the scientifically fortunate position of being reduced to obsolescence as they speak.

H. R. GOULD, Esso Production Research Co., Houston, Tex.

ENVIRONMENTAL INDICATORS—A KEY TO STRATIGRAPHIC RECORD

Since Leonardo da Vinci made his first environmental analysis in the 15th century, geologists have become increasingly concerned with sedimentary environments. Accordingly, their methods for recognizing environments of deposition have become more sophisticated, and their determinations have become more precise.

The major types of criteria conventionally used in recognizing sedimentary environments are the physical, chemical, and biologic characteristics preserved in the rock. These features can be determined from a single small outcrop or subsurface core. Where larger or multiple outcrops are accessible, or where numerous subsurface cores are available, criteria of a much larger order of magnitude, such as lateral and vertical facies relations and the three-dimensional geometric framework of the strata, can be employed to strengthen and broaden the environmental interpretation.

In the symposium papers presented at this meeting, the speakers review the major sedimentary environments and identify for each the unique set of criteria which permit its recognition. Such information is important, not only to interpret the stratigraphic record, but also to explore for and produce most natural resources, including oil and gas, mineral deposits, and underground water supplies. Knowledge of sedimentary environments also is essential in engineering-geology studies of numerous and diverse types.

A. HALLAM, Oxford Univ., Oxford, England

ASPECTS OF MESOZOIC SHELF IN WESTERN EUROPE

During the Mesozoic, the major paleogeographic units of western Europe were the Tethyan Ocean on the south, where predominantly calcareous marine sediments were deposited, and a shelf zone on the north, where dominantly arenaceous and argillaceous marine sediments and nonmarine intercalations were deposited. Clear-cut distinctions cannot be made between the two units because of gradational changes and fluctuations in space and time. An additional complicating factor is the fact that in some parts of the section, particularly in lower Mesozoic strata, extensive Tethyan deposits on the margins of the present-day Mediterranean apparently were laid down in shallow water.

Within the areas of sedimentation there can be distinguished a series of basins, such as the Lower Saxony, Paris, and Wessex basins, characterized by relatively thick, continuous sequences, and swells which are areas of relatively thin, discontinuous sequences which in many places correspond to the margins of Precambrian or Paleozoic massifs, *e.g.*, Scandinavia, Scottish Highlands, Brittany, Massif Central, and Harz Mountains. These massifs were transgressed by the sea only to a limited extent before Late Cretaceous time.

The Triassic of the northern shelf zone is composed largely of continental redbeds with subordinate evaporites. However, there is a marine intercalation, the Muschelkalk, between the Bunter and Keuper of Germany and the southern North Sea region. The Muschelkalk consists of limestone and dolomite with a restricted fauna suggesting abnormal salinity. The Triassic deposits of the southern (Tethyan) zone are thick and largely marine; particularly striking are several thousand meters of Carnian, Norian, and Rhaetian shallow-water limestone and dolomite.

Just before the Jurassic, the sea began to transgress progressively northward across the shelf zone. Except for some minor regressions, the transgression persisted until late Oxfordian-early Kimeridgian time and was accompanied by the gradual northward spread of shallow-water, calcareous, relatively open-sea deposits at the expense of terrigenous clastic and ferruginous deposits laid down close to river deltas. Salinity probably controlled the regional faunal distribution. The latest Jurassic and Early Cretaceous was a time of widespread regression when nonmarine deposits (Purbeckian-Wealden) were laid down from southern England across northern France to Germany. Renewed transgression in Aptian-Albian time preceded the major Mesozoic transgression in the Late Cretaceous, when great thicknesses of chalk were deposited. During the deposition of the ancient coccolith ooze, most of western Europe was, for the first time, a deep shelf. Mesozoic history ended with a Cretaceous regression.

BRUCE B. HANSHAW, U.S. Geol. Survey, Washington, D.C.

INORGANIC GEOCHEMISTRY OF CARBONATE SHELF ROCKS[1]

Carbonate rocks constitute approximately 20% of the sedimentary record; their economic value is even more important than this percentage would indicate. For example, carbonate rocks contain about 50% of the world's known petroleum reserves; they serve as important host material for base-metal deposits; and they are important industrial minerals.

At the time of formation, by organic or inorganic processes, carbonate rocks consist primarily of the two calcium carbonate minerals, aragonite and calcite. Aragonite is metastable with respect to normal, low-magnesium calcite. In addition to calcium, these minerals commonly contain varying amounts of other divalent cations, especially magnesium, strontium, manganese, iron, and barium. The ecosystem of the depositional environment is reflected by the trace-element composition of the carbonates. For example, strontium and magnesium content of carbonates increases near a reef complex and reflects the aragonitic and high-magnesian calcitic carbonates of organic origin. The inorganic precipitation of aragonite rather than calcite is favored by the presence of strontium ion, warm water, high pH, high ionic strength, and pronounced supersaturation of the water with respect to calcite. The precipitation of calcite is inhibited by a high magnesium content of the solution. Calcite may contain several mole percent magnesium which substitutes for calcium in the lattice; some organisms contain as much as 30 mole percent magnesium. High-magnesian calcite is even more metastable than aragonite and generally inverts to low-magnesian or relatively pure calcite. Aragonite, with time, generally inverts to calcite although it is known to occur in shells from rocks at least as old as early Paleozoic. Indeed, one of the enigmas of carbonate geochemistry is that normal modern marine deposits are composed predominantly of the metastable phases, aragonite and high-magnesian calcite, whereas ancient rocks are chiefly low-magnesian calcite and dolomite.

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[1] Publication authorized by the Director, U.S. Geol. Survey.

