicated by the coiling directions of *Globoratalia truncatulinoides* using the method of Ericson, Wollin and Wollin (1954). An immediate contrast can be seen between a core taken on an abyssal plain and one on a gentle rise just off it, the latter showing none of the turbidite layers described above, except in so far as the upper part of a turbidity current might have spread over adjacent country.

The effects of a large scale turbidity current were observed following an earthquake on the Grand Banks south of Newfoundland in 1929 when many submarine telegraph cables were broken. Subsequent coring on the Sohm abyssal plain several hundred miles from the shelf edge showed well sorted silt beds extending to a metre or so below the surface and graded to a coarse sub-angular sand (Heezen *et al.* 1954). These beds included shallow water foraminifera indicating that the material had travelled from the continental shelf edge. In other instances pieces of wood and vegetation have been recovered in deep sea cores from abyssal plains.

Geophysical measurements have indicated the thickness of the plains and the shape of the underlying rocks. Local variations in both the gravitational and magnetic fields over the plains are as large as they are over the abyssal hills which emerge from the seaward side of them, suggesting that the plains have simply drowned a topography as rough as that observed off the plain. This interpretation has been confirmed by the methods of continuous seismic profiling which have penetrated the sediments and show the basement rocks (Ewing *et al.* 1964). The method showed that not only were there layers within the sediment but that these were distorted by differential compaction over buried topography.

Layering at smaller depths can be seen on precision echo sounders. As many as five layers have been revealed in the top twenty metres using a short transmitted pulse, and the pinching out of these at small rises indicates the ponding nature of the sedimentation process on the plain.

Associated with the abyssal plains and the turbidity currents which cause them are deep sea channels, inter-plain channels and abyssal gaps. For reasons not yet fully understood, some turbidity currents are confined to shallow steep sided flat bottomed channels as they traverse the continental rise. Such channels were seen in the Bay of Bengal (Dietz 1953) and in many other places, and the velocity of turbidity current flow through one, the Cascadia channel in NE Pacific Ocean, has been discussed by Hurley (1960 unpublished MS). On reaching the abyssal plain these channels disappear even though the gradient change is very small, and in spite of the fact that the currents may travel another hundred miles.

As a basin fills up with abyssal plain deposits a sill is sometimes reached over which further turbidity currents will flow into another basin. The gap through which the excess material travels is known as an abyssal gap. The increase in slope after crossing the sill accelerates a turbidity current and may change it from a depositional to an erosional state. In this case an interplain channel can be cut through the gap linking two abyssal plains (Laughton 1960). The funelling of turbidity currents through an abyssal gap modifies their behaviour on the plain and a dendritic pattern of feeding channels can be formed for as much as 60 miles up slope from the gap.

Various theories have been put forward to explain the extreme flatness of abyssal plains. Early suggestions were that they were atectonic regions representing a primordial flatness: the geophysical data is opposed to this. By contrast another theory held that extreme tectonic activity had reduced all features by shearing to a flat mylonite deposit. However, the sands of the abyssal plains are not mylonitic and can be explained in other ways. Subaerial erosion requires impossible eustatic changes of sea level, and the theory of extensive lava flows requires an extremely fluid and slowly cooling lava to give slopes of 1 in 3000 extending for hundreds of miles. Furthermore the slopes point to sediment sources and not volcanic sources.

The steady accumulation of pelagic sediments combined with the finer clay particles carried by currents from coastal regions can explain the thickness of sediment cover and it is conceivable that given enough time and material and bottom currents, this sediment could be distributed in the deepest parts of a basin and fill it up. But it is difficult to explain the extreme flatness, the uniformly changing slope with distance from the sediment source, the ponding and stratification of the beds observed, the presence of coarse material derived from shallow water and the channels associated with the plains.

The only theory which explains adequately the known facts of the abyssal plains is that periodically they are fed by turbidity currents carrying sediments from the continental shelves. The currents are gravity controlled and reach the deepest part of the basin before decaying and depositing their load. In their decaying stage they spread out uniformly over areas at least tens of miles wide and lay down extensive turbidite layers. Although pelagic sedimentation is always continuing and the winnowing effects of deep currents contribute to the infilling of the basins, the turbidity current contribution is responsible for the ultimate flatness and uniformly varying gradients. The loading of sedimentary material may compact the lower sediments or bend the crust, reducing the rate of levelling. Tectonic activity may subsequently tilt an abyssal plain and alter the course of subsequent flows creating the relic abyssal plains such as those found in the Aleutian basin.

The universal discovery of abyssal plains in enclosed basins, large or small, when they are adjacent to sediment supplies, shows the world wide significance of the turbidity current mechanism which causes them.

Bibliography

DIETZ R.S. (1953) *Possible deep-sea turbidity current channels in the Indian Ocean, Bull. Geol. Soc. Amer.*, **64**, 375.

EMERY K.O. (1960) *Basin plains and aprons off Southern California, J. Geol.*, **68**, 464.

EWING J. J. ANTOINE and EWING M. (1960) *Geophysical measurements in the Western Caribbean Sea and in the Gulf of Mexico. J. Geophys. Res.*, **65**, 4087.

EWING M., EWING J.I. and TALMANI M. (1964) *Sediment distribution in the Oceans: the Mid-Atlantic Ridge, Bull. Geol. Soc. Amer.* **75**, 17.

EWING J.I., WORZEL J. L. and EWING M. (1962) *Sediments and oceanic structural history of the Gulf of Mexico, J. Geophys. Res.*, **67**, 2509.

EWING M. and HEEZEN B.C. (1955) *Puerto Rico Trench topographic and geophysical data, Geol. Soc. Amer. Spec. Paper* **62**, 255.

HEEZEN B.C., ERICSON D. B. and EWING M. (1954) *Further evidence for a turbidity current following the 1929 Grand Banks earthquake, Deep-Sea Res.*, **1**, 193.

HEEZEN B.C., EWING M. and ERICSON D. B. (1955) *Reconnaissance survey of the abyssal plain south of Newfoundland, Deep-Sea Res.*, **2**, 122.

HEEZEN B.C. and LAUGHTON A. S. (1963) *Abyssal Plains, The Sea* (Ed. M.N. HILL) Vol. 3, New York: Interscience.

LAUGHTON A.S. (1960) *An interplain deep-sea channel system, Deep-Sea Res.*, **7**, 75.

MENARD H.W. (1956) *Archipelagic aprons, Bull. Amer. Assoc. Petrol. Geol.*, **40**, 2195.

UDINTSEV G.B. (1957) *Relief of Okhotsk sea floor, Trudy Inst. Okeanol. Akad. Nauk S.S.S.R.*, **22**, 3. (In Russian.)

UDINTSEV G.B., BOITCHENKO J. G. and KANAIEV V. F. (1959) *The bottom relief of the Bering Sea, Trudy Inst. Okeanol. Akad. Nauk S.S.S.R.*, **29**, 17. (In Russian.)

A. S. LAUGHTON

ACCELEROMETER. A seismograph designed to measure primarily the acceleration of the ground motion as a function of the time, during the passage of an earthquake disturbance.

See also: Seismographs (pendulum).

ACCUMULATION IN THE SOLAR NEBULA. In recent decades the idea of the formation of planets from a circum-solar gas-dust nebula has become generally accepted. Most students in this field consider the growth of planets from much smaller "embryos" by means of the sweeping up of solid bodies and particles. (For giant planets the accumulation of gas possibly also played an important role.)

In the fifties G. P. Kuiper put forward the hypothesis that large massive protoplanets—one for each planet—were formed in the solar nebula and they evolved into the present planets by a loss of excess mass. The dynamical basis of this hypothesis was not correct and at present Kuiper himself does not develop or defend it.

As already stressed by Kant (1755) and Laplace (1796), the regularities of motion of the planets (motion in the same direction along almost circular orbits of small inclinations) show that they were formed from diffuse material distributed over the whole space of the present planetary system and rotating around the Sun. Both Kant and Laplace assumed that the medium was continuous—dust or gas.

In 1944–50 this mechanical line of approach was extended by O. J. Schmidt. He suggested that the immediate predecessor of planets was a rotating swarm of bodies large enough to move round the Sun in individual elliptical orbits. In the accumulation process the individual motions of the bodies which unite are averaged and this has led to the observed regularities of planetary motions. Schmidt also showed that the accumulation process explains, or opens the way to explaining, the regularity of planetary distances from the Sun, (see *Bodes law*) the direct axial rotation of the planets and the origin of regular satellites

The differences in chemical composition and mass between the terrestrial and the giant planets were explained by B. Levin in 1949 as due to differences in temperature between the inner and outer zones of the pre-planetary swarm. The bodies in the warm inner zone were composed of the non-volatile substances only, while in the cold outer zone they also contained volatile substances which are very abundant in cosmic matter. These differences in composition of the pre-planetary bodies arose during their formation in the solar nebula. Owing to its great opacity the temperatures in its outer zone were very low, permitting the condensation of the most volatile substances, excluding helium and possibly hydrogen (Gurevitch and Lebedinsky 1950).

