The base map is an enlarged version of the Mapa físico político, República del Perú (Physical political map, Republic of Peru), 1970, scale 1:2,000,000, published by the Instituto Geográfico Militar (IGM) del Peru. Locations of cities and towns, contour lines, and drainages were taken from this base.Ergs, dune fields, and other eolian features were mapped on the Hojas de la Carta Nacional (Quadrangles of the National Map), 1969–1976, also published by the IGM, scale 1:100,000, contour interval 50 m, then transferred onto the 1:1,000,000 scale base. Locations and elevations of selected mountain peaks are from Operational Navigation Charts I-26, M-25, N-25, edition 3, 1980, scale 1:1,000,000, of the U.S. National Oceanic and Atmospheