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SUBMARINE CANYONS AND DEEP-SEA FANS
Modern and Ancient

Edited by

J. H. McD. WHITAKER

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Edited by
J. H. McD. WHITAKER
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Congo Submarine Canyon
Congo Submarine Canyon and Fan Valley
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Growth Patterns of Deep-Sea Fans
Physiography and Sedimentary Processes of La Jolla Submarine Fan and Fan-Valley, California
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AMERICAN JOURNAL OF SCIENCE (YALE UNIVERSITY)—*American Journal of Science*
Canyons off the New England Coast
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The Structure and Origin of the Large Submarine Canyons of the Bering Sea
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THE GEOLOGICAL ASSOCIATION OF CANADA—*Flysch Sedimentology in North America*
Deep Sea Sediments in the Lower Paleozoic Québec Supergroup

GEOLOGICAL SOCIETY OF AMERICA—*Geological Society of America Bulletin*
Growth of the Bengal Deep-Sea Fan and Denudation in the Himalayas

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THE GEOLOGICAL SOCIETY OF JAPAN—*The Journal of the Geological Society of Japan*
A Fossil Submarine Canyon near the Southern Foot of Mt. Kano, Tiba Prefecture

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The Geology of the Area Around Leintwardine, Herefordshire

THE GEOLOGICAL SURVEY OF JAPAN—*Geological Survey of Japan, Bulletin*
Stratigraphy and Sedimentation of the Upper Cretaceous Himenoura Group in Koshiki-jima, Southwest Kyushu, Japan

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Journal of Sedimentary Petrology
Shale Grit and Grindslow Shales: Transition from Turbidite to Shallow Water Sediments in the Upper Carboniferous of Northern England
Modern and Ancient Geosynclinal Sedimentation
Ancient Submarine Canyons and Fan Valleys
Depositional Trends of Modern and Ancient Deep-Sea Fans

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Excerpts

SERIES EDITOR'S PREFACE

The philosophy behind the "Benchmark Papers in Geology" is one of collection, sifting, and rediffusion. Scientific literature today is so vast, so dispersed, and, in the case of old papers, so inaccessible for readers not in the immediate neighborhood of major libraries that much valuable information has been ignored by default. It has become just so difficult, or so time consuming, to search out the key papers in any basic area of research that one can hardly blame a busy man for skimping on some of his "homework."

This series of volumes has been devised, therefore, to make a practical contribution to this critical problem. The geologist, perhaps even more than any other scientist, often suffers from twin difficulties—isolation from central library resources and immensely diffused sources of material. New colleges and industrial libraries simply cannot afford to purchase complete runs of all the world's earth science literature. Specialists simply cannot locate reprints or copies of all their principal reference materials. So it is that we are now making a concerted effort to gather into single volumes the critical material needed to reconstruct the background of any and every major topic of our discipline.

We are interpreting "geology" in its broadest sense: the fundamental science of the planet Earth, its materials, its history, and its dynamics. Because of training and experience in "earthy" materials, we also take in astrogeology, the corresponding aspect of the planetary sciences. Besides the classical core disciplines such as mineralogy, petrology, structure, geomorphology, paleontology, and stratigraphy, we embrace the new fields of geophysics and geochemistry, applied also to oceanography, geochronology, and paleoecology. We recognize the work of the mining geologists, the petroleum geologists, the hydrologists, the engineering and environmental geologists. Each specialist needs his working library. We are endeavoring to make his task a little easier.

Each volume in the series contains an Introduction prepared by a specialist (the volume editor)—a "state of the art" opening or a summary of the object and content of the volume. The articles, usually some thirty to fifty reproduced either in their entirety or in significant extracts, are selected in an attempt to cover the field, from the key papers of the last century to fairly recent work. Where the original works are in foreign languages, we have endeavored to locate or commission translations. Geologists, because of their global subject, are often acutely aware of the oneness of our world. The selections cannot, therefore, be restricted to any one country, and whenever possible an attempt is made to scan the world literature.

To each article, or group of kindred articles, some sort of "highlight commentary" is usually supplied by the volume editor. This commentary should serve to bring that article into historical perspective and to emphasize its particular role in the growth of the field. References, or citations, wherever possible, will be reproduced in their entirety—for by this means the observant reader can assess the background material available to that particular author, or, if he wishes, he, too, can double check the earlier sources.

A "benchmark," in surveyor's terminology, is an established point on the ground, recorded on our maps. It is usually anything that is a vantage point, from a modest hill to a mountain peak. From the historical viewpoint, these benchmarks are the bricks of our scientific edifice.

RHODES W. FAIRBRIDGE

PREFACE

Submarine canyons are "steep-walled, sinuous valleys, with V-shaped cross sections, axes sloping outward as continuously as river-cut land canyons, and relief comparable even to the largest of land canyons. Tributaries are found in most of the canyons and rock outcrops abound on their walls" (Shepard, 1973a, pp. 305–306). They are among the largest excavational features on the face of the earth, some being greater in size than the Grand Canyon of the Colorado. Although they have been known for over a century, their relative inaccessibility to direct observation made it difficult for early workers to study them in detail. Gradual improvements in exploration techniques, especially since World War II, have yielded more and more data on their morphology, sedimentary fills, and probable histories. In the 1930s there were widely differing theories of origin for canyons, and while there is now more general agreement, there are still strong differences in opinion among specialists in this field of research, in particular about the relative importance of different cutting agents, such as turbidity currents, sand creep and sand flows, and of slumping, up-building of the walls, reexcavation of former canyons, and the significance of structure in the siting of canyons. These differences will become apparent in the papers reprinted in this volume.

Progress up to 1966 was well summarized by Shepard and Dill in their book *Submarine Canyons and Other Sea Valleys,* which all students of canyons should consult. Some excerpts from their book are reprinted here, including their comprehensive bibliography. To give historical perspective, three early papers are reproduced in this volume, followed by studies of Congo, Scripps, and the Bering Sea Canyons.

Deep-sea fans are "cone- or fan-shaped accumulations of terrigenous sediment off shore from most of the world's great rivers, extending down to abyssal depths. They are built up at the lower ends of nearly all submarine canyons" (Fairbridge, 1966, p. 870). They are cut by valleys, "many of which have bordering levees that are built above the fans, most have distributaries, but very few have tributaries, and the walls are locally steep and are cut into unconsolidated fan sediments" (Shepard, 1973a, p. 306). Fans and fan valleys have been the subject of intense study only in the last few decades. In this volume, Menard's important paper of 1955 is followed by detailed studies of the Rhône, La Jolla, and Bengal Deep-Sea Fans and a synthesis of growth patterns of fans by Normark.

Today, sedimentologists are endeavoring to interpret sedimentary successions in terms of their environments of formation, and it seemed appropriate to devote the second half of this book to inferred ancient examples of both submarine canyons and deep-sea fans and fan valleys. This could not have been attempted even fifteen years ago, but such has been the growth of interest in this aspect of marine sedimentation that now it has proved difficult to select from the wealth of examples: the final choice has aimed to give as varied a selection as possible in time and space. Ancient canyons are described from California, Texas, Australia, Japan, Italy, and Great Britain, ranging in age from Silurian to Tertiary. Ancient fans are chosen from California, eastern Canada, northern England, and Spain: these also range from Lower Paleozoic to Tertiary in age.

I should like to thank all the authors and publishers of the papers used in this volume for their unfailing courtesy and helpfulness. Many authors went beyond what was asked of them and have made suggestions for improving the book. I thank particularly D. W. Scholl, A. Bosellini, J. Lajoie, and U. von Rad, who have contributed addenda and modifications to bring their work up to date; H. Okada for translating parts of the two Japanese papers and H. C. Jenkyns for translating the Italian contribution; and V. J. Ansfield, Stephanie Hrabar, R. Kepferle, H. W. Menard, A. A. Meyerhoff, T. H. Nilsen, L. E. Redwine, F. P. Shepard, and D. C. Van Siclen for dealing with specific questions. The Series Editor (Rhodes W. Fairbridge), George H. Keller, and Sam Thompson III read the whole manuscript and made constructive comments. Francis P. Shepard and Sam Thompson III drew my attention to a number of references on modern and ancient canyons, respectively. M. Adachi, A. Iijima, Y. Kanie, T. Matsumoto, S. Mizutani, H. Okada, and K. Tanaka enlightened me on Japanese ancient canyons. On the production side, Sally Ward cheerfully and promptly typed the manuscript. I have enjoyed working with such helpful and understanding publishers, especially the Benchmark Production Editor, Bernice Wisniewski.