A new approach to the problem of the formation process of the planets has been developed since 1951 by H. C. Urey. Instead of explaining the chemical properties of the planets on the basis of their formation process, determined from the mechanical properties of their motion, he determined this process by applying the methods of physical chemistry. In the chemical composition of the Earth and meteorites he found evidence for their accumulation from cold particles.

In 1962 Fowler, Greenstein and Hoyle made the first step in a third line of approach based on the analysis from the point of view of nuclear physics of the peculiarities of abundances and isotopic compositions of chemical elements in the Earth and meteorites.

It is most important that all three approaches lead to the same conclusion—that the material of the Earth and of the meteorite parent-bodies was at some early stage of the solar system in the form of small cold solid bodies which later accumulated into large bodies.

Two Stages of Accumulation

The accumulation of planets from a solar gas-dust nebula can be somewhat arbitrarily divided into two stages:

(A) Formation of bodies of asteroidal or lunar size (10^2–10^3 km) from dust particles. (These bodies can be called "intermediate" because they are intermediate between the primordial dust-particles and the present planets.)

(B) Accumulation of planets from intermediate bodies and their fragments and, in the case of giant planets, possibly from gas.

Several alternative modes of origin of the solar nebula are proposed and this uncertainty sets up serious difficulties for studies of the early history of its further development. For any origin of the nebula— by gravitational capture (according to a scheme of three bodies), by capture based on the dissipation of energy at the accretion axis, by separation from the rapidly rotating proto-sun whether or not accompanied by magnetic coupling, etc.—the duration of formation must be of the order of 10^5–10^6 years. This is of the same order of magnitude or even greater than the duration of stage A. Therefore only tentative pictures of this stage can be discussed at present. Stage B lasted about two orders of magnitude longer and is much less dependent on the origin of the nebula.

Stage A. Two alternative modes of formation of intermediate bodies are considered:

1) by gravitational forces, e.g. through the onset of gravitational instability in the layer of dust settled towards the equatorial plane or in the whole flattened gas-dust nebula (Edgeworth (1949) and Gurevitch and Lebedinsky (1950) even considered a nebula consisting only of dust.)

2) by chemical forces, i.e. through coagulation of dust particles.

In a nebula rotating round a massive central body gravitational forces can become operative only when the density in the equatorial plane approaches the critical Roche density ϱ_R, i.e. the density of a condensation in which, at a given distance from the central body, the internal gravitational forces are equal to the disrupting tidal forces of the central body.

In a flattened rotating nebula, and moreover in a layer of dust, local condensations have the form of very flattened disks. For them, at the distance *R* from the Sun,

$$\varrho_R \approx 10\varrho^* = 10\frac{M_\odot}{\frac{4}{3}\pi R^3}, \qquad (1)$$

where ϱ^* is the density of the Sun extended to a radius R.

The mass m and the equatorial diameter d of condensations are

$$m \approx \frac{b^3}{2\varrho^{*2}} \qquad d \approx \frac{b}{\varrho^*}. \tag{2}$$

Here b is the surface density of the nebula or of the dust layer (per unit area of equatorial plane). Thus d is about one order of magnitude greater than the thickness of the nebula or the layer $b/\varrho_R \approx b/10\varrho^*$ (Gurevitch and Lebedinsky 1950; Safronov 1960a).

A ring-shaped condensation which is not disrupted by differential rotation can be formed with a smaller density than a local condensation. However, the estimate by Bel and Schatzman (1958) who obtained $\varrho \approx \frac{1}{6}\varrho^*$ is probably too low. According to Safronov (1960b), under the most favourable conditions $\varrho \approx 2\varrho^*$. But further division of the ring into local condensations occurs only when its contraction increases its density up to ϱ_R given by (1).

In a solar nebula of moderate mass, smaller than that of the Sun, to attain the Roche density ϱ_R requires a great concentration of matter towards the equatorial plane. This is possible only if there are no turbulent motions.

A laminar rotation of gas is stable if the specific angular momentum increases with distance from the rotation axis. In a nebula rotating with Keplerian velocities this condition is fulfilled. Any turbulence not maintained by external forces must die during a few revolutions, i.e. during 10^1 years in the inner part of the solar nebula and during 10^3 years in the outer (Safronov and Ruskol 1956, 1957; Safronov 1958a). These time-intervals are small as compared with the probable duration of formation of the solar nebula. If its formation process was quiet enough, then its rotation could be almost laminar.

