Late Miocene Desiccation of the Mediterranean

K. J. HSÜ
Geologisches Institut, ETH, Zürich

W. B. F. RYAN
Lamont-Doherty Geological Laboratory, Palisades, New York

M. B. CITA
Università degli Studi, Milano

This article presents evidence that the Mediterranean Sea was a desiccated deep basin some 6 million years ago.

THE presence of an evaporite deposit of Late Miocene Messinian age under the Mediterranean Sea was discovered two years ago by the Deep Sea Drilling Project (DSDP) Cruise Leg XIII (refs. 1–4). To start with, our postulates were greeted with disbelief, but detailed analyses of samples and syntheses of regional geology during the past two years have led to a confirmation of this apparently preposterous idea. We shall present in this article our principal conclusions and some of the critical evidence. Detailed documentation will be published in due course[5].

Three Models

The origin of the Mediterranean evaporites could be accounted for by three different models. In the first, there was evaporation of a deep water Mediterranean basin, which received constant inflow from the Atlantic so that its brine level was maintained at or slightly below the world wide sea level. The second involves evaporation of a shallow water Mediterranean basin, which, similarly, received constant inflow from the Atlantic so that its brine level was maintained at or slightly below the world wide sea level. According to the third, desiccation of a deep Mediterranean basin, isolated from the Atlantic, took place, so that evaporites were precipitated from playas or salt lakes whose brine levels were dropped down to thousands of metres below the Atlantic sea level.

The first may be called the "deep water, deep basin model"[6] and the second the "shallow water, shallow basin model"[5]. The third, namely the desiccated deep basin model, is, however, the one we prefer.

Late Miocene Basin Geometry

Geophysical evidence—chiefly the basin-wide distribution of an acoustic reflector[8] (Fig. 1) which has been identified by drilling as the top of the Mediterranean evaporites[5]—clearly indicates that the Late Miocene Mediterranean had a configuration not greatly different from that of today. The surface of the reflector conforms more or less to the contours of the intricate submarine topography, indicating that the Mediterranean basin had already been created when the evaporite was being deposited.

More convincing evidence is provided by stratigraphical and palaeontological studies. The strata underlying the evaporites are deep marine pelagic sediments. During the DSDP Leg XIII, Middle Miocene pelagic marls were cored from sites 126 and 129 (see Fig. 2) in the Ionian Basin[1,5], and lower Upper Miocene (Tortonian) marls were sampled from site 121 in the Alboarn Basin[5]. The correlative Tortonian marl underlying the Upper Miocene evaporites (Messinian) of Sicily has been proved to be a deep water deposit by a study of its benthonic foraminiferal faunas[9]. Deep marine pelagic marls of Lower Miocene age are also known on the island of Pianosa in the Tyrrhenian Sea[10]. These facts clearly indicate that the Mediterranean basins were already deep before the salinity crisis.

The strata directly overlying the Messinian evaporites are also deep marine pelagic sediments. These earliest Pliocene strata contain a benthonic ostracod fauna, which could only live in ocean bottom below 1,000 m (ref. 11). The associated benthonic Foraminifera are likewise indicative of a deep marine environment of deposition[9]. The fact that of the deep-swimming planktonic genus *Spheroidinellopsis* is the dominant (up to 90%) microfauna lends further credence to the concept of a deep Mediterranean in the earliest Pliocene[5]. Additional data in support of deep marine sedimentation immediately after the salinity crisis have been provided by the oxygen isotope measurements[5]. As geophysical considerations exclude the possibility of a catastrophic subsidence[5], the only alternative is the sudden drowning of a desiccated deep basin.

Pelagic oozes are, in fact, intercalated in the Messinian evaporites. At site 134, to the west of Sardinia, we cored a

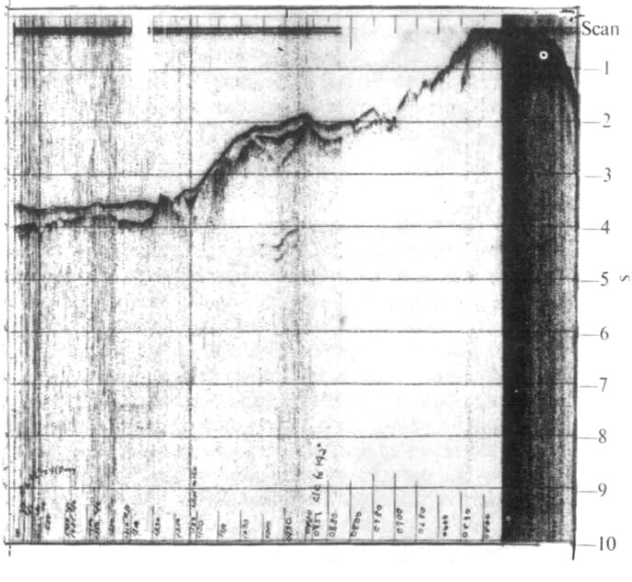

Fig. 1 The Mediterranean reflector. This strong reflector corresponds to the top of the Upper Miocene evaporite formation. The relief of the reflector conforms the bottom topography, suggesting that the evaporites were deposited in a basin similar in topography to that of the present Mediterranean.

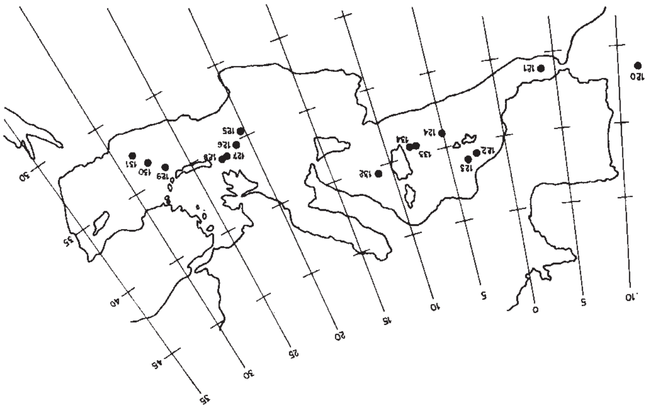

Fig. 2 Drill sites of Leg XIII of the Deep Sea Drilling Project.

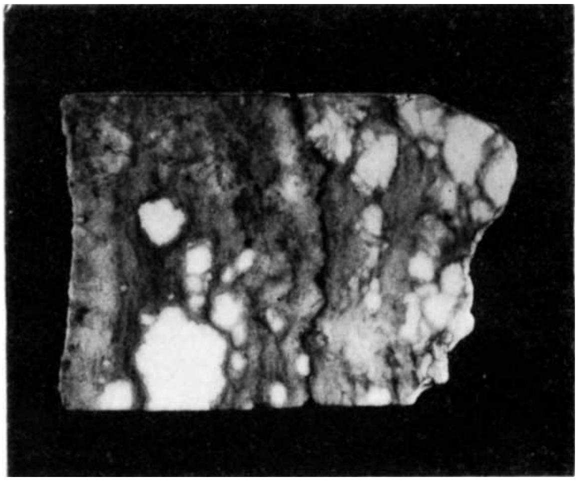

Fig. 3 Nodular and "chicken wire" anhydrite, characteristic precipitates from ground waters under hot and arid coastal flats.

deep marine foraminiferal ooze of Messinian age between two sterile halite layers[5]. Similar marl oozes have been encountered between anhydrite layers at site 124 south of Mallorca[5] and in the Messinian evaporites now uplifted and exposed on Sicily[7]. Where a Late Miocene Mediterranean basin was located near land, as in the case of Periadriatic Trough in Italy or Khania Basin in Crete, deep water turbidities are interbedded with the evaporites[12,13].

If the Late Miocene Mediterranean had been shallow, the marine sediments associated with the evaporites would have been shallow water deposits. This is not the case. The occurrence of deep marine sediments below, above, and within the evaporite sequence proves conclusively that the Mediterranean was already a deep basin during Middle and Late Miocene times.

Environment of Deposition

Although the Upper Miocene marine sediments are deep water deposits, mineralogical, petrographical, sedimentological, and geochemical data strongly suggest that the Upper Miocene evaporites were, on the whole, not precipitated from a deep brine pool; they were formed chiefly in shallow waters or subaerially.

The presence of anhydrite as a dominant sulphate mineral in the Mediterranean evaporites is a strong argument against the idea of a deep water genesis. Anhydrite, $CaSO_4$, is the higher temperature polymorph of calcium sulphate. Below a critical temperature of phase transition, gypsum ($CaSO_4.2H_2O$) should be precipitated. This critical temperature is 58° C for the $CaSO_4.H_2O$ system[14], but is about 20° C for calcium sulphate precipitated from brines saturated with sodium chloride (ref. 14 and F. W. Dickson, personal communication). Deep aqueous bodies rarely acquire a temperature high enough to precipitate anhydrite. Even the Dead Sea, where the surface temperature exceeds 30° C and may locally exceed 40° C, anhydrite is not formed[15]; only gypsum is found on the shores and on the bottom of it.

The occurrence of anhydrite in the form of nodules proves further that it has been crystallized in a subaerial environment. Nodular anhydrite is found today exclusively on hot and arid coastal flats, called *Subkhas* in Arabic, where it is precipitated at the ground water table, 0.5 m or so beneath the surface at temperatures above 35° C (J. Schneider, personal communication); this diagenetic mineral replaces carbonates and sulphates deposited earlier and may form a whole anhydrite bed in which only wisps of organic materials remain. The resulting structure has been given a vulgar name of "chicken wire anhydrite" by geologists working in the petroleum industry and has been considered by some to be an infallible criterion of subaerial crystallization[16] (see Fig. 3).

A careful examination of the cores from site 124, to the south of Mallorca, reveals that the process of formation of evaporite there consists of several cycles of inundation and desiccation (Fig. 4). Each cycle commences with the deposition of laminated carbonates. The predominant carbonate is a dolomite rich in organic matter, and its evenly laminated structure is indicative of deposition in quiet, and probably fairly deep, bodies of water. The carbonates yield either marine micro and nannofossils, or a brackish fauna and flora; they were either

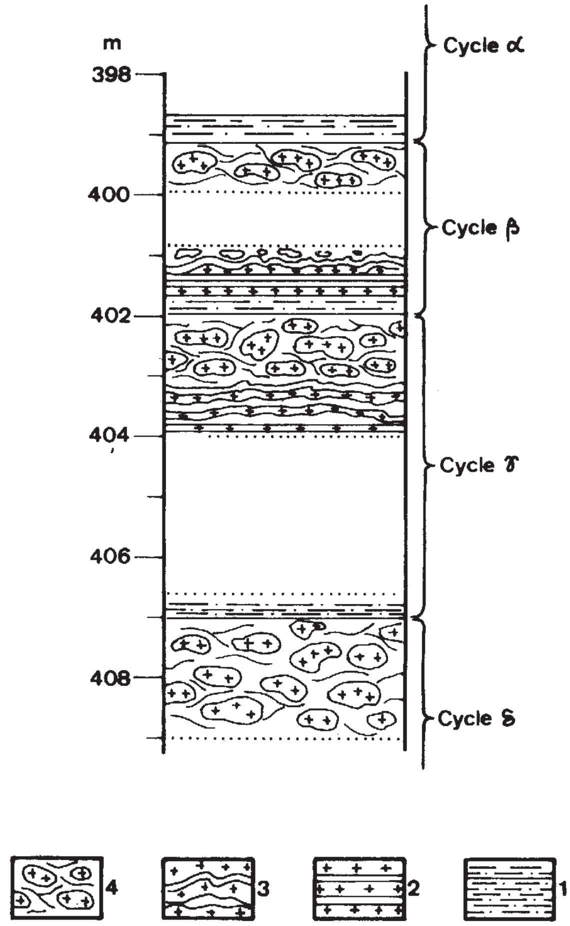

Fig. 4 Schematic diagram of desiccation cycles in hole 124. 1, Laminated carbonates; 2, interlaminated dolomite and anhydrite; 3, stromatolitic deposits; 4, nodular anhydrite.

deposited in a deep sea or in a large brackish lake. Overlying the laminated carbonates are interlaminated dolomite and anhydrite; the laminations are less well defined near the top, a trend suggestive of increasing agitation as the water became shallower. Stromatolites appear near the top of the depositional sequence; they formed only when the brine pool was sufficiently shallow to permit the growth of algae. At the very top of every cycle is the nodular anhydrite, presumably a product of subaerial diagenesis. The anhydrite is covered in turn by very evenly laminated carbonates of the next cycle of inundation.