J. H. McD. WHITAKER

CONTENTS BY AUTHOR

About the Editor

JOHN H. McD. WHITAKER was born in 1921 in Cambridge, England. He received the B.A. and M.A. degrees at Cambridge University, the B.Sc. from London University, and the Ph.D. from Leicester University. After three years as Assistant Lecturer at the University of Manchester, he moved to the University College (later the University) of Leicester in 1951 to start a new Department of Geology; he is currently Senior Lecturer there. His main research interests are in the Silurian and lower Devonian stratigraphy and sedimentology of the Welsh Borderlands and southern Norway, where he worked for 14 months as a Postdoctoral Fellow with the Royal Norwegian Council for Scientific and Industrial Research. He is also working on the lower Tertiary flysch of Japan, where he recently spent three months on a Royal Society Study Visit. Finding ancient submarine canyon heads in the Silurian of the Welsh Borderlands, as outlined in Paper 18 of this volume, led him to a general study of ancient canyons and fan valleys, and he has had the opportunity of visiting examples of these features in California and Japan. His review of pre-Pleistocene submarine canyons and fan valleys appears in this book as Paper 21.

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PART I: MODERN SUBMARINE CANYONS

INTRODUCTION

MODERN SUBMARINE CANYONS

To begin a volume in four parts, of which the first section only is to deal with modern submarine canyons, seems rather like composing Tchaikovsky's First Piano Concerto—starting with a great flourish but run the danger of ending weakly. To avoid this, we have deliberately soft-pedaled this opening section, especially because it has had excellent treatment from Shepard and Dill in their book *Submarine Canyons and Other Sea Valleys* (1966, Paper 8), and we have given approximately equal weight to the sections on modern deep-sea fans, ancient canyons, and ancient fans, which have received much less attention in review articles. We have had to resist the temptation to discuss the many theories of origin for submarine canyons except where appropriate in the introductions to individual papers, and we have had to omit many fine articles for lack of space and to achieve balance among the four sections. We would have liked to include more of Shepard and Dill's book and to have reproduced Martin and Emery's detailed study of Monterey and Carmel Canyons (1967); Nelson and others on Astoria Canyon and Fan (1970); some of the papers by Stanley, Kelling, Fenner, Pratt, and others on the U.S. East Coast canyons; the French work led by Bourcart in the Mediterranean and the Bay of Biscay; and the recent studies of the Great Bahama Canyon (Andrews and others, 1970), among others.

To give a general coverage of the subject, we have chosen an early publication by Buchanan (1887, Paper 1) on the Congo Canyon and two papers from the 1930s with contrasting views on the origin of canyons, one by Shepard on the U.S. East Coast canyons and part of the often-cited paper by Daly which led to the development of the turbidity-current hypothesis of submarine erosion of canyons. We return to the Congo Canyon (Heezen and others, 1964, Paper 4; Shepard and Emery, 1973, Paper 5) and then see a good example of the detailed studies made in Scripps Submarine Canyon head by Scuba diving (Dill, 1964b, Paper 6), investigations that led to new ideas about ways in which canyons could be eroded. The world's largest and longest canyons in the Bering Sea are awe inspiring, and a well-illustrated paper by Scholl and others (1970, Paper 7) deals with these impressive features. Finally, Shepard and Dill's data on all canyons known up to 1966, with their comprehensive bibliography, concludes this section.