In a nebula with laminar rotation with $\varrho \approx 10^{-12}$ g/cm^3 dust particles of 10^{-4} cm settle to the equatorial plane in 10^3–10^5 years. In a quasi-stationary state the thickness of a dust layer is determined by the velocities of the Brownian motion of dust grains while the thickness of a gas component is determined by the thermal velocities of gas-molecules. Therefore the density inside the dust layer is several orders of magnitude greater than outside and this layer can more easily reach the Roche density. However, the dust layer must become extremely thin—about 10^{-4}–10^{-6} of the distance from the Sun. The random velocities of dust particles must be a few cm/sec at the Earth's distance from the Sun and a few m/sec at Jupiter's distance and one can doubt whether such damping of turbulence and uniformity of motion could be reached (Safronov and Ruskol 1957; Safronov 1960a).

If the Roche density ϱ_R is reached the gravitational instability will disrupt the dust layer into disk-shaped condensations. Their rotation, inherited from the differential rotation of the parent dust-layer will be direct. Its angular velocity will be

$$\varpi = \frac{1}{2}\,\mathrm{curl}\,V = \frac{1}{2R}\frac{\mathrm{d}}{\mathrm{d}R}(VR) = \frac{1}{4}\omega_K \tag{3}$$

where $V = \sqrt{\frac{GM_\odot}{R}}$, is the linear velocity of rotation of dust particles and $\omega_K = \sqrt{\frac{GM_\odot}{R^3}}$, the angular velocity of Keplerian rotation around the Sun. The rotation of condensations will be accelerated in the course of their contraction and will prevent their direct transformation into solid bodies. Only after encounters and the combination of several tens of condensations will the rotation be slowed down and solid bodies of asteroidal and lunar size be able to form (Safronov 1960a).

H. C. Urey (1958, 1962) considers a case in which dust is not separated from gas and the latter determines the density throughout the nebula. Then to attain the Roche density over the whole equatorial plane the mass of the nebula must be about $\frac{1}{2}M_\odot$ even if its temperature was as low as 8–10°K in the zone of terrestrial planets and 4–6°K in the zone of giant planets. For more realistic temperatures such as $T = \frac{300°\mathrm{K}}{R}$, suggested by Kuiper, the necessary mass of the nebula will exceed $1M_\odot$ (Ruskol 1958). Under the conditions suggested by Urey, gravitational instability leads to the formation of condensations with a mass of 10^{27}–10^{29} g. He neglects their rotation and assumes that inside each condensation the dust agglomerates into a single body.

The two main difficulties of Urey's picture are: a) Special conditions are needed to obtain such low temperatures in the nebula. The scattering of solar radiation in the parts of the nebula distant from the equatorial plane can heat its equatorial parts to much higher temperatures (Safronov 1962b). To eliminate this heating an opaque ring of considerable thickness had to exist on the inner edge of the nebula (for example, due to the turbulence produced there by solar corpuscular streams, or simply by the large temperature gradient) and cast a large shadow over all other parts. b) It remains unclear why only about $^1/_{250}$ of the mass of the nebula was incorporated into planets and where the remainder disappeared to. The ejection of intermediate bodies from the zone of formation of giant planets (see below) was probably two orders of magnitude smaller.

While smooth laminar rotation of the nebula is required for the formation of intermediate bodies by gravitational instability, continual turbulence is favourable for their formation by coagulation. If we start with a hot nebula, its cooling will lead to a rapid condensation of innumerable smoke particles, not to a slow growth of large bodies (Urey 1956). Particles with clean surfaces, condensed in the solar nebula or previously in the interstellar space, will stick (weld) together on contact and thus coagulate. However, each grain during its settling towards the equatorial plane of the nebula will touch only a restricted number of other grains, so that growth to the size of greater than a few cm is then impossible (Safronov and Ruskol 1956, 1957). (At the Earth's distance from the Sun the surface density b of non volatile-dust was about 10 g/cm^3.) Even growth by coagulation of bodies with dimensions of a metre, suggested by Fowler *et al.* (1962), requires turbulence to prevent the onset of gravitational instability and to provide time to bring more particles into contact. But it is not clear whether a long period of turbulence is sufficient to go much further in this direction up to asteroidal size.

At present the author favours the formation of intermediate bodies by gravitational instability in a thin dust layer. But he realizes that the situation can change when instead of several possible modes of formation of the solar nebula we know the single true process.

Stage B. The intermediate bodies formed from a flattened nebula or even from a thin dust layer had to move initially along nearly circular orbits nearly in the same plane. When these bodies collided the relative velocities were small and they would usually become united. But the intermediate bodies were large enough to disturb one another at close encounters. In the course of time the dispersion of eccentricities and inclinations must increase, as would the relative velocities of collisions and this must cause more and more frequent disruptions and fragmentations instead of agglomeration. However, for the largest bodies the probability of disruption was smaller and they continued to grow by sweeping up the intermediate bodies and their fragments.

C. von Weizsäcker (1944) calculated the rate of growth of a planetary embryo assuming a constant density of surrounding diffuse matter. But in reality this density must decrease in the course of accumulation. Therefore at the early stages of the process its rate must increase due to the increase of cross-section of the embryo but later begins to decrease and fall asymptotically to zero (Schmidt 1945).

O. Schmidt considered a simplified scheme: the growth of a single embryo which sweeps up smaller particles evenly distributed over a circular "feeding zone". For the Earth, and also for Mercury and Venus, all particles initially present in their "feeding zones" were accumulated into planets. Therefore

$$\frac{dm}{dt} = \pi r_e^2 \varrho v = \pi r_e^2 \frac{4}{P} b(t) = \frac{4r_e^2}{P} \frac{M - m}{R_2^2 - R_1^2}. \quad (4)$$

Here m and r_e are the mass and the effective radius of the growing planet (embryo), M—the mass of the present planet, P—its period of revolution, $\varrho(t)$ and $b(t)$—the space and surface densities of particles in the feeding zone, R_1 and R_2—the radii of the boundaries of this zone, v—the mean velocity of particles relative to the embryo or the mean velocity of their random motion. The space density ϱ is inversely proportional to v and therefore the product ϱv depends only on b. According to Safronov's calculations (1954, 1958) the accumulation of 97 per cent of the Earth's mass, which can be regarded practically as the time of its formation, lasted for $1–2 \times 10^8$ years. More complicated schemes of accumulation in which some fragmentation on collision is taken into account (Safronov 1958b; Urey 1962) do not substantially change the above estimate of the duration of Earth's formation. Stage B was longer by two or three orders of magnitude than stage A.

The impacts of accumulating bodies heated the surface then existing. If the major part of the Earth's mass was formed by small bodies up to about 1 km in size, the heat would be liberated near the surface and could escape into space. In this case even for layers formed at the time of maximum, intensity of bombardment (at present they are buried at a depth of about 2000 km) the increase of temperature would be only about 100° (V. Safronov, 1959), and the initial temperature of the Earth would be determined by the radiogenic heat liberated during its formation and by the compression of the inner parts under the growing weight of the accumulating outer parts. The same would be true for other terrestrial planets which are smaller than the Earth. However, at the beginning of stage B many competing embryos were formed for each planet but later the largest (or the "lucky") one absorbed the others and grew into a planet. Calculations for such a scheme of accumulation show that a substantial part of the Earth's mass was brought by large bodies perhaps up to 10^3 km in size (Safronov 1962c). Although at impact their material was widely scattered over the surface of th Earth of that time this result is important for the study of the inhomogeneity of the Earth's mantle (Safronov 1964). The heat generated by impacts of large bodies is liberated at some depth from which its escape into space is more difficult. It could substantially heat the layers which are now at the depth of 500–1000 km. The initial temperature of the Earth deserves further studies.

For giant planets heating by impacts was substantial even if they accumulated from small bodies (Safronov 1954). For Jupiter this is shown at present by the chemical composition of its Galilean satellites: their densities indicate that the two closest to the planet are composed entirely of rocky material while the two outer contain about 50 per cent of light volatile matter.

The giant planets have such great masses that near the end of their accumulation they strongly perturbed the motion of smaller bodies passing near and forced them into more and more elongated orbits. Finally they ejected them out of the solar system. This ejection, and not the accumulation into the planet as in the inner zone of the pre-planetary swarm, cleaned the "feeding zones" of the giant planets and stopped their growth. With increasing distance from the Sun its gravitational attraction decreases and a smaller mass is sufficient for large perturbations. Therefore Jupiter and Saturn grew to a larger mass than the more distant Uranus and Neptune. A small part of the ejected bodies was captured by stellar perturbations to form the Oort's cloud of comets (Levin 1959, 1963).

The cometary nuclei have an icy composition as intermediate bodies of the outer, cold zone of the pre-planetary swarm. The modern asteroids are, in their turn, remnants of intermediate bodies of the warm, inner zone. Although at stage A owing to the opacity of the gas-dust nebula the zone of modern asteroids probably belonged to the cold zone, at stage B, when the agglomeration of dust into intermediate bodies cleared the intervening space, they were heated by solar radiation and transformed into bodies of the inner zone composed of nonvolatile substances.

O. Schmidt (1946) showed that the accumulation process