Recent dolomite has now been found in several geologic environments—in restricted marine environments, closed basins, and reefs. Other than reefs, these occurrences cannot account for the enormous amount of dolomitic rock in the record. One might say that the dolomite problem is in reality a magnesium problem for the main difficulty seems to be to get sufficient magnesium in solution to dolomitize calcite or aragonite. It is probable that many regional dolomites are formed by the action of interstitial waters, of sufficient magnesium activity, on a calcitic or aragonitic precursor.

The isotopes of carbon and oxygen have played a significant role in unraveling prior history of carbonate deposits. Oxygen isotopes have been extremely useful in developing a paleotemperature scale for determining the ecological environment of ancient marine organisms. Carbon-isotope composition has been used to differentiate between marine and nonmarine limestone deposits. However, these data must be interpreted with care; recent work has indicated that, above the water table and in a tropical environment, extensive carbon-isotope alteration may occur which can greatly change the isotopic composition of any or all carbonate minerals above the regional water table. Also, evaporative processes may alter the isotopic composition of a solution and of the minerals precipitating from it; these effects can lead to erroneous interpretations of ancient geologic environments.

Trace element and isotopic studies of the carbonate rock minerals and similar studies of the coexisting aqueous phase can aid greatly in understanding the environment of deposition, diagenetic changes which have occurred, in predicting regions of porosity development and dolomitization, and in unraveling conditions in the geologic past.

LAWRENCE A. HARDIE, Dept. Earth and Planetary Sciences, Johns Hopkins Univ., Baltimore, Md.

ALGAL CRUSTS FROM BAHAMAS

Lithified crusts are common on the Holocene carbonate tidal flats of Florida, the Bahamas, the Caribbean, the Arabian Gulf, and Western Australia. Because these crusts form at the surface by early cementation, they will preserve primary features diagnostic of the environment. One example is the preservation of algal filaments and storm layers in the aragonitic crusts on the tidal flats of northwest Andros Island, Bahamas. These thin (0.01–5.0 cm) surface algal crusts occur at about the same elevation (just above "normal" high-water mark) in three subenvironments of the tidal flats: (1) on the backslope of beach storm-ridges, (2) on the backslope of natural levees of tidal creeks, and (3) on the inland algal marsh.

The upper surface of the crusts, although essentially flat, is characterized by low knobs and mounds. Internally these knobby crusts show two kinds of structure: (1) overlapping planar to crescentic layers of radiating fibers (100 μ across) or thicker columns (500 μ across), which in plan view have a marked honeycomb structure (the voids may or may not be filled with pelleted mud); and (2) thin (<5 mm) uncemented laminae of loose, soft, ovoid, aragonitic pellets. The fibrous and columnar structures replicate the tufted structure of mats of the filamentous blue-green alga *Scytonema* (mainly *Crustaceum* sp.) now living on the tidal flats. The pellet layers are deposited mechanically during winter storms. "Frozen-in" these crusts then is a remarkable record of soft parts of the indigenous algae and of the sedimentation during the annual northwesterly winter gale season.

WILLIAM W. HAY, Institute of Marine Sciences, Univ. Miami, Miami, Fla., and Dept. Geology, Univ. Illinois, Urbana, Ill., and PAVEL CEPEK, Sektor Paleontologie, Czechoslovak Acad. Sciences, Prague, Czechoslovakia

NANNOFOSSILS, PROBABILITY, AND BIOSTRATIGRAPHIC RESOLUTION

The appearance of a new species or disappearance of an old species may be considered a biostratigraphic event. If simultaneity does not exist, each first and last occurrence can be separated into a sequence of events. If dispersal rates are high compared with evolutionary rates, the sequence should be the same in all sections. The stratigraphic record is then divisible into several increments ("concurrent range zones") equal to the number of events minus one. Most fossils do not satisfy the requirements of occurrence and distribution, but calcareous nannofossils are admirably suited for refining biostratigraphic resolution. For example, Upper Cretaceous strata contain about 82 distinctive species of coccoliths which have their first and last occurrences in Cenomanian-Maestrichtian strata, so that as many as 163 increments may be distinguishable in this interval.

Biostratigraphic correlation now may be defined as the probability that a specified assemblage belongs at a certain point in a sequence of events. The correlation depends on three factors, each of which may be expressed in statistical terms: (1) the probability that the events used to define a biostratigraphic increment are in the true order, (2) the probability that the species used to define the superjacent or subjacent increment is absent, and (3) the probability that the critical species determinations are correct.

PHILIP H. HECKEL, Kansas Geol. Survey, Lawrence, Kans.

RECOGNITION OF SHALLOW MARINE ENVIRONMENTS

Shallow-marine environments encompass a great variety of conditions from shoreline to a depth of about 600 ft. In sedimentary rocks, these environments are inferred most readily from diverse assemblages of fossils whose modern relatives are marine. Some sparse and restricted biotas may represent fully marine environments in which certain factors were unfavorable to many types of organisms. Many unfossiliferous black shales represent a foul environment that supported no benthonic life and are inferred to be marine mainly by stratigraphic relations. Marine environments that lack significant sedimentation would be represented in the record only by a submarine paraconformity.

Recognition of marine subenvironments is possible through direct lithic analogy with distinctive modern sediments of known depositional environments, such as oölite, sea-margin carbonate laminites, and certain organism-controlled features such as reefs. In less distinctive marine facies, subenvironments are difficult to discriminate because visible differences may have resulted from a complex interplay of many variable factors that did not coincide to produce unique subdivisions. Ecologic consideration of fossil assemblages may distinguish clear-water from turbid-water, or soft-substrate from hard-substrate environments. Petrographic considerations also allow environmental inference. The presence of calcilutite indicates a quiet-water environ-