Active research on canyons using improved techniques is discovering the details of their morphology and the nature of their walls and sedimentary fills, leading to a better appreciation of the processes forming them. To draw attention to work not included in Shepard and Dill's book (1966, Paper 8) or published since then, we have included a selection of references grouped under the general but overlapping headings of *Techniques; General Studies of Canyons and their Sediments; Currents and Sedimentary Processes Operating in Canyons;* and *Structural Control.*

Techniques of studying canyons are well summarized by Shepard (1973a, Chap. 2) and the results illustrated by Heezen and Hollister (1971). They include the use of deep-tow vehicles with transducers (e. g., Normark, Paper 12) which show up minor irregularities; side scanning by Asdic (see Belderson and Stride, 1969; Kenyon and Belderson, 1973); seismic reflection profiling (e. g., Kelling and Stanley, 1970; Rona, 1970; Belderson and others, 1972); improved methods of photographing the walls and floors of canyons (e. g., Gennesseaux, 1966; Stanley and Kelling, 1968a; Heezen and Hollister, 1971) and observing them by underwater television (Stanley and others, 1972; Stanley and Fenner, 1973). There has been a great increase in Scuba diving (e. g., Dill, 1969) and the use of deep-diving vehicles (e. g., Ross, 1968b; Got and others, 1969; Keller and others, 1973; Stanley, 1974), sampling with oriented box cores (e. g., Bouma and Shepard, 1964; Bouma, 1965; Rees and others, 1968) and the measurement of bottom currents with free instruments (e. g., Shepard and Emery, Paper 5). ^{14}C dating (Reimnitz and Gutiérrez-Estrada, 1970) is an important tool in the study of canyon development. Russian oceanographers have used luminescent sand to trace sediment movement from the Inguri River into the Inguri Canyon, Black Sea (Yegorov and Galanov, 1966; Trimonis and Shimkus, 1970).

Studies of specific canyons and their sediments include: Jordan, 1951 (De Soto); Northrop, 1953 (Hudson); Creager, 1958 (Campeche); Zenkovich, 1958 (Black Sea canyons); Jordan and Stewart, 1961 (Florida); Northrop and others, 1962 (Veatch and Hydrographer); La Fond, 1964 (east coast of India); Reyss, 1964 (western Mediterranean); Ryan and Heezen, 1965 (Ionian Sea canyons); Hopkins, 1966 (Australian canyons, including some filled canyons); Harbison, 1968 (De Soto Canyon and its relation to salt diapirs); Martin and Emery, 1967 (Monterey and Carmel); Rona and others, 1967 (Hatteras and Pamlico); Varadachari, 1967 (Coromandel Coast); Von der Borch, 1967, 1968 (Australian canyons); Bouma and others, 1968 (Alaminos Canyon winds among salt diapirs); Bouysse and others, 1968 (Cap Breton Canyon, Bay of Biscay); Dietz and others, 1968 (Cayar); Glangeaud and others, 1968 (Rech Bourcart); Nesteroff and others, 1968 (Cap Breton); Rees and others, 1968 (magnetic fabric of sediments in La Jolla Canyon and Fan Valley); Simpson and Forder, 1968 (Cape); Stanley and Kelling, 1968a, 1968b, 1970 (Wilmington); Uchupi, 1968a, 1968b (Wilmington and other canyons); Beer, 1969 (suspended sediment in Redondo); Carlson and Nelson, 1969 (Astoria); Duplaix and Olivet, 1969 (Rech Bourcart, Golfe du Lion); Il'yin and Lisitsyn, 1969 (map of Atlantic canyons and discussion of their origin in relation to climate); Newton and Pilkey, 1969 (Hatteras); Von der Borch, 1969 (New Guinea); Andrews and others, 1970 (Great Bahama); Dulemba, 1970 (Corsica); Duncan and Kulm, 1970 (Astoria and Willapa); Kelling and Stanley, 1970 (Wilmington and Baltimore); Mauffret and Sancho, 1970 (Gulf of Valencia, western Mediterranean); Nelson and others, 1970 (Astoria Canyon and Fan); Pryor, 1970 (deepwater submarine canyon head in Tongue of the Ocean); Scholl and others, 1970, Paper 7 (Bering Sea Canyons); Trimonis and Shimkus, 1970 (Inguri Canyon, Black Sea); Allen and others, 1971 (Cap Breton, Europe's largest canyon); Beer and Gorsline, 1971 (Redondo); Bouma and others, 1971 (Alaminos); Dietz and Knebel, 1971 (Trou Sans Fond, Ivory Coast); Field and Pilkey, 1971 (Hatteras); Felix and Gorsline, 1971 (Newport, now "dead" and filling with fine organic-rich sediments); Gennesseaux and others, 1971 (Var Canyon, Alpes Maritimes); Lonardi and Ewing, 1971 (canyons of the Argentine Basin); Pequegnat and others, 1971 (bottom photographs of De Soto Canyon); Burke, 1972 (Niger Delta canyons); Duplaix, 1972 (heavy minerals in sands of the French Mediterranean canyons); Emery and Uchupi, 1972 (their figure 37 is a 1 to 4 million colored map with canyons named, from Grand Banks to Caribbean); Goedicke, 1972 (Lebanon); Moyes and others, 1972 (Gascogne I); Houbolt, 1973 (Gulf of Guinea); Shepard and Emery, 1973, (Congo); Trumbull and Garrison, 1973 (canyons south of Puerto Rico); Vasiliev and Markov, 1973 (two canyons in the Sea of Japan); Coulbourn and others, 1974 (Hawaii);

Herman, 1974 (canyons of the Arctic Seas); Stanley and others, 1974 (Cap Creus and Lacaze-Duthiers Canyons, western Mediterranean); Sonnenfeld, 1975 (Mediterranean and Black Sea).

At present there is much interest in current movements and sedimentary processes operating in canyons, with attempts to quantify the active processes. A symposium on this topic was held at the Geological Society of America annual meeting in 1974. These aspects are dealt with by: Hand and Emery, 1964 (turbidites off California); Inman and Murray, 1964 (auto-suspended sand currents); Sprigg, 1964 (slumping and buried canyons off Australia); Marlowe, 1965 (the Gully Canyon); Shepard, 1965 (canyons as funnels); Agarate and others, 1967 (Lacaze-Duthiers and Cap Creus Canyons reexcavating earlier channels); Martin and Rex, 1967 (submarine weathering in Carmel and Monterey); Trumbull and McCamis, 1967 (mass transport in Oceanographer Canyon); Hulsemann, 1968 (internal waves and associated currents); Ross, 1968a, 1968b (Corsair and Lydonia); Scholl and others, 1968 (Bering Sea Canyons); Starke and Howard, 1968 (fluming out of ancestral stream-eroded canyon); Von der Borch, 1968 (subaerial cutting of southern Australian canyons in early Tertiary); Beer, 1969 (Redondo); Emery, 1969 (canyons as funnels); Moore, 1969 ("drowned" canyon heads); Shepard, 1969 (canyons as funnels: filling and reopening); Shepard and Marshall, 1969 (internal waves in La Jolla and Scripps); Von der Borch, 1969 (rim upgrowth and axial downcutting, New Guinea); Andrews and others, 1970 (Great Bahama Canyon: upbuilding of sides and reexcavation of old filled troughs); Inman, 1970 (currents in Scripps Canyon); Mathewson, 1970 (Molokai, Hawaii, upbuilding of walls); Reimnitz and Gutiérrez-Estrada, 1970 (Rio Balsas Canyon, Mexico); Rona, 1970 (Cape Hatteras, upbuilding of walls; canyon heads now buried); Winterer, 1970 (erosional entrenchment and backfilling of Coral Sea Canyons); Beer and Gorsline, 1971 (Redondo); Fenner and others, 1971 (Wilmington bottom currents); Gennesseaux and others, 1971 (currents in submarine valley of Var, off Nice); Montadert and others, 1971 (upbuilding of Cap Breton Canyon); Palmer, 1971 (erosion of submarine outcrops, La Jolla); Reimnitz, 1971 (currents in Rio Balsas Canyon); Rowe, 1971 (Hatteras); Bouma and others, 1972 (two canyons off Magdalena River); Cannon, 1972 (wind effects on currents in Juan de Fuca Canyon); Ballard and others, 1973 (Oceanographer Canyon in preexistent feature presently being reexcavated); Drake and Gorsline, 1973 (suspended sediment in Hueneme, Redondo, Newport, and La Jolla Canyons); Gonthier and Klingebiel, 1973 (Gascogne I, Bay of Biscay); Keller and others, 1973 (bottom currents in Hudson Canyon); Robb and others, 1973 (three submarine valleys off Liberia modified by large slumps: one of the valleys may mark the termination of an oceanic frac-