Chapter 17

GULF OF CALIFORNIA

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INTRODUCTION

The peninsula of Baja California was first described by Hernan Cortes, who pioneered the exploration of the Pacific soon after the conquest of Mexico–Tenochtitlan. In his fourth letter to the king of Spain (1524) he wrote about an island — Baja California — his captains had reported to him, and Cortes himself sailed to the area of La Paz bay in 1535 (Leon-Portilla, 1972). Finally, in 1539 Cortes sent Francisco De Ulloa with three ships to explore further north. De Ulloa circumnavigated the Gulf and named it "Mar Bermejo", the Vermilion Sea, because of the reddish color of the muddy waters of the Colorado Estuary, and not, as is often assumed, because of the red plankton blooms of the central region (Van Andel and Shor 1964). The first hydrographic cruise into the Gulf was made by the U.S. Fish Commission Steamer *Albatross* in 1889 (Townsend, 1901). Fifty years later, the modern investigation of the Gulf began with the *E.W. Scripps* cruise in 1939, which made a series of 53 hydrographic stations throughout the Gulf, including measurements of temperature, salinity, oxygen and calcium, besides sampling for phytoplankton and zooplankton (Sverdrup, 1941; Roden and Groves, 1959).

The Gulf of California occupies an oceanographically unique position among the marginal seas of the Pacific Ocean (Fig. 17.1A). Lying between the arid peninsula of Baja California in the west and the almost equally arid states of Sonora and Sinaloa to the east, it includes a large evaporation basin, which is open to the Pacific at its southern end (Roden, 1964). It is approximately 1000 km long and 150 km wide on the average. Topographically it is divided into a series of basins and trenches, deepening to the south and separated from each other by transverse ridges (Shepard, 1950) (Fig. 17.1B). It is separated into two areas by the islands Angel de la Guarda and Tiburon. The northern portion is relatively shallow with the exception of Dolphin Basin. Much of this area is at shelf depth with few shelf breaks. South from Angel de la Guarda and Tiburon the Gulf has well-developed continental shelves. On the western side the shelf is generally rocky and narrow, with a sharp shelf break between 80 and 100 m; the eastern shelf is wider (Van Andel, 1964). The coast of Sinaloa, to the east, has many coastal lagoons, most of them in the area of the mouth of the Gulf.

Theories about the formation of the Gulf have developed with the theories of sea-floor spreading, continental drift and plate tectonics (Reichle, 1975). Shepard (1950) concluded that the topography of the Gulf resulted primarily from strike-slip faulting. According to Rusnak and Fisher (1964), the Gulf may have evolved as fractured plates of crustal material moved northwestward toward the Pacific by gravitational sliding on extremely gentle slopes from the regions of western Mexico uplifted by batholithic intrusions. Sykes (1968) suggested that the tensional faults separating the strike-slip faults may be loci of sea-floor spreading. Larson et al. (1968) analyzed magnetic anomalies generated at the East Pacific Rise near the mouth of the Gulf and concluded that the motion of the tip of Baja California away from mainland Mexico has been an average of 6 cm yr^{-1} for the past four million years. The rates of spreading may be obtained from the magnetic patterns and the dates of the earth's magnetic field reversals (Bullard, 1969). Moore and Buffington (1968) suggested the existence of a proto-Gulf before the present spreading episode

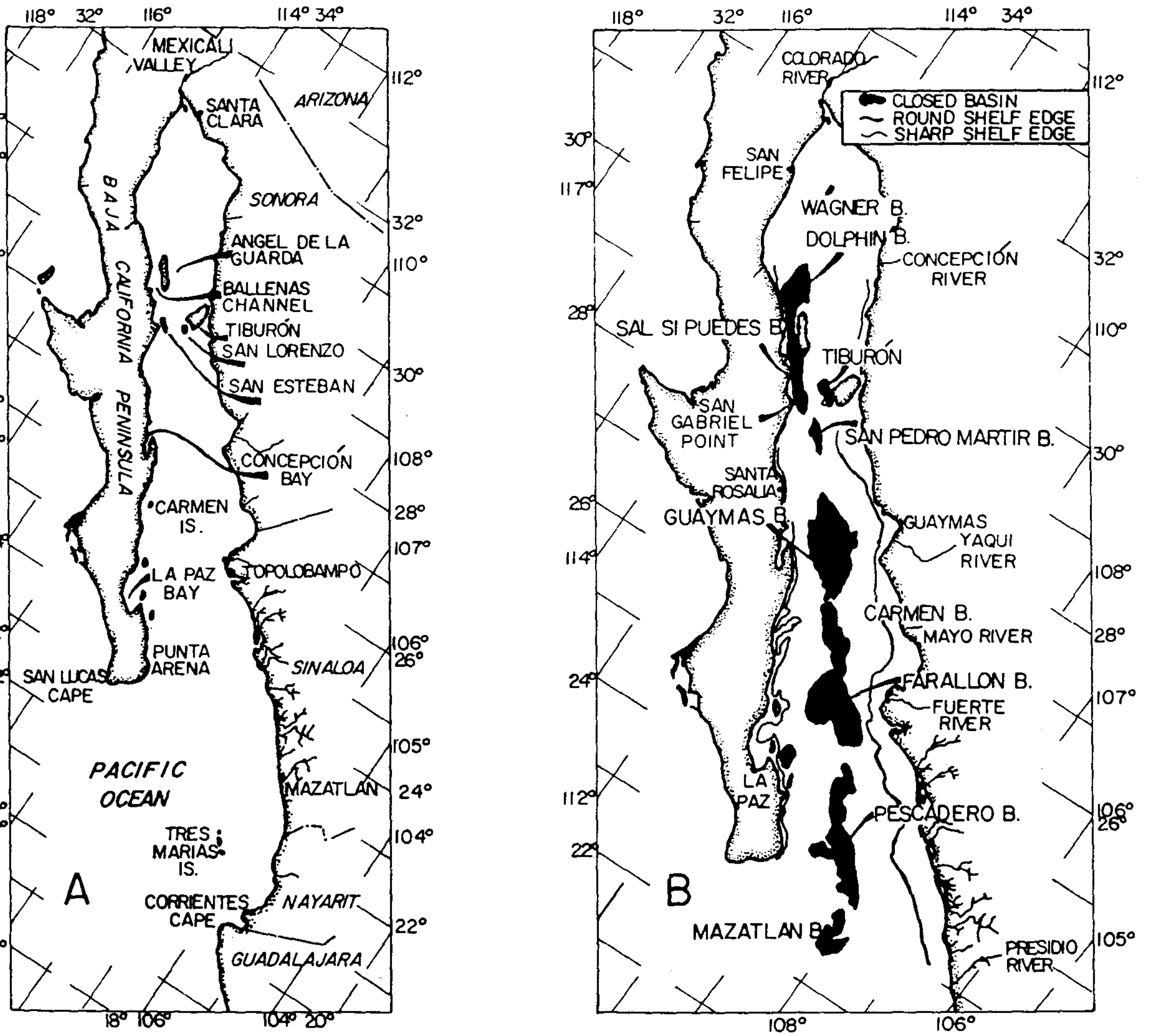


Fig. 17.1. A. Gulf of California. B. Shelves and basins in the Gulf of California. Basins are defined by depth contour at sill depth (after Van Andel, 1964).

began four million years ago. Reichle (1975) has discussed the regional tectonics of the Gulf and presented a general description of a series of transform faults and spreading centers (Fig. 17.2).

CURRENTS, MIXING AND WATER MASSES OF THE GULF

Meteorological aspects

The moderating effect of the Pacific Ocean upon the climate of the Gulf of California is greatly reduced by an almost uninterrupted chain of mountains, 1 to 3 km high, in Baja California. The climate of the Gulf is therefore more continental than oceanic, a fact which contributes to the large annual and diurnal temperature ranges observed there (Hernandez, 1923; cited by Roden, 1964). Roden (1964), using data from Page (1930) and Ward and Brooks (1936), made a summary of the areal distribution of air temperature and rainfall in the Gulf and adjacent regions (Fig. 17.3). In winter the air temperatures decrease toward the interior of the Gulf; there are small air temperature differences between the Gulf and the Pacific coasts of Baja

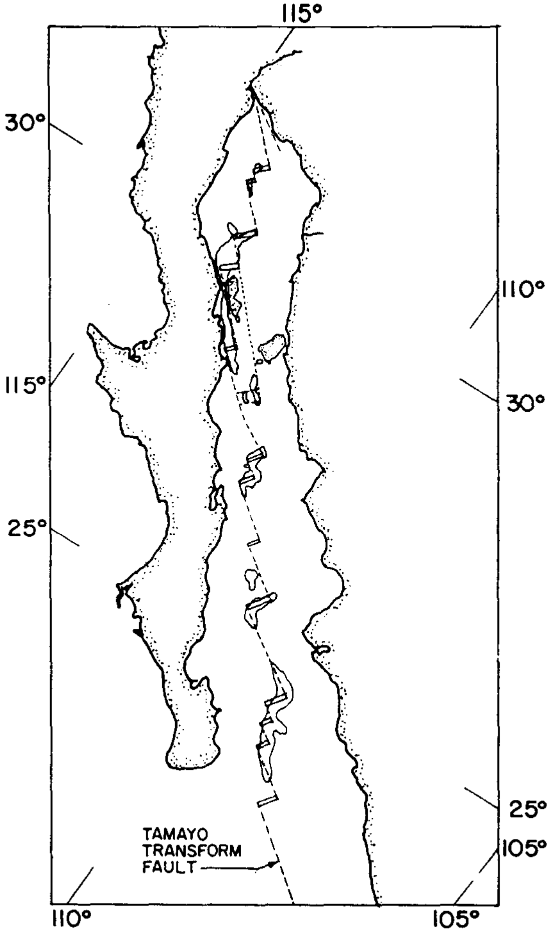


Fig. 17.2. Schematic map of the Gulf of California tectonics. Dashed lines show approximate positions of transform faults; double solid lines show locations of spreading centers as suggested by the bathymetry (after Reichle, 1975).

California, but for the same latitude the air temperatures of the Mexico mainland's coast are higher by about 2°C than those of the Baja California coast. In summer the air temperature increases toward the interior of the Gulf and the temperature differences between the east and west coasts of Baja California are large, sometimes exceeding 10°C. There is more precipitation on the east than on the west side of the Gulf. The northern half of the Gulf is dry and desert-like, with annual rainfall of less than 100 mm. In the southeast, rainfall along the coast increases to about 1000 mm per year. South of Angel de la Guarda and Tiburon Islands most of the rain falls between June and October, but in the north most of the rain falls during winter. The mean annual air temperature range increases from about 6°C at Cape Corrientes to 18°C at the northern end of the Gulf. The number of rainy days per year decreases from about 60 at Cape Corrientes to about 5 along the central Baja California coast.

The year-to-year variation of rainfall in the Gulf is large and depends very much on the incidence of tropical storms and hurricanes. Harris (1969), using data from weather satellites and a review of available literature, indicated that from 1961 (the year the first Tiros satellite was launched) to 1968 there were 93 tropical cyclones in the eastern North Pacific, with wind velocities higher than 34 knots (63 km h^{-1}); 30 of them were hurricanes with wind velocities higher than 74 knots (137 km h^{-1}). According to Harris (1969) the eastern North Pacific is an area of frequent tropical cyclone activity and is second in the world only to the typhoon region of the western Pacific. Hurricanes and tropical storms occur from June to November, with the greatest frequency in September. The general trend of these tropical cyclones is to travel north or northwestward from their origin, which is from 15 to 20°N, and 100 to 110°W. Some of them enter the Gulf of California and dissipate at different places in the states of Sinaloa and Sonora, but a few travel all the way to Arizona. There is a long list of damages that hurricanes cause every year at places such as Manzanillo, Mazatlan, La Paz and San Felipe, including many sunk fishing boats and homeless families. Sometimes there are hundreds of deaths, as there were during hurricane Liza that reached La Paz on October 1, 1976. No systematic studies have been done on the ecological effects of these hurricanes, especially their effects on coastal lagoons and estuaries of the east coast where some commercially important species, crustaceans and molluscs mainly, spend part or all of their lives.

Winds in the gulf are extremely variable. Near the coast a land and sea breeze system prevails and diurnal wind changes are usually larger than annual ones. In the offshore regions of the Gulf northwesterly winds prevail from November to May, and southeasterly ones during the rest of the year. Moderate northwest gales that last two or three days at a time are frequently experienced in the upper Gulf between December and February. These winds are particularly strong in Ballenas channel between the mountainous Baja California

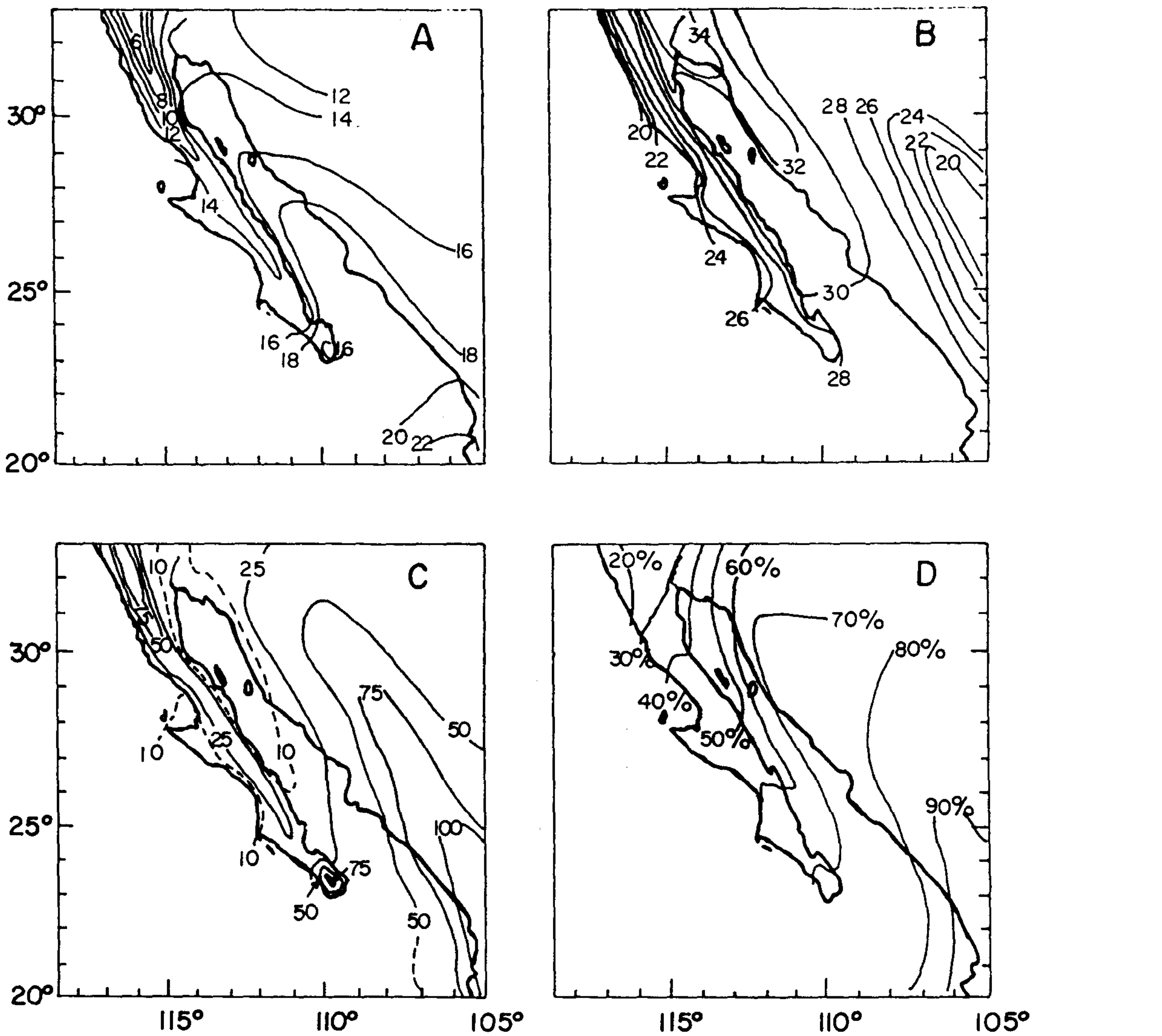


Fig. 17.3. A. Mean air temperature for January (C). B. Mean air temperature for July (C). C. Mean annual rainfall (cm). D. Mean percentage of summer rain (May to October) (after Page, 1930; and Ward and Brooks, 1936; cited by Roden, 1964).

coast and the equally high island of Angel de la Guarda; they may on occasion raise such a heavy sea that navigation becomes impossible (Roden, 1964).

Roden (1964) estimated the evaporation from the sea surface of the southern portion of the Gulf to be roughly 130 cm yr^{-1}; he used the equation $E = K\Delta e W$ for this purpose, where E is evaporation, Δe is the vapor pressure difference between the sea surface and the air above it, W is the wind speed and K is a proportionality factor. He did not apply the equation to the northern portion of the Gulf because advection of dry desert air is considerable there. Direct measurements from evaporation pans at coastal stations give figures that fluctuate between 200 and 250 cm yr^{-1}, with minima in winter and maxima in summer (Roden, 1964).

Fresh-water input by rivers has only a local impact, mostly during the rainy season. Most river water is impounded and used for agricultural and urban purposes, and progressively less river water is allowed to reach the Gulf. The northern states of Sonora and Baja California suffer from an acute lack of water. This semitropical desert area could use huge amounts of water if it were available. There is also a great need for fresh water in the southern areas of Arizona and California. During the late 1960s there was a plan to construct a nuclear power and water desalination plant on the northern Sonora coast, with an anticipated freshwater production capacity of 4×10^9 litres per day (United States–Mexico–International Atomic Energy Agency study team, 1968). It was not constructed because of political reasons. Therefore, we can anticipate that sometime in the near future no fresh river water at all will reach the Gulf.

General aspects of circulation and tides

Circulation in the Gulf is not yet well described. It is complex and changes with time in a way that is far from being fully understood. Currents in the Gulf have rarely been measured directly. According to Roden (1958), the bulk of water in and near the Gulf is the same as in the equatorial Pacific, modified at the surface by evaporation and by admixture with California Current water. Thorade (1909), using temperature charts constructed from ships' logs, deduced the general circulation in the Gulf. He concluded that the low temperatures along the east coast in winter are the result of upwelling produced by northerly winds. He may have been the first to describe the frontal system near Cape San Lucas, between the cold California Current water and the warm Gulf water.

Using 1947 charts of ship-drifting prepared by the U.S. Hydrographic Office, Roden (1958) concluded that in winter the surface circulation of the Gulf is characterized by southward currents north of Cape Corrientes, and during summer a current flows northward along the coast of Mexico and enters the Gulf at the eastern and central regions of the mouth, with a southward flow near Baja California. This is in agreement with the results obtained by Granados-Gallegos and Schwartzlose (1974), who used drift bottles. These authors concluded that there is a general pattern of southward flow in winter throughout the entire Gulf, northward flow in summer south of Tiburon, San Esteban and San Lorenzo islands, and some northward flow in the northern Gulf, with some eddy circulation. During the spring and fall the flow may be in many directions. Counterclockwise gyres have been detected in the northern Gulf by means of satellite photographs (Vonder Haar and Stone, 1973; Granados-Gallegos and Schwartzlose, 1974; Lepley et al., 1975).

Currents in the Gulf have been estimated, using dynamic computations (Sverdrup, 1941; Roden and Groves, 1959; Griffiths, 1968; Stevenson, 1970; Warsh and Warsh, 1971; Roden, 1972; Rosas-Cota, 1976; Alvarez-Sanchez et al., 1978), but only Stevenson (1970) and Rosas-Cota (1976) have presented results for all seasons of the year. Roden (1964) estimated the surface currents at the central portion of the Gulf, near Guaymas, using a linear and stationary model and considering the effects of geostrophic forces, a component due to the horizontal atmospheric pressure gradient and a component produced by wind stress. For February he obtained southward values of 4, 1 and 5 cm s^{-1} respectively for the three components, with a total speed of 10 cm s^{-1}, and for August northward values of 13, 2 and 6 cm s^{-1}, with a total speed of 21 cm s^{-1}. He also estimated vertical currents at both sides of the Gulf for February and found upwelling velocities of roughly 3.2 m day^{-1} near the east coast. Upwelling occurs on the east coast during winter with northwesterly winds, and on the west coast during summer with southeasterly winds.

Results from dynamic computations are in fair agreement with data from drift bottles. Rosas-Cota (1976) reports geostrophic currents to the south in winter and to the north in summer (Fig. 17.4), with more complex reversing conditions and with gyres present during spring and fall. Maximum computed speeds are about 40 to 50 cm s^{-1}. Alvarez-Sanchez et al. (1978) compared geostrophic currents at the mouth of the Gulf with results from drifting drogues and found an agreement for the upper 100 m of better than 70% at three stations and 85% at two stations. Brown (1965) made a series of six drogue stations in the Gulf, from the mouth near La Paz to the area between San Lorenzo Island and Baja California in November 1963. Drogues were situated at 10, 50, 100, 200, 300 and 1000 m. His results show the great complexity of the Gulf circulation, with currents changing with geographic location and depth. Round (1967) concluded that lateral transport in the Gulf of California is not great, basing his observation on the good agreement between the diatom content of surface sediment samples, their position in the Gulf, and the phytoplankton communities above them.

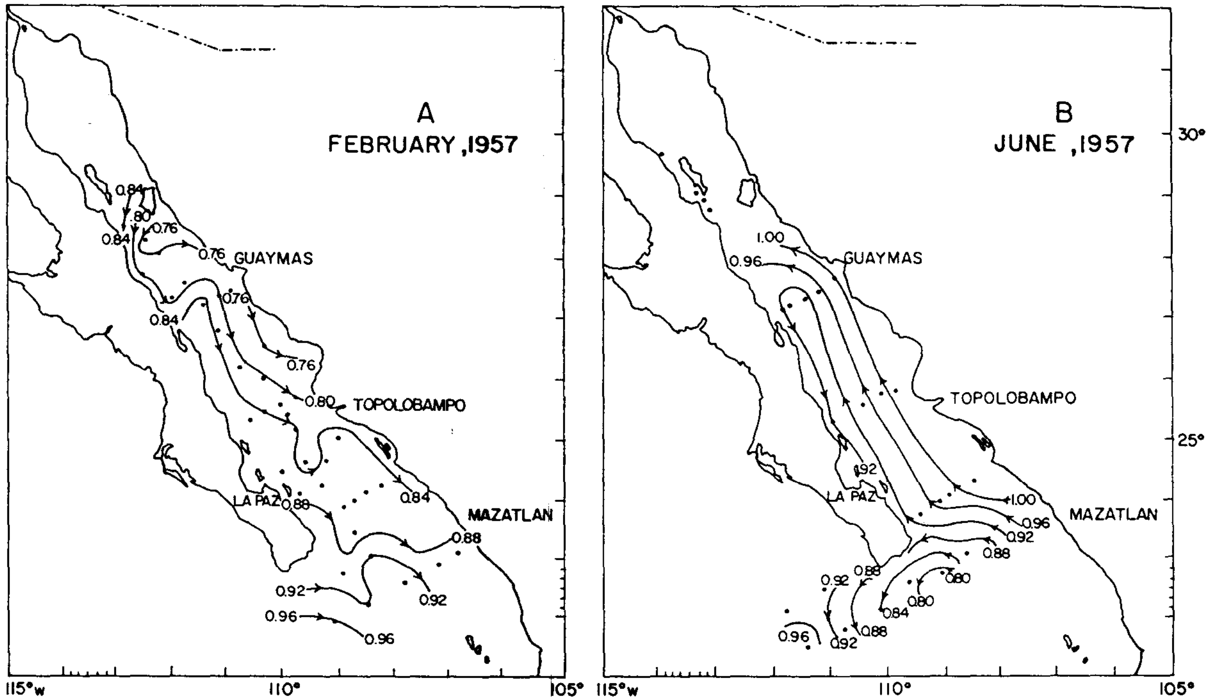


Fig. 17.4. Dynamic topography of the sea surface (meters) referred to the 500-dbar surface (after Rosas-Cota, 1976).

Grijalva-Ortiz (1972) and Stock (1976) computed tidal currents for different points in the Gulf and found that the current ellipses for the principal lunar diurnal component (M_2) have the major axis increasing from the mouth (3 cm s^{-1}) to the head (60 cm s^{-1}) (Fig. 17.5). Stock (1976) compared his computed results for the northern Gulf with current meter data of R.A. Schwartzlose (unpublished results) and found fair agreement for the component along the Gulf axis, but the computed transverse component was significantly larger than the measured data. Tidal currents in the narrows between the islands and the coast and in the passages connecting semi-enclosed lagoons with the Gulf are strong. The speed of these currents is variable and depends upon the stage of the moon and the prevailing winds, but they have been reported up to 3 m s^{-1} (6 knots) (Roden, 1964).

The tides in the Gulf of California are among the most spectacular and dangerous in the world, with reported spring ranges of 10 m at the northern end. The tidal wave is progressive (see Ch. 1, p. 6) so that the time of high or low water is progressively later travelling north up the Gulf, with the time difference between the entrance and the vicinity of the Colorado River being approximately 5.5 h for high water and 6 h for low water. The result is that low water at one end of the Gulf occurs at about the same time as high water at the other end (Roden, 1964). This is shown for the principal lunar semidiurnal component in Fig. 17.6A.

The difference between semidiurnal and diurnal tides is striking. The semidiurnal tide enters the Gulf with a moderate amplitude of 30 cm for the principal lunar component (M_2). The speed of the wave decreases within the Gulf and the amplitude decreases to one third of its initial value near the middle of the Gulf. It then accelerates and its amplitude increases at the head to fifteen times the amplitude in the middle of the Gulf (165 cm for M_2). There it seems to be absorbed by the coastline, suggesting that most of the tidal force is dissipated, an observation that is also indicated by the amphidromic region near the middle of the Gulf (Fig. 17.6B). Hendershott and Speranza (1971) also indicated the existence of a virtual amphidrome for the semidiurnal tides in the Gulf, but their computed results situated it further to the south.

By contrast, the amplitude of the diurnal tide increases very slowly and monotonically to about

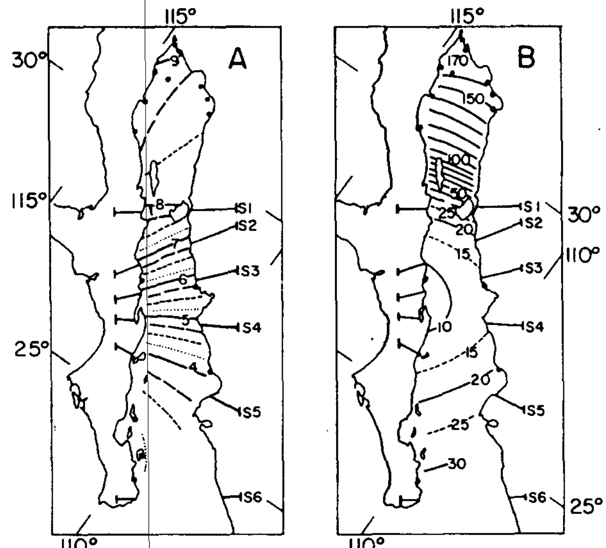


Fig. 17.6. The effect of the principal lunar semidiurnal tidal component (M_2) on A, the phase lag in lunar hours after equilibrium tide at Greenwich; and on B, the tidal amplitude in centimeters (after Filloux, 1973). Cross-sections (*S1–S6*) used in the computations are identified on the right side of each figure.

twice its amplitude at the mouth. Its nearly uniform phase suggests that it is like a standing oscillation, and that most of the energy entering the Gulf does leave again (Filloux, 1973).

Currents and water masses at the entrance

Different authors have defined the entrance to the Gulf of California in different ways. For the purpose of the following discussion, the region of the entrance to the Gulf will be considered roughly as that between a line connecting Cape San Lucas and Cape Corrientes and a line connecting La Paz with Topolobampo (Fig. 17.1). This is a transitional zone that has a very complicated and dynamic oceanographic structure. Sverdrup (1941) studied currents in the outer portions of the Gulf by means of dynamic computations, using data from the February–March 1939 cruise of the *E.W. Scripps*, with discouraging results. With hydrographic lines across the mouth, the dynamic topography of the 500-dbar relative to the 1500-

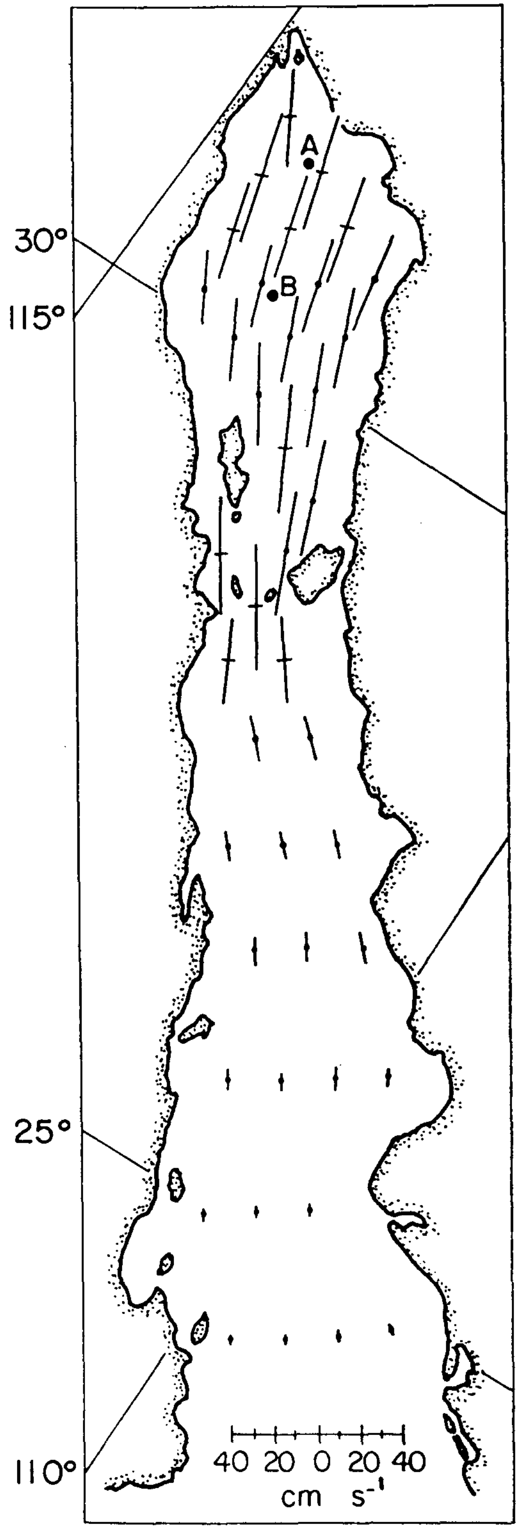


Fig. 17.5. Model current ellipses for the principal lunar semidiurnal tidal component (M_2). *A* and *B* indicate current meter locations (after Stock, 1976).

dbar surface did not indicate to him any regular exchange of water between the Gulf and the adjacent region of the Pacific; instead it showed a sequence of separate highs and lows.

The influence of the Gulf upon the adjacent Pacific Ocean is small. Flux into and out of the Gulf has been estimated as $1.19 \times 10^6\ m^3\ s^{-1}$ and $1.17 \times 10^6\ m^3\ s^{-1}$, respectively, the difference being accounted for by evaporation, roughly estimated as $1.7 \times 10^4\ m^3\ s^{-1}$ (Roden, 1958). Warsh and Warsh (1971), using a variable reference level to obtain agreement between inflow and outflow, estimated minimum transports from 2.57 to $3.65 \times 10^6\ m^3\ s^{-1}$. However, Roden (1972) reported fluxes of the order of 10 to $12 \times 10^6\ m^3\ s^{-1}$, without discussion on the discrepancy with previous results.

At the entrance to the Gulf of California there are three kinds of surface water: cold California Current water of low salinity ($S‰ \leq 34.60$), which flows southward along the west coast of Baja California; warm eastern tropical Pacific water of intermediate salinity ($34.65 \leq S‰ \leq 34.85$), which flows into the area from the southeast; and warm highly saline ($S‰ \geq 34.90$) Gulf of California water (Roden and Groves, 1959; Griffiths, 1968; Stevenson, 1970).

Beneath these three water masses, successively with depth, are: subtropical subsurface water, with a salinity maximum of about 34.80‰, which is obscured in the Gulf; Antarctic intermediate water, characterized by a deep salinity minimum of about 34.50‰ (Griffiths, 1968); and Pacific bottom water below the intermediate water characterized by an increase in salinity to about 34.68‰.

Roden (1972) made very intensive sampling across the mouth of the Gulf, using a salinity, temperature, depth recorder (STD) with 34 stations spaced approximately 9 km apart, to 1500 m depth where possible (Fig. 17.7). He distinguishes four distinct salinity layers. At the surface, values in excess of 34.8‰ result from evaporation. This water lies above the high stability layer and extends almost to the coast of Sinaloa. In the immediate vicinity of this coast, surface salinities were low at the time of Roden's observations because of the rainy season and the discharge from the Presidio River, 20 km south from Mazatlan. The thickness of the high salinity surface layer varies from 150 m near the Baja California coast to 50 m in the eastern half of the section. Below the saline top layer lies the

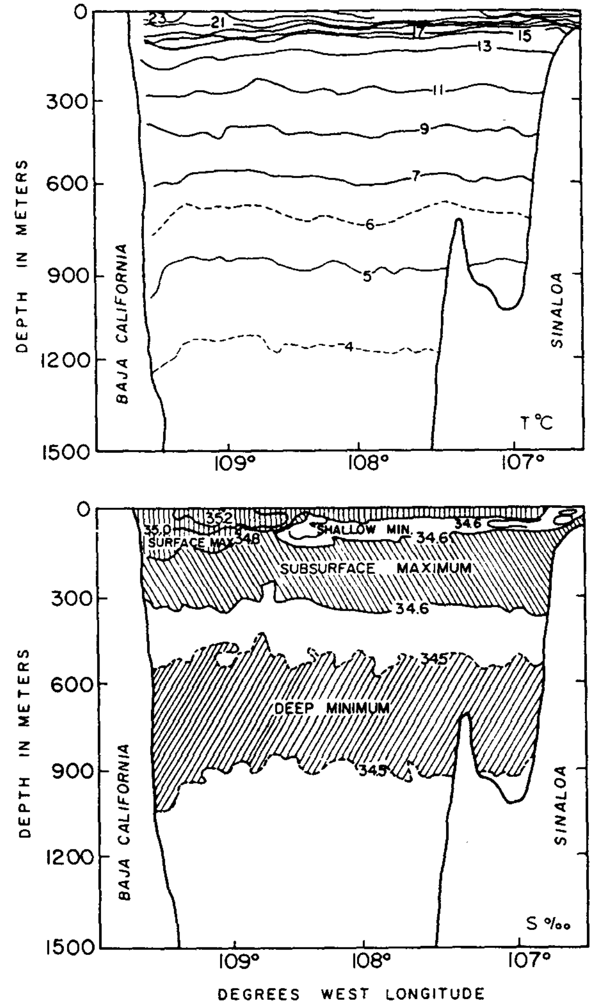


Fig. 17.7. Temperature (°C) and salinity (‰) across the Gulf of California entrance. The section runs along latitude 23°15′N, and was occupied on 5–6 December 1969 (after Roden, 1972).

shallow salinity minimum. It has a typical thickness of 50 m and occurs between 75 and 125 m. The lowest salinities observed within this layer increase from 33.9‰ in the open ocean to 34.3‰ at the Gulf entrance to 34.7‰ halfway up the Gulf (Roden, 1964). Beneath the shallow salinity minimum lies the subsurface salinity maximum. It occupies the depth range between 125 and 400 m and is characterized by salinities between 34.6 and 34.8‰. The deep salinity minimum occupies the depth range between 600 and 900 m (Fig. 17.7). The temperature does not show any special structure; it decreases monotonically with depth from about 25°C at the surface to about 4°C at 1200 m.

The formation of fronts at the entrance to the Gulf is a feature that has attracted the attention of those interested in commercial fisheries, such as that for tuna. Griffiths (1968) notes that the most important oceanographic feature of the entrance to the Gulf is a strong front between the California Current and Gulf surface waters. At Cape San Lucas this front is roughly straight, but to the south and west it becomes more sinuous and much weaker and is formed more and more by California Current and subtropical surface waters (Fig. 17.8). Griffiths (1968) used spring 1960 data for his study of this frontal system. According to him, at Cape San Lucas the stronger flow of the California Current water seemed to hold back the Gulf outflow at the surface, and to the south of the Cape it penetrated Gulf surface water at depths between 50 and 100 m, spreading horizontally or affecting in some way the entire Gulf entrance, often in a complicated manner.

Hydrographic conditions inside the Gulf of California

Sverdrup (1941) was the first to present detailed temperature, salinity and oxygen sections across the Gulf. He found that south from Angel de la Guarda and Tiburon Islands temperature decreases regularly with depth, with less than 2°C below 2600 m; but at Ballenas Channel, between Angel de la Guarda and Baja California, and in the northern Gulf, the vertical distribution of temperature is entirely different, with values of about 11°C even in

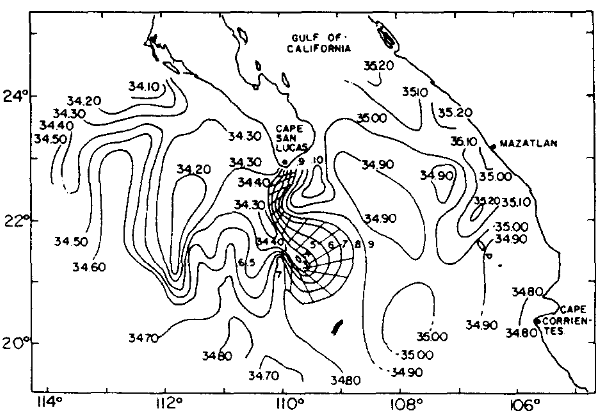


Fig. 17.8. Horizontal salinity (‰) distribution at 10 m, for April–May 1960 (after Griffiths, 1968). Cross-hatched area indicates the front.

the deepest parts (Fig. 17.9B). Temperature and salinity in different sections indicated upwelling at the eastern ends. A salinity minimum is present at depths between 500 and 1100 m, south of Angel de la Guarda and Tiburon, corresponding to Antarctic intermediate water (Fig. 17.9C). The highest surface salinity, 35.5‰, was found by Sverdrup (1941) in the central part of the northern Gulf, but about 70 km from the Colorado River mouth the salinity was nearly as high, 35.12‰. Thus, a direct effect of the Colorado River fresh water was not evident in March–April 1939, due to excessive evaporation even in winter.

Compared to temperatures for similar latitudes in the neighboring Pacific, surface temperatures in the Gulf are warmer from April to September and about equal during the remaining months of the year. The annual range is large and increases from about 9°C near Cape Corrientes to roughly 22°C near the Colorado River mouth. The lowest surface temperatures are persistently found in the vicinity of Angel de la Guarda, where tidal mixing is strong. During October to June, temperatures at the mouth are higher than at the head of the Gulf.

There is no clearcut sequence of change from the winter conditions with warmer water on the west side to summer conditions with warmer water on the east side of the Gulf. December through May, isotherms run mostly east to west south of 28°N, but north of Angel de la Guarda the trend changes and becomes parallel to the coast. Beginning in June and extending through September, the isotherms run parallel to the Gulf over most of its length, with warmer water on the Sonora and Sinaloa coast and upwelling along the Baja California coast. October is a month of change, and the opposite situation develops in the central and southern area, with higher temperatures on the Baja California coast and upwelling on the east coast. Charts show that upwelling is better developed and extends over a greater distance (23–28 N) along the east coast than off the Baja California coast, where it extends from Punta Arena to Concepción Bay (Fig. 17.10) (Roden, 1964; Robinson, 1973). Surface salinities in the northern two-thirds of the Gulf range between 35.0‰ and 35.8‰ and are 1 to 2‰ higher than those at comparable latitudes outside the Gulf. Salinities higher than 36‰ are encountered locally in semi-enclosed and shallow bays in the northern region and along the Baja California coast (Roden, 1964).

In the central Gulf of California, roughly considered as the region between a line connecting La Paz with Topolobampo and a line south of Tiburon Island, depths are great and the water is open to the Pacific Ocean to the southeast. Here the thermocline is well developed between April and October; it reaches its maximum strength in August when the temperature difference between the surface and 150 m is about 16°C. In August the salinity distribution in the upper layers is characterized by a minimum of about 34.8‰ between 25 m and 75 m in the eastern half of the Gulf. Since the only source of low-salinity water is from the southeast, the salinity minimum probably indicates the presence of a current flowing to the northwest between these depths (Roden, 1964). This minimum is related to the shallow salinity minimum found by Roden (1964, 1972) at the mouth of the Gulf. Below the thermocline the water is essentially the same as in the equatorial Pacific. This water is characterized by a salinity minimum of approximately 34.5‰ (Antarctic intermediate water) and a temperature of about 5°C (Sverdrup, 1941) (Fig. 17.9).

At depths between 2500 and 3000 m there is a temperature minimum of slightly less than 1.85°C. From 3000 m to the bottom, temperature increases again at a rate of approximately 0.1°C per 1000 m, due to the adiabatic pressure effect. The salinity distribution between 1000 m and the bottom is surprisingly complex. In general, there is a tendency for salinity to increase from 1000 m towards the bottom (Roden, 1964).

The Ballenas channel is completely isolated from the central part of the Gulf by a submarine ridge connecting Angel de la Guarda Island with San Gabriel Point. The sill depth of this ridge is about 450 m (Rusnak et al., 1964). The topography of the channel (also called Sal Si Puedes basin) is very irregular, with maximum depths exceeding 1500 m. The water in the basin comes from mixing by strong tidal currents between the surface and sill depths.

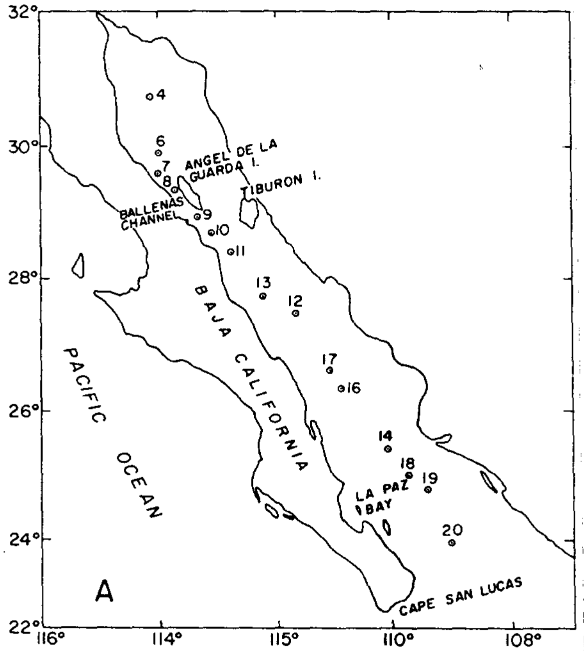
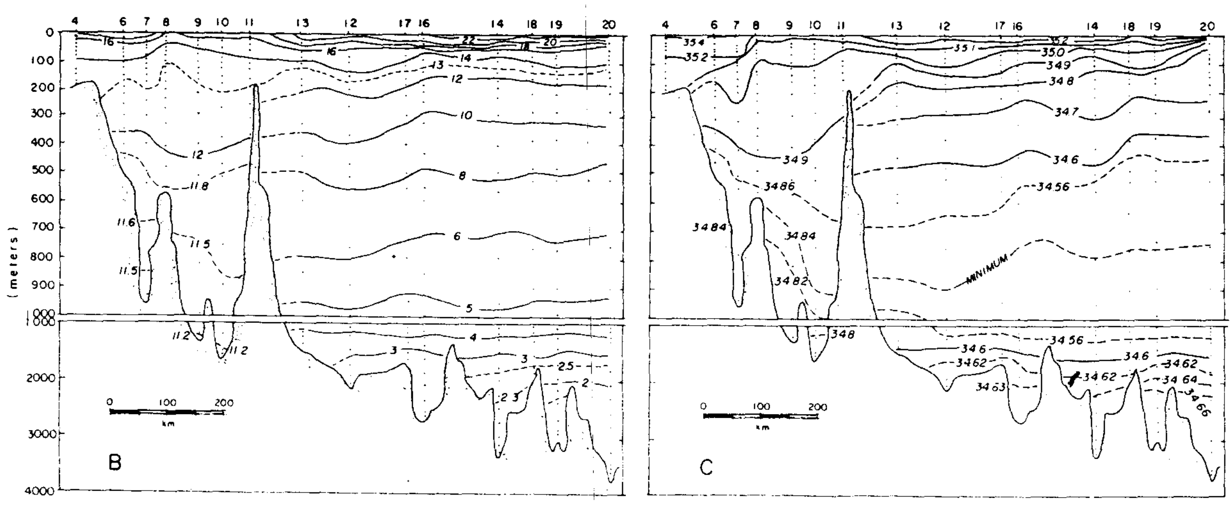


Fig. 17.9. A. Station locations for the April–May 1974 cruise of the *Alexander Agassiz*. B. Vertical temperature (°C) distribution. C. Vertical salinity (‰) distribution (after Alvarez-Borrego et al., 1978).



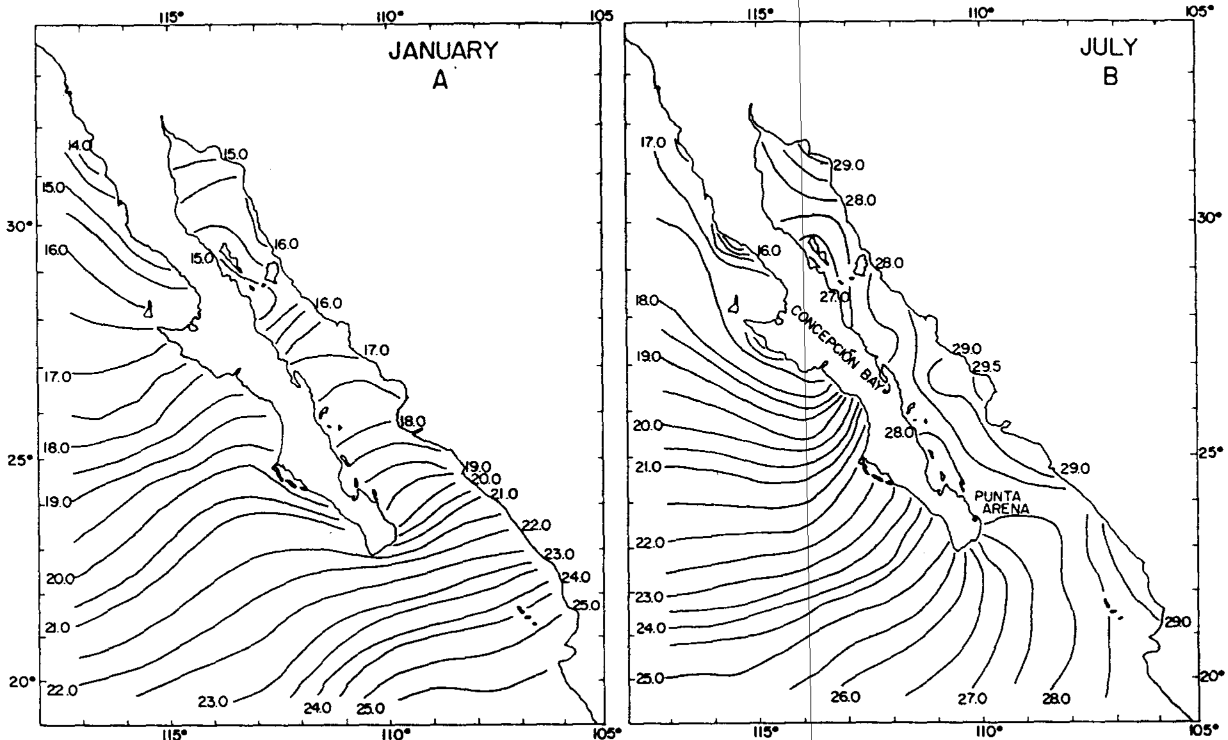


Fig. 17.10. A, January and B, July mean sea surface temperatures (°C) [constructed from graphs that Robinson (1973) presented in °F].

The outstanding hydrographic features of the channel are high temperatures and salinities at great depths. Compared to conditions elsewhere in the Gulf, there is a difference in temperature at 1000 m of 6°C, and of 0.4‰ salinity. The deep salinity minimum, characteristic of the southern half of the Gulf, does not occur here (Fig. 17.9). Above 450 m exchange of water between the northern and central parts of the Gulf is unrestricted. Alvarez-Borrego et al. (1978) compared salinity and temperature data from April and October, 1974. Near the bottom of Ballenas channel ($\sim$1500 m) they found differences of 0.4°C and 0.04‰, with higher values in April. This indicates a greater proportion of sill depth water at the bottom of the basin in October than in April. During winter months stability in the upper layers is weak and limited convection of cold and high salinity water from the bays is likely. During summer the thermocline in Ballenas channel is well developed, as elsewhere in the Gulf (Roden, 1964).

The graphs constructed by Sverdrup (1941) and Granados-Gallegos (1974) indicate that hydrographic conditions at Tiburon basin, between Angel de la Guarda and Tiburon Islands, are very similar to those at Ballenas channel, with very much the same salinity, temperature and oxygen values for the same depths. However, maximum bottom depths for Tiburon basin are only about 550 m, and it has more open communication with the southern Gulf than Ballenas channel. In general tidal mixing plays an important role in the vertical hydrographic structure of the northern Gulf.

In the shallow area north of Angel de la Guarda Island the water is almost isothermal during winter. During late summer the thermocline is strong and the temperature difference between the surface and 150 m amounts to almost 14°C. Salinity in general decreases with depth. In the central northern Gulf it is about 35.2‰ at 100–150 m depth (Roden, 1964). But, with winter conditions, the salinity vertical distribution may show a minimum at about 100 m. Possibly this is due to the influx of colder and more saline water from the head of the Gulf, which moves southward at the bottom (Alvarez-Borrego et al., 1978). The most drastic temperature and salinity changes occur north of 31°N. At the

Colorado River mouth there is no longer a significant fresh-water input. North from Angel de la Guarda and Tiburon Islands, this was the only river with fresh water input throughout the year. The main cause of the change in flow has been the construction of dams on the river, particularly the Hoover dam, but dramatic decrease was introduced by the water storage project begun in Lake Mead in 1934 (Schreiber, 1969). Surface salinities at the Colorado River mouth and adjacent region are about 36.5‰ in winter, and more than 38.5‰ in summer, maintaining in general the same gradient with values increasing northwestward. This clearly indicates that evaporation exceeds precipitation and river input during most of the year. Only during few occasions, caused by local rain and lasting for only a few days, do salinities decrease to about 35‰ here. Surface temperatures range from about 10°C in winter, to about 32°C in summer. The surface temperature gradient reverses at the beginning of spring and fall due to the annual cycle of atmospheric temperature and the shallow depths here, less than 20 m (Alvarez-Borrego and Galindo-Bect, 1974; Alvarez-Borrego et al., 1975).

Roden (1964) explored the possibility that convective overturn was produced by winter cooling in the northern part of the Gulf. For the process to take place, surface density must exceed the density of the subsurface layers. Because density increases with decreasing temperature and increasing salinity, and because the lowest temperatures and highest salinities occur near the coast, the most likely places for convective overturn are the coastal regions. With the data he had, Roden (1964) indicated that the mean minimum temperature in coastal regions is about 13°C, whereas the salinities are generally in excess of 35.5‰. For these values the density at the surface is 1.02680 g cm^{-3}. The same density (*in situ*) is found at a depth of about 100 m, where the temperature is 14°C and the salinity is 35.2‰. Roden (1964) concluded that convective overturn due to winter cooling can therefore be expected to reach roughly 100 m near the coast. Alvarez-Borrego et al. (1975), reported surface temperature minima for December through February at the northernmost part of the Gulf in the range of 8.25 to 12.21°C, producing water heavier than 1.02680. This water could sink deeper than 100 m. However, this region is for the most part shallower than 100 m, so horizontal advection would have to bring this water southward, along the bottom, to move to deeper parts. In the more offshore areas of the Gulf, surface temperatures do not drop much below 15°C, whereas the salinities average about 35.4‰. With these conditions, convection is insignificant (Roden, 1964).

Oxygen distribution

Low oxygen concentrations at intermediate depths are very characteristic of the Gulf waters (Sverdrup, 1941; Roden, 1964) (Fig. 17.11). Sections across the Gulf mouth show that oxygen concentrations are higher than 1 ml l^{-1} in the upper 100 m, and that at a depth of less than 150 m they decrease to less than 0.5 ml l^{-1}. This is the situation for most of the Gulf, with exception of the northern area. At intermediate depths (500–1100 m) the concentration of oxygen occasionally is undetectable by the Winkler method. This plays an important role in the ecology and geology of the Gulf of California, as it relates to organisms and sedimentation patterns. The oxygen minimum at the entrance to the Gulf is more pronounced than in the interior, and covers a larger depth interval. Oxygen increases from a minimum to about 2.4 ml l^{-1} at 3500 m. However, in the central part of the Gulf oxygen concentrations near the bottom are much lower than at comparable depths (2000 m) outside (Roden, 1964).

Another outstanding hydrographic feature of

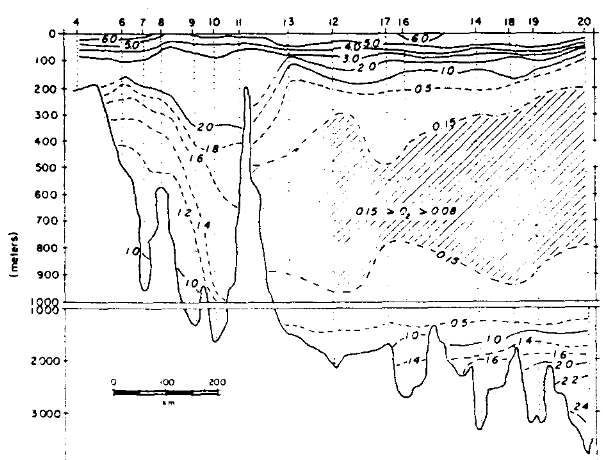


Fig. 17.11. Vertical dissolved oxygen (ml l^{-1}) distribution. For station locations see Fig. 17.9A (after Alvarez-Borrego et al., 1978).

Ballenas channel is high oxygen concentration at great depths. There is no oxygen minimum there (Sverdrup, 1941). Compared to conditions elsewhere in the Gulf, the difference in dissolved oxygen at 1000 m is 1 ml l^{-1} (Roden, 1964), high values being due to tidal mixing in the channel. Oxygen concentration in Ballenas channel was higher in April than in October of 1974, with a difference of 0.45 ml l^{-1} at 1200 m, for the same reason that salinity and temperature were higher in April (Alvarez-Borrego et al., 1978).

North from Angel de la Guarda Island there is no oxygen minimum. Oxygen decreases from about saturation values at the surface (5 to 6 ml l^{-1}) to about 2 ml l^{-1} at 100–150 m depth, and about 1 ml l^{-1} at 300–500 m depth (Sverdrup, 1941; Roden, 1964; Rosenberg, 1969; Granados-Gallegos, 1974; and Villaseñor-Casales, 1974).

Carbon dioxide system

The pH data are very consistent with oxygen data. The *in situ* pH vertical distribution has a minimum of about 7.65 in the central and southern Gulf between 500 and 1000 m. In this region of the Gulf, pH values decrease in spring from about 8.25 at the surface to about 7.80 at 100 m (Fig. 17.12). In the northern Gulf and Ballenas channel there is no pH minimum. In Ballenas channel surface pH readings are the lowest of the whole Gulf, with values of about 8.10, decreasing to 7.95 at 100 m, and decreasing monotonically to 7.70 at 1500 m.

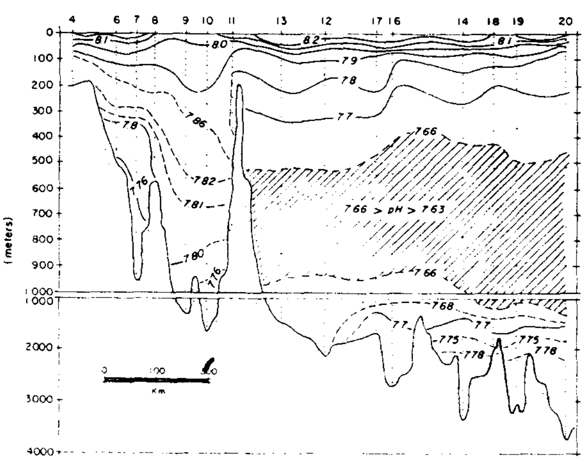


Fig. 17.12. Vertical *in situ* pH distribution. For station locations see Fig. 17.9A (after Gaxiola-Castro et al., 1978).

Surface total inorganic carbon (T_{CO_2}) is maximum in Ballenas channel, with values of about 2.13 mmol kg^{-1} compared to 2.07 mmol kg^{-1} in the southern region of the Gulf and 2.04 mmol kg^{-1} in the northern region. Again, T_{CO_2} has a maximum at intermediate depths in the central and southern regions, which is not present in the northern region and Ballenas channel. Due to the rapid decrease of pH near the surface in the central and southern regions of the Gulf, the percent saturation of calcium carbonate with respect to calcite and aragonite decreases rapidly to undersaturation at about 300 m and 70 m, respectively. Thus, only the surface layer is oversaturated with these minerals south of 28°N. At Ballenas channel the higher temperature and pH at depth causes oversaturation of calcite and aragonite down to 900 m and 130 m, respectively. In the shallow northern Gulf most of the water is oversaturated with these minerals, with the exception of near-bottom waters in Wagner basin, which are not saturated with aragonite (Gaxiola-Castro et al., 1978).

THE GULF AS AN ENVIRONMENT FOR ORGANISMS

Nutrients, organic primary productivity and phytoplankton in the Gulf of California

Although the Gulf of California has been described as an area of great fertility since the time of early explorers, few details are known about the variability in space and time of the concentration of nutrients there. Zeitzschel (1969) reviewed the scarce available data concerning nutrients, and drew the following conclusions. During summer and winter, the surface phosphate concentration is >0.4 μmol l^{-1} in the whole Gulf, even in the southern area. In the northern area surface phosphate concentrations are between 0.9 and 1.9 μmol l^{-1}. The data suggest that phosphate concentrations in the Gulf are far greater than the experimentally established minimum limit of 0.22 μmol l^{-1} for growth of tropical oceanic diatoms (Thomas and Dodson, 1968). Warsh et al. (1973) presented the vertical distribution of phosphate and silicate across the mouth of the Gulf for July 1967. Their graphs show surface phosphate values of about 0.2 μmol l^{-1} increasing rapidly with depth to about 2.3 μmol l^{-1} at 100 m, and to a maximum of about 3.4 μmol l^{-1} at 800 m.

Surface silicate values were about 2 μmol l^{-1}, increasing monotonically with depth to about 100 μmol l^{-1} at 800 to 1000 m. In the upper 50 m, both phosphate and silicate were higher near the west coast, probably due to upwelling there during summer.

In April–May and October, 1974, the R.V. *Alexander Agassiz* of Scripps Institution of Oceanography collected phosphate, nitrate, nitrite and silicate data. Surface concentrations are summarized in Table 17.1. In general, there is a tendency for the surface nutrient concentrations to increase from the mouth to the region of Angel de la Guarda Island, and then decrease again to the central northern Gulf. Highest values were observed at Ballenas channel because of the effect of strong tidal mixing. Values in April and May in general were greater than those of October. Hydrographic stations were occupied at a section along the middle of the Gulf during the April–May cruise; therefore the data are not useful for studying the effect of upwelling. Data from the October cruise do not show gradients across the Gulf that could indicate the effect of upwelling, possibly because the upwelling season had not yet started (Alvarez-Borrego et al., 1978).

During these cruises a subsurface nitrite maximum was detected at 30 to 80 m in most of the locations, with values from 0.2 to 0.6 μmol l^{-1}. In the Ballenas channel there were values greater than 1.0 μmol l^{-1} at this maximum. A second nitrite maximum between 150 and 400 m was observed at the entrance to the Gulf, with concentrations up to 0.7 μmol l^{-1} in April–May, and up to 1.9 μmol l^{-1} in October. With the exception of these maxima, nitrite concentrations were lower than 0.1 μmol l^{-1} at depths greater than 100 m, with values below the detectable level in many cases. The shallow subsurface nitrite maximum is a common characteristic of the oceans and it is caused by bacterial nitrification (Wada and Hattori, 1971), by phytoplankton excretion (Vaccaro, 1965), or both. The deeper nitrite maximum is characteristic of oxygen-deficient zones and it is caused by denitrification (Cline and Richards, 1972). Marine denitrification occurs with oxygen concentrations below 0.1 ml l^{-1} (Goering, 1968). It is not understood why the deeper nitrite maximum was not detected in the interior of the Gulf where the oxygen is almost totally depleted at 400 to 500 m (Alvarez-Borrego et al., 1978).

TABLE 17.1

Surface concentrations of nutrients (μmol l^{-1}) for the different regions of the Gulf of California

Southern Gulf	Central Gulf	Ballenas Channel	Northern Gulf
Phosphate			
0.6	1.0	1.7—2.0	0.8–1.0
0.4	0.5	0.9–1.5	0.7–1.0
Nitrate			
0.6	1.9	13.0	0.2–0.4
0.1	0.3	1.0–7.5	0.0–0.2
Nitrite			
0.0	0.09	0.31	0.02–0.20
0.01	0.01	0.13–0.45	0.00–0.09
Silicate			
1.0	0.0–5.0	29.0	11.0–18.0
2.4	2.9	6.6–19.6	6.1–10.2

Upper numbers are from the April–May 1974 cruise of the *Alexander Agassiz*; lower numbers are from the October cruise (after Alvarez-Borrego et al., 1978)

In the shallow central northern Gulf, very weak phosphate, nitrate and silicate maxima were found at 80 to 125 m, in the April–May cruise, with 2.3 to 2.5 μmol l^{-1} for phosphate, 21 to 23 μmol l^{-1} for nitrate, and 53 to 67 μmol l^{-1} for silicate. These maxima were not detected in October. In April–May these maxima were found with a salinity minimum. They are consistent with the explanation given above that these extremes may be caused by colder, more saline and nutrient-poor water coming from the head of the Gulf and moving southward at the bottom (Alvarez-Borrego et al., 1978). In Ballenas channel, in accordance with the oxygen vertical distribution discussed above, these three nutrients increase monotonically with depth to about 3.0 μmol l^{-1}, 30 μmol l^{-1} and 70 μmol l^{-1}, respectively, at 1500 m. At 1000 m, nutrient concentrations are lower in Ballenas channel than in the central and southern Gulf, with differences of 0.6 μmol l^{-1} for phosphate, 12 μmol l^{-1} for nitrate and 60 μmol l^{-1} for silicate. South from Angel de la Guarda and Tiburon Islands the vertical distribution of these nutrients is very much like that of the open ocean. Silicate increases monotonically with depth to about 170 μmol l^{-1} at 3000 m. Phosphate has a maximum of about 3.5 μmol l^{-1} at 800 to 1200 m, and then decreases to about 2.8 μmol l^{-1} at 3000 m, and nitrate has a very weak maximum of 43 to 44 μmol l^{-1} at 1000 to 1300 m and decreases to about 39 μmol l^{-1} at 2500 to 3000 m. There is a linear relationship between nitrate and phosphate for the whole Gulf of California with the ratio of the change in nitrate to that in phosphate 16.2 ± 0.7 at the 95% confidence level (Fig. 17.13), which is consistent with the ratio proposed by Redfield et al. (1963) (Alvarez-Borrego et al., 1978).

In the Gulf of California great amounts of silicate are lost from the water column to the sediments through settling and deposition of exoskeletons of microorganisms, mainly diatoms and radiolarians. During the 1939 and 1940 cruises of the *E.W. Scripps* to the Gulf, bottom samples were taken, and revealed that diatomaceous sediments are being laid down over large areas (Sverdrup and Staff, 1940). Gilbert and Allen (1943) studied the vertical distribution of diatoms in the water column, from the surface to 1000 m, in the Gulf. They found that below 60 m the number of empty

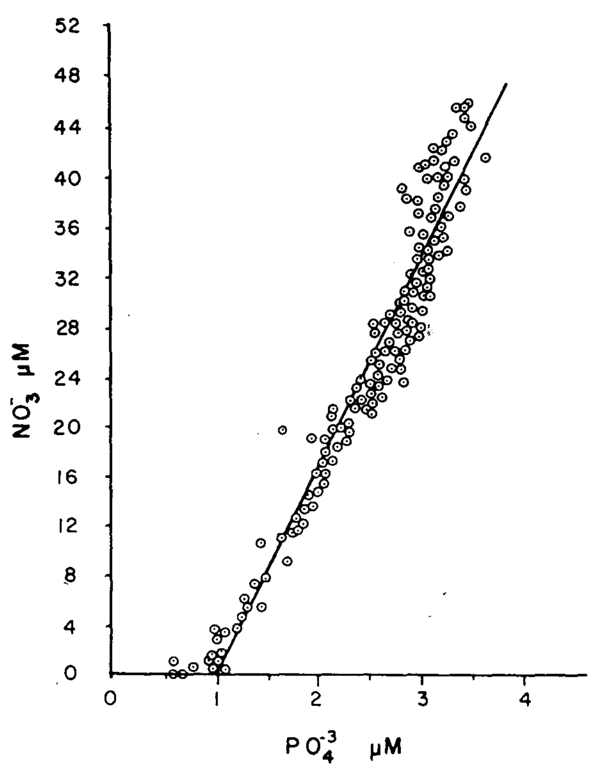


Fig. 17.13. Nitrate versus phosphate diagram, constructed with data from all stations of Fig. 17.9A. The least-squares straight line is shown. The slope interval is 16.2 ± 0.7 at the 95% confidence level (after Alvarez-Borrego et al., 1978).

frustules greatly exceeded that of living cells, usually with a sharp decrease in the number of total frustules between 60 and 300 m, followed by a more gradual decrease below 300 m, so that at 750 m only a few hundred, or at the most one or two thousand, cells per liter were found. The exception was at about 28°20′N, where 15 000 frustules were found at 750 m, whereas populations of only a few thousand cells per liter were found in the upper layers. The specific composition changed considerably with depth. The heavily silicified forms, which were rarely present in large quantities in the surface layers, increased relative to depth and dominated the residue of the diatom population.

Laminated sediments are formed at certain sites where the deposition of silicate has been studied (Calvert, 1964, 1966a, b). Laminated, diatomaceous sediments of the Gulf of California consist of regularly alternating light-colored (diatom-rich) and dark-colored (clay-rich) laminae, approximately 2 mm thick. The mean contents of opal and quartz in the laminae, determined by X-ray diffraction methods, are: light-colored laminae, 52.4% opal and 7.0% quartz; dark-colored laminae, 26.5% opal and 10.0% quartz. Opal is produced biogenetically and quartz is of terrigenous origin. Calvert (1966b) could not distinguish the laminae on the basis of diatom assemblages, but could identify them on the basis of the total content of biogenous and terrigenous materials. Rates of deposition, determined by radiocarbon dating of organic and carbonate carbon in selected core sections, demonstrate that one light-colored lamina and one dark-colored lamina are deposited in a year, and a couplet of laminae constitute a varve (Calvert, 1966b). These varves in the central Gulf of California are confined to the slopes of the basins. They occur where the basin floor intersects the oxygen minimum in the water column. Burrowing organisms do not occur in this poorly oxygenated zone, and the laminations remain undisturbed. Such organisms are present in deeper parts of the basin where oxygen concentrations are higher and their digging activities homogenize the sediments.

In contrast to previously described occurrences of laminated sediments, those of the Gulf of California occur on the slopes of a basin which has free communication with the open ocean (Calvert, 1964). Sediments containing more than 10% by weight opal are confined to the central part of the

Gulf; in the Guaymas basin values exceed 50% by weight. Diatoms constitute the major source of the opal in the sediments. Radiolarians contribute less than 10% by weight of opal, and sponge spicules are an insignificant source. Phytoplankton production is greatest in the central Gulf, the area of richest diatomaceous sediments. The diatom frustules settle to the Gulf floor rather rapidly and are not dispersed uniformly over the entire Gulf (Calvert, 1966a). According to Calvert (1966b), phytoplankton production in the central Gulf is reasonably constant throughout the year. Since river discharge fluctuates greatly during the year as a result of torrential summer rains in coastal Sonora and Sinaloa, the terrigenous sediment supply to the central Gulf is highly variable.

Calculations of accumulation rates of opal and quartz in the laminae using data on lamina compositions and thicknesses demonstrate that the varves originate by a more or less constant rate of accumulation of biogenous material and an annually increased rate of accumulation of terrigenous material as a result of the summer floods. In the central Gulf sediments containing more than 10% opal by weight extend over an area of 3×10^4 km^2, and within this area the mean opal concentration is 25% by weight. The mean sedimentation rate is 2 mm yr^{-1}, and the mean sediment bulk density is 1.0 g cm^{-3}. Thus, the accumulation of biogenous silica in the sediments of the central Gulf proceeds at a rate of approximately 1.5×10^{13} g yr^{-1}. The rivers draining into the Gulf supply approximately 5.5×10^{11} g of dissolved silica per annum; about 4% of the amount deposited (Calvert, 1966a). This river input is now decreasing as more dams are built upstream to divert the water for agricultural uses. Calvert (1966a) indicates that the water exchange between the Gulf and the Pacific Ocean supplies approximately 10^{14} g of dissolved silica per annum to the Gulf. Sufficient silica is available in sea water to account for the accumulation of such richly diatomaceous sediments, given a mechanism — upwelling — which continuously supplies dissolved nutrients to the euphotic zone. Recourse to volcanic sources of silica is then not necessary (Calvert, 1966a).

The Gulf of California represents a subtropical area with exceptionally high rates of primary productivity (Fig. 17.14). From very limited data it can be concluded that rates of primary productivity in

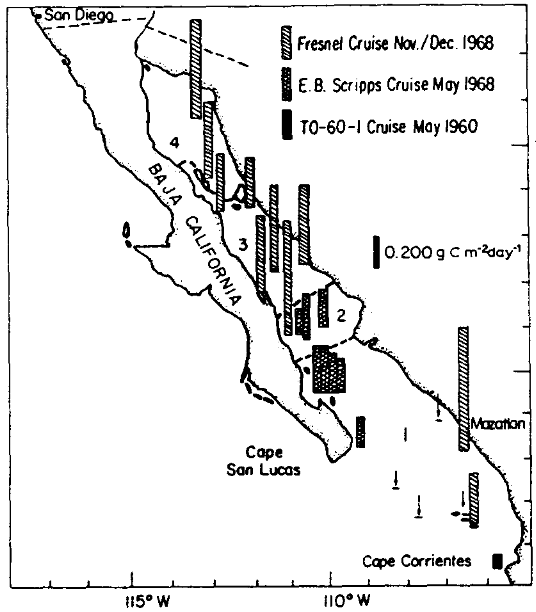


Fig. 17.14. Primary productivity in the Gulf of California integrated over the euphotic zone (after Zeitzschel, 1969).

the Gulf of California are comparable to those of the Bay of Bengal, the upwelling areas off the west coast of Baja California, or North Africa. They are about two to three times greater than that in the open Atlantic or the open Pacific at similar latitudes (Zeitzschel, 1969). Phytoplankton patchiness, and great variability with time, were recognized as important problems in the early studies of organic productivity of the Gulf (Allen, 1938). Differences between localities are striking. In general, diatoms are well represented in the Gulf and dinoflagellates are less abundant (Allen, 1934, 1938). The dinoflagellates are greatly subordinate to the diatoms in spring and even less abundant in autumn. Three dinoflagellate species, *Dinophysis caudata*, *Peridinium oceanicum* and *Ceratium furca* are the most frequently recorded and are widespread, tolerant, oceanic forms (Round, 1967). Small organic particles, 2 to 6 μm in diameter, are abundant throughout the Gulf of California; on an average, 72% of total phytoplankton by number are naked flagellates smaller than 5 μm in diameter, but they are only 10% of the phytoplankton carbon. On the other hand, diatoms make up only about 10% by number on an average, but contribute roughly 51% of the phytoplankton carbon because of their larger size (Zeitzschel, 1970). Gilbert and Allen (1943) give a list of early phytoplankton samplings in the Gulf, and mention that in 1939 the *E.W. Scripps* cruise was the first to sample the Gulf systematically to a depth of 60 m, at intervals of 10 m. They emphasized the need of both continuity of observations and a knowledge of water movements. At any one spot both the biomass and the specific composition may change completely within few hours. Near Guaymas, at noon on December 27, 1940, at an anchor station, there was a mean population of 2000 diatoms per liter with *Pseudoeunotia doliolus* and *Guinardia flaccida* making up almost half of this number; at 07:30 the next morning a second series of samples revealed an increase in numbers of diatoms to 161 400 cells per liter with *Bacteriastrum* sp. and *Chaetoceros* sp., constituting over 90% of this population.

Based on the distribution of phytoplankton, the Gulf has been divided into three geographical regions: the region south of 25°N is the southern region; the region between 25°N and 27°N, the middle section; and the region north of 27°N the northern section (Allen, 1937; Cupp and Allen, 1938; Gilbert and Allen, 1943). Round (1967) distinguished two different zones in the region north of 27°N, one covering the shallow Gulf north of Tiburon, Ballenas channel and Dolphin basin, and the other covering the southern part. The southern region is characterized by the lowest phytoplankton populations of the entire Gulf (Gilbert and Allen, 1943). It supports a large number of *Nitzschia seriata*, *Rhizosolenia alata*, *Chaetoceros atlanticus* and *C. peruvianus*, and many other diatoms. These are predominantly of oceanic character, and are either completely absent or sparse in the other regions of the Gulf. Gilmartin and Revelante (1978) found that these characteristic tropical communities extended into coastal waters immediately adjacent to the southeastern lagoons, indicating that the impact of lagoons on the Gulf in this region is low. These southeastern lagoons had less diversity, a higher degree of dominance, and few elements in common with adjacent waters, reflecting the effect of low flushing rates. Mean numbers of cells per liter for the 60-m water column of the Gulf were 1000 to 10 000 (Gilbert and Allen, 1943; Round, 1967). At the entrance to the Gulf, from April to August 1967, the median concentration of surface chlorophyll *a* increased from 0.65 to 0.97 mg m^{-3}, while the median productivity measured by the ^{14}C method, increased from 5.6 mg C m^{-3} day^{-1} in April to 17.8 mg C m^{-3} day^{-1} in June before returning to 2.6 mg C m^{-3} day^{-1} in August. In this region productivity was highest near Las Tres Marias Islands and second highest near Cape San Lucas, both locations of local upwelling. Chlorophyll *a* and phaeophytin *a* data indicated that the standing crop of phytoplankton was subjected to progressively heavier grazing pressure in the spring and summer by zooplankton (Stevenson, 1970). The average integrated primary productivity value for this region is about 0.27 g C m^{-2} day^{-1} (Zeitzschel, 1969).

The region between 25°N and 27°N has been found to have diatom populations larger than those of the southern section but still relatively poor compared to the more northern regions of the Gulf. In March 1959, Round (1967) found a poor phytoplankton standing crop in the region of Carmen basin, but Gilbert and Allen (1943) reported populations of over 100 000 cells per liter at several stations near Carmen Island taken in 1921, and over 500 000 cells per liter off Topolobampo Bay in 1937. Gilmartin and Revelante (1978) found that the central eastern lagoons had many floristic elements in common with adjacent waters, great diversity and a low degree of dominance, reflecting high flushing indices, which not only tend to export phytoplankton populations but to modify the inshore environment, permitting their survival and growth. The average integrated primary productivity value for this region of the Gulf is about 0.38 g C m^{-2} day^{-1} (Zeitzschel, 1969).

The region between 27°N and 29°N includes the Guaymas area in which samples of over three million cells per liter had been taken in 1937 and 1939. These samples have, as the main constituents, *Asterionella japonica*, *Chaetoceros compressus*, *C. debilis*, *C. radicans* and *Skeletonema costatum*. In 1939 samples from this area were almost a pure culture of *Asterionella japonica*; out of four million diatoms per liter, 3 600 000 were *A. japonica*. In 1940 the dominant species were neritic *Chaetoceros* and *Bacteriastrum* species. No *Asterionella japonica* were found (Gilbert and Allen, 1943). Northwest of Angel de la Guarda Island a tremendous growth of *Coscinodiscus lineatus* and *Asteromphalus heptactis* has been found (Round, 1967). The average integrated productivity value for December is about

0.53 g C m^{-2} day^{-1} in the region north of 27°N up to Ballenas channel (Zeitzschel, 1969).

Gilmartin and Revelante (1978) made a comparative study of the lagoons and the central and southern Gulf during summer of 1972, before the full development of the rainy season. They found a dramatic inshore increase in cell densities, chlorophyll *a* standing crops and rates of primary production. Offshore Gulf stations had mean assimilation numbers of 2.7 mg C (mg Chl)$^{-1}$ h^{-1}, inshore eastern stations a mean of 6.7, and the means of eastern lagoons were between 7.4 and 10.7.

In the northern shallow Gulf Round (1967) found that standing crops of diatoms were very low, in March 1959, with few species from the south extending into this region. In March 1939 Gilbert and Allen (1943) found large numbers of diatoms, with some sampling stations having over 100 000 cells per liter. These authors found enormous numbers of the dinoflagellate *Gonyaulax catenella* or some species closely resembling it. The average integrated primary productivity for this region has been reported as 0.68 g C m^{-2} day^{-1} for December only (Zeitzschel, 1969). During March of 1973 the R.V. *Alexander Agassiz* of Scripps Institution of Oceanography occupied 92 hydrographic stations where chlorophyll *a* samples were taken in the Gulf north of 29°N. Chlorophyll *a* samples were taken down to 50 m where possible, and analysis was made by fluorimeter. Chlorophyll distribution was in general very patchy. Lowest values were found at the central northern Gulf at all depths between the surface and 50 m (1.5 to 2.5 mg m^{-3}). Relatively low surface values were found between Angel de la Guarda and Tiburon Islands, to the north and northwest of Angel de la Guarda (2.5 to 3.5 mg m^{-3}), and at Ballenas channel (~5.0 mg m^{-3}). Highest surface values were found near the northernmost coasts of Baja California and Sonora (30 to 40 mg m^{-3}). There was no clear dependency of chlorophyll concentration as a function of depth, but in general it decreased with depth with the exception of the area around Angel de la Guarda Island, where the concentration was fairly constant down to 30 m, and decreased to about 2.0 to 3.0 mg m^{-3} at 50 m. At 50 m the highest values were found at Ballenas channel and near San Felipe (Gendrop-Funes et al., 1978).

Zooplankton in the Gulf of California

Zooplankton studies of the Gulf of California are very few. Alvariño (1962, 1963) made studies on the systematics of Chaetognatha in the Gulf of California, and gave a description of the different species. Mundhenke (1969) found no clear relationship between the water masses of the Gulf and the geographic distribution of euphausiids. Stevenson (1970) found that plankton abundance was relatively high in the front region near Cape San Lucas, and in the vicinity of Las Tres Marias Islands. At the entrance to the Gulf zooplankton abundance in general increased from April to August. Only in the area north of 31°N had samples been taken systematically throughout a year to study the zooplankton biomass variability as a function of location and time (Farfan, 1973; Cummings, 1977). Zooplankton displacement volumes in the northernmost region of the Gulf vary from the same magnitude to twice as large as those of temperate coastal waters, but they are 3.5 to 7 times greater than values reported for subtropical and tropical seas. Zooplankton volumes in the northern Gulf are maximum during winter (up to 13 to 25 ml of plankton m^{-3} in January), and during this season exceed values for regions of upwelling generally by a factor of two. Copepods are numerically the dominant organisms in all samples, with euphausiids and crab larvae having secondary importance. Copepods also show the greatest variability. Euphausiids have been found only during winter and spring (Cummings, 1977). In the area adjacent to the Colorado River mouth, there is no clear seasonal variation in zooplankton biomass in terms of dry weight. Low and high values were reported for October 1972 and 1973 from 1 to 4 mg m^{-3} and from 3 to 60 mg m^{-3}, respectively. Patchiness is again a problem. High values are reported for January (10–400 mg m^{-3}) and February (10–40 mg m^{-3}), relatively low values for March and April (4–20 mg m^{-3}), intermediate values for May and July (2–40 mg m^{-3}), and high values again for August (25–150 mg m^{-3}) (Farfan, 1973). This area of the Gulf has great turbidity, and encompasses a region where fishing is prohibited throughout the year. It has been reported to be an area of reproduction of many fish and crustacean species, and juveniles are abundant here (Berdegue, 1955; Guevara-Escamilla, 1973). Turbidity is so great that Secchi disk depths are less than 0.5 m near the Baja California coast, and 1 to 2 m near the Sonora coast. Seston concentration values of about 100 mg l^{-1} were found near Baja California at about 31°30′N, in May 1973, using filters of 3 μm pore size. The percentage of organic matter is high, sometimes near 100%, more often about 30% (Garcia-De-Ballesteros and Larroque, 1976).

Fish populations of the Gulf of California

The Gulf of California offers a paradoxical environment for those organisms that would invade its waters and flourish. It has some of the greatest environmental extremes of any of the world's seas, and great productivity (Moser et al., 1974). The fish fauna found here indicate that the Gulf is clearly part of the tropical American or Panamic faunal province. Walker (1960), in his review of the Gulf ichthyofauna, recorded 586 species of fish in the Gulf, of which 526 were shore fishes. Nearly three quarters of the shore fish are tropical or subtropical species with their principal ranges to the south of the Gulf. About 50 species, or 10% of the total, have their principal distributions to the north of the Gulf. The majority of these are found in the northern region of the Gulf as disjunct species from the Southern California or San Diegan fauna. The remaining 92 species, or 17% of the total, are endemic to the Gulf. In a comparison with the Panamic fauna to the south, Walker (1960) has noted that the Gulf has an unusually high number of rocky shore species, a relatively poor representation of muddy bottom forms, and a high percentage of endemic species. The paucity of certain Panamic groups (croakers, catfishes, and anchovies) indicates their inability to adapt to the environmental extremes of the Gulf. These extremes, however, along with the abundance and isolated nature of rocky shore habitats, have permitted an impressive evolution of blennioid fishes. The blennioid families Clinidae, Tripterygiidae, and Chaenopsidae are perhaps the best examples of the profusion of rocky shore fishes in the Gulf. These groups have been reviewed extensively by a number of investigators including Hubbs (1952), Springer (1958), Rosenblatt (1959) and Stephens (1963), and are among the best known of eastern Pacific shore fishes. The mid-water fish fauna, also dominated by warm-water species, is even more depauperate than the shore fish fauna. There seem to be no endemic mid-water fishes in the Gulf. Typically, those mid-water species that are recorded from the Gulf do not penetrate very far north, and most are limited to the southernmost basins. *Benthosema panamense* and *Triphoturus mexicanus* are the only mid-water species that occur in significant numbers in the northern regions of the Gulf. All of the abundant mid-water Gulf species have wide latitudinal ranges outside the Gulf and are equipped to tolerate the seasonal temperature range of the Gulf. Probably more important than this is their ability to tolerate the low oxygen concentrations at the minimum (Moser et al., 1974).

Since 1967 there has been an important sardine fishery of the Gulf of California. A subpopulation of *Sardinops caerulea*, that seems to spend all of its life within the Gulf, has its maximum concentration in the Guaymas area during winter, which is the spawning season. Based on the concentrations of larvae, the mature portion of the subpopulation has been estimated to be between 200 and 250 × 10^3 t (Sokolov and Wong-Rios, 1973; Sokolov, 1974; De-La-Campa-De-Guzman et al., 1976). A hake population, *Merluccius* sp., has been found principally north of Tiburon Island and along the east coast of the Gulf as far south as Guaymas. The population has been estimated as 28 × 10^3 t (Mathews et al., 1974). Ichthyoplankton samples were taken in a series of seven cruises to the Gulf of California, during 1956 and 1957, by Scripps Institution of Oceanography and the U.S. National Marine Fisheries Service. In 1956 the northern anchovy, *Engraulis mordax*, was by far the most abundant species, about 38% of the total, followed by the hake, *Merluccius productus*, with about 28%. These were followed by the sardine, *Sardinops sagax*, and the genera *Sebastes* and *Citharichthys*, each of which made up about 4% of the catch. The lanternfish *Triphoturus mexicanus* and the tropical gonostomatid *Vinciguerria lucetia*, ranked sixth and seventh at about 3% of the catch. In 1957, a warmer year, *E. mordax* remained the most abundant, but was followed closely by *V. lucetia*. The hake remained abundant, in third place, followed by *T. mexicanus*, *Citharichthys* sp. and the warm-water lanternfish, *Diogenichthys laternatus*. Larvae of the Pacific mackerel, *Scomber japonicus*, were widespread in the southern region of the Gulf during the February cruises of both years (Moser et al., 1974). The distribution, abundance and ecology of larval tunas at the entrance to the Gulf, were studied during October 1966–August 1967, with samples taken in seven cruises of Direccion General de Pesca e Industrias Conexas of Mexico and the Inter-American Tropical Tuna Commission. *Auxis* sp., the frigate mackerel, was the most abundant with 95.2% of the catch; *Thunnus albacares*, the yellowfin tuna, was second with 3.6%, and *Euthynnus lineatus* was third with 1.2%. Adult specimens of these species, and other tunas, are caught in this region for commercial purposes. Water masses had no influence *per se* on the distribution of larval tunas in this area (Klawe et al., 1970).

During summer 1973 Guevara-Escamilla (1973) collected fish samples with shrimp nets, using commercial shrimp boats, in the region adjacent to the Colorado River mouth, north of San Felipe. He collected a total of 73 species, 18% of which were endemic to the Gulf, 42% were San Diegan and 40% Panamic. One species of special interest in this region is the totoaba, *Cynoscion macdonaldi*, which used to support an important fishery, and now is so scarce that it may even disappear from this area. This region, adjacent to the Colorado River mouth, has an abundance of juveniles and has been declared a sanctuary by the Mexican government, from a line connecting Santa Clara, Sonora, at 114°31′W, with a point 9 km north of San Felipe, Baja California, to the north.

MAN'S IMPACT ON THE GULF OF CALIFORNIA

The waters and organisms of the Gulf of California may still be considered as existing in a natural state with respect to certain types of man's activities. For example, it may still be free of certain pollutants that are already causing problems in other seas of the world. But, unfortunately, man's activities are already altering the Gulf's ecosystems, in some cases dramatically, as in the upper Gulf. Pesticides used in the agricultural areas of the Mexicali valley and Sonora and Sinaloa states may already be entering the Gulf waters in significant quantities. However, there are almost no data on this subject. Guardado-Puentes and Nuñez-Equer (1975) found total concentrations of DDT (dichlorodiphenyl trichloroethane) and its metabolites as high as 0.122 p.p.m. in the sediments of the upper Gulf near the Colorado River mouth. They also found total DDT concentrations up to 0.150 p.p.m. in the clam *Chione californiensis* on the beaches north of San Felipe. Nevertheless, the greatest changes in the upper Gulf have other causes. The decrease of Colorado River fresh-water input has drastically changed the ecological conditions of what used to be an estuarine system, and is now an area of the highest salinities of the whole Gulf. There once was an important fishery of the totoaba, *Cynoscion macdonaldi*, an endemic fish of the northern Gulf. Now this fishery does not exist. There are three possible reasons for this: the lack of estuarine waters for reproduction; the intense fishing of adults near the Colorado River mouth until recent years; and — probably the most important factor and one that is seldom mentioned — the capture of juveniles by shrimp nets (Guevara-Escamilla, 1973). Capturing juveniles by shrimp nets may be a severe problem for many species, especially in the shallow northern Gulf, and the effect may be overlooked simply because there are no important fisheries for all of them. Mathews (1974) has expressed concern about a growing Pacific Mexican shrimp fleet that may already be overexploiting that resource. He estimated that on the average the shrimp nets were passing over each square meter of the Mexican Pacific shrimp grounds about seven times per year. In the upper Gulf the number must be much higher. Many other species caught with the shrimps are considered as "garbage" by the fishermen. Many of these could be useful, but they may already be diminished as a resource. All of them have a role in the Gulf's ecosystem, and man's activities may be changing them without any awareness of the ultimate effects.

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