The halite rock samples from beneath the Balearic abyssal plain also show signs of desiccation. Euhedral "hopper crystals" precipitated in brine pools have been partially replaced by anhedral clear crystals during times of subaerial exposure. A desiccation crack is present, filled with clear halite (Fig. 5). Intercalated in the halite is a cross-laminated foraminiferal silt that has apparently been deposited in an aeolian environment.

Playa deposition is further supported by investigations of stable isotopes. Fig. 6 shows the range of oxygen isotope values of the Mediterranean evaporites[17]. The great variability argues against the idea of precipitation from a brine pool. In fact, the wide range is very similar to that of the playa evaporites, by contrast with the narrow range characterizing the marine evaporites.

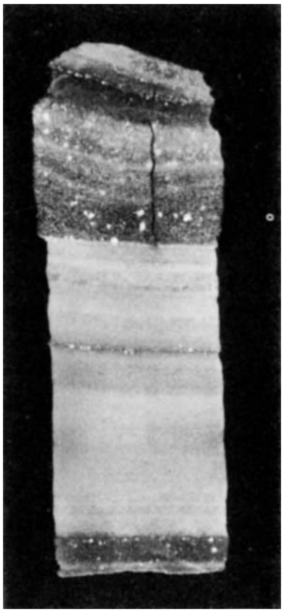

Fig. 5 Halite core from site 134.

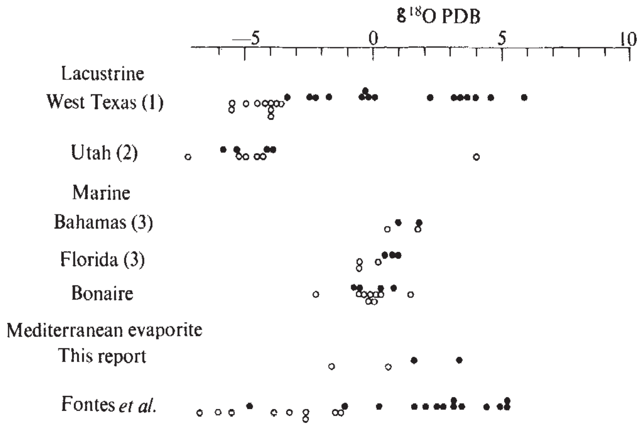

Fig. 6 Oxygen isotope range of the Mediterranean evaporites by comparison with marine and playa evaporites. ●, Dolomite; ○, calcite.

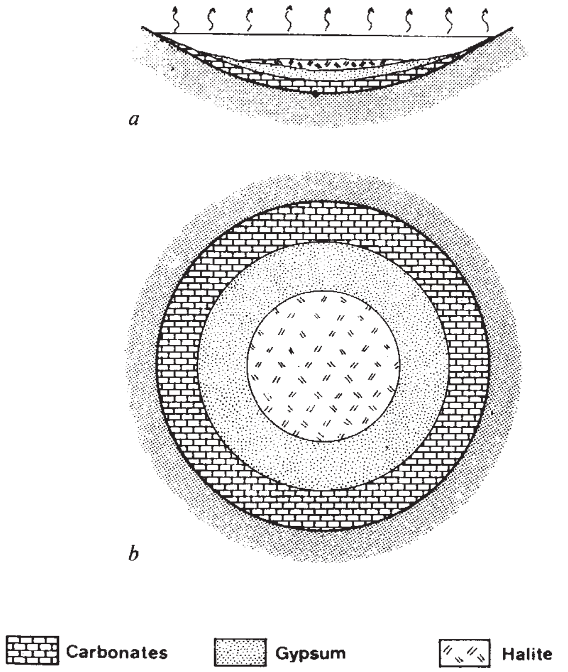

Fig. 7 Idealized bull's eye pattern of evaporite distribution typical of isolated basins. *a*, Cross-section; *b*, map.

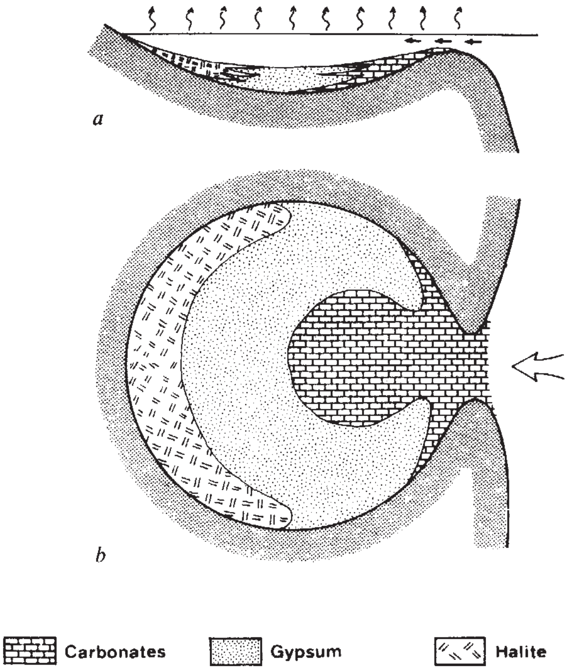

Fig. 8 Idealized tear drop pattern of evaporite distribution typical of partially restricted basins. *a*, Cross-section; *b*, map.

Finally, the distribution pattern of the Mediterranean evaporites is not at all what has been predicted on the basis of a deep water model; deep water evaporites should have a tear drop pattern rather than the bull's eye pattern typical of playa deposits. The latter is well known: a gradual desiccation of a playa should result in concentric zones of saline minerals[18,19], the outermost carbonate being the first salt to precipitate from a brine, and the inner core a most soluble salt (Fig. 7). By contrast, a restricted deep marine basin with an opening at one end would have less soluble salt deposited proximal to the opening and more soluble near the distal end (Fig. 8). If the

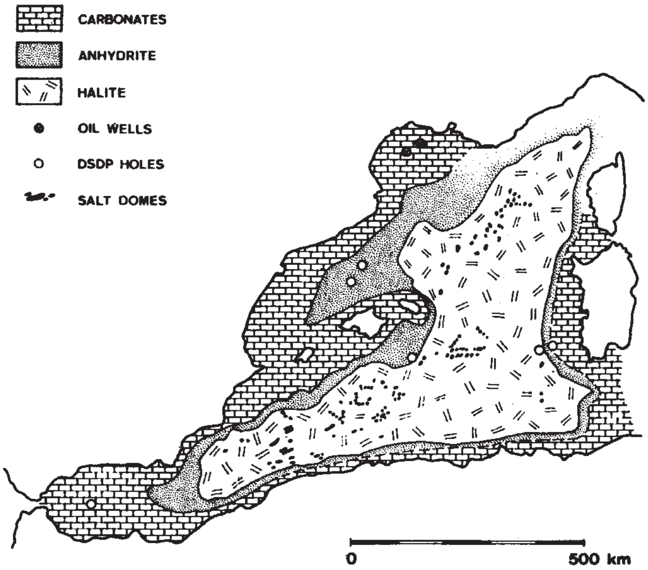

Fig. 9 Probable distribution of evaporites in the western Mediterranean Balearic Basin.

deep water model were applicable, we should have found potash salts and halite in the eastern Mediterranean, but only gypsum and/or dolomite in the western basins. The drilling results showed no evidence of such a "tear drop" pattern. In fact, drilling confirmed the suggestions arising from seismic profiling, namely that halite lies only in the deepest part of each Mediterranean basin and that the evaporite distribution conforms to a bull's eye pattern (see Fig. 9).

Geomorphological Evidence

A desiccated Mediterranean during the Late Miocene dictates that the base level of erosion must then have been thousands of metres below the sea levels. Shelf seas should have withdrawn from continental areas, and coastal plains and newly exposed shelf should have been dissected by rejuvenated streams. They should have cut canyons of steep gradients hundreds of metres into a slightly older marine sediment, and should have left alluvial and terrestrial clastics in the channels. Such a stream system should have been drowned during the final submergence of the desiccated Mediterranean in the earliest Pliocene.

Such an important regression has indeed been deciphered from the available geological records on land. In southern France, for example, a marine sequence, ranging up to Upper Miocene Tortonian, has been cut by a deep channel system. The channels were filled with alluvial gravels, which in turn underlie marine Pliocene sediments. The event recorded by the channel cutting has been known to stratigraphers as the Pontian regression, but its cause was unknown until we formulated our model of Late Miocene desiccation.

Pontian regression has also been reported in Egypt, where the River Nile at Aswan cut a gorge 200 m below sea level. It should be recalled that Aswan is a long way upstream, some 1,250 km from the coast; buried beneath the Marine Pliocene and Quaternary alluvial sediments of the Nile Delta area is a grand canyon comparable to the Grand Canyon of Colorado[11]. Similar buried gorges have been found in Libya, Syria, Israel, and other Mediterranean lands.

We might extend our reasoning a step further. When the Mediterranean was desiccated, the river channels should not only have cut the shelf margins, but should also have continued down towards the flat bottom of the Late Miocene playas, and extended 2,000 to 3,000 m below the present sea level. Post-Miocene sedimentation probably did not fill these channels completely, so drowned river valleys of Late Miocene age should be present on modern continental margins as submarine canyons.

Such submarine canyons have indeed been found, indenting the continental margins of southern France, Italy, Corsica, Sardinia and North Africa[8,22,23]. They were sculptured by streams and subsequently drowned during the Early Pliocene marine transgression. Similar submarine canyons are also present in the eastern Mediterranean[8].

The extension of Miocene streams down to the continental rises left behind floodplain silts and channel gravels. Such terrestrial clastics have been cored in a hole (site 133) at the foot of the continental rise to the west of Sardinia[5], and similar detrital deposits are present on the periphery of the Messinian evaporite basins of Sicily[24]. These occurrences are only explicable in terms of the model of basin desiccation.

History of Evaporite Deposition

The Mediterranean Sea, excluding the Black Sea, has an area of 2.5 million km^2 and a water volume of 3.7 million km^3. The annual loss by evaporation is 4.7×10^3 km^3. The annual precipitation is 1.2×10^3 km^3 and the annual volume delivered by river influx is 0.2×10^3 km^3. The net loss is thus 3.3×10^3 km^3 yr^{-1}. If the Strait of Gibraltar were closed today, the present Mediterranean could be evaporated dry in about 1,000 yr.

The thickness of halite salt that could be precipitated isochemically from one basinful of Mediterranean waters (averaging 1,500 m in depth) is, however, only about 20 m. Even if all the salt was deposited within a restricted basinal area covering one-third of the total, the resulting deposit should still be only 60 m thick. Yet the seismic record shows that the halite deposit under the Mediterranean may be two or three kilometres thick[5]. It is unlikely the freshwater influx from the rivers supplied all the salts, so repeated marine invasions must be postulated. Both the drilling results and the study of the correlative salt deposit of Sicily indicated that this was indeed the case; the Mediterranean was dried up and refilled repeatedly during the few million years represented by the Messinian stage. It should be recalled that the refilling of a basin could not have been instantaneous. Considering the inevitable evaporative losses during the transient stage, several basinfuls of water must have found their way across before the basin was filled up; thus each marine incursion into the Mediterranean might have brought enough salt to deposit a few hundred metres of halite in basinal areas. A detailed computation of the material balance budget led us to conclude that eight or ten marine invasions, represented by the interbeds of marine marls in the Upper Miocene evaporite-formation of Sicily, could have been sufficient to account for all the salts under the Mediterranean abyssal plains[5].

Although the flood gate at the Strait of Gibraltar apparently swung open and shut repeatedly during the Late Miocene, the gate was irreparably crushed at the beginning of the Pliocene. The earliest Pliocene sediment of the Mediterranean is a deep marine ooze, characterized by a cold water bottom fauna. Although the recurrent Messinian "refills" might have been related to spill-overs caused by eustatic rise of the world wide sea level, the final deluge was probably related to a rifting movement along the Azores–Gibraltar fracture zone. The initial gap was deep enough to permit the entrance of deep Atlantic bottom faunas into the Mediterranean. The Strait of Gibraltar was gradually shoaled during the Pliocene, and eventually the supply of deep Atlantic waters was cut off, causing the extinction of the cold Mediterranean benthonic faunas. Yet the Strait is still open sufficiently to permit the reflux of partially evaporated Mediterranean waters so as to keep its salinity only slightly above that of the open ocean.

Explaining an Improbable Fact

We have presented in this article the evidence which led us to conclude that the Mediterranean was a desiccated deep basin some 6 million years ago. The full documentation of the data will be published in our cruise report[5]. We realize that our deduction seems improbable because none of the desert basins today are comparable in size or depth to a desiccated Mediterranean. Yet the improbable fact that the Mediterranean Sea is underlain by a salt deposit demands an improbable explanation. We welcome comments from our colleagues in the Earth and biological sciences, particularly if some of their own observations bear out, or disprove, the idea that the Mediterranean was a desert during the Late Miocene.

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Voltage Dependent Charge Movement in Skeletal Muscle: a Possible Step in Excitation–Contraction Coupling

M. F. SCHNEIDER* & W. K. CHANDLER

Department of Physiology, Yale University School of Medicine, 333 Cedar Street, New Haven, Connecticut 06510

It is suggested that a link in excitation-contraction coupling involves the movement of a fixed amount of charge free to move between different locations across the membrane.

STARTING with the experiments of Huxley and Taylor[1] and Huxley and Straub[2] the view has developed that, under physiological conditions, contraction in skeletal muscle is triggered by depolarization of the membranes of the transverse tubular system (T-system)[3]. This network of tubules extends throughout the cross-section of a fibre[4] and is positioned at regular intervals along the fibre length[5], thus providing a means whereby a change in surface potential can be rapidly transmitted into the interior[6,7]. There is also evidence[8–10] indicating that the final stage of excitation–contraction coupling involves a release of calcium ions into the myoplasm from its intracellular storage location, the sarcoplasmic reticulum (SR); the elevated Ca^{2+} then activates the contractile proteins[11]. It has not been clear, however, how a change in potential across the tubule membrane could bring about the release of Ca^{2+} from the neighbouring SR. The experiments reported here are an attempt to detect an ionic current or movement of charge across the T-system membrane which could play a role in triggering this response.

Voltage-clamp Measurements

In our experiments sartorius muscles from English frogs, *Rana temporaria*, were cooled to approximately 2° C in a solution designed to eliminate virtually all of the time and voltage dependent changes in sodium and potassium currents. The composition was 117.5 mM tetraethylammonium (TEA) chloride, 5 mM RbCl, 1.8 mM $CaCl_2$, tetrodotoxin (10^{-6} g $ml.^{-1}$), and 1 mM Tris-maleate buffer to give a *p*H of 7.1. Movement due to contraction was practically eliminated by making the solution hypertonic with sucrose addition, 350 to 583 mmol to 1 l. Sucrose hypertonicity appears to have little effect on calcium release as the heat of activation is decreased only 10 to 20% on adding 450 mmol sucrose per 1 normal Ringer's solution[12]. Voltage-clamp measurements were carried out using the three microelectrode technique described by Adrian, Chandler and Hodgkin[13]. In this method two voltage sensing microelectrodes were positioned at intervals 1 and 21 from the end of a particular fibre and a third electrode was used for passing current, as is shown in Fig. 1*A*. The membrane current density at x = 1 is related to the difference in potential $\Delta V (= V_2 - V_1)$ by the relation

$$i_m = 2\Delta V/3r_i l^2 \qquad (1)$$

in which i_m is current and r_i is internal resistance per unit length of fibre. Feedback electronics were used to set the

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* Present address: Department of Physiology, University of Rochester School of Medicine and Dentistry, Rochester, NY 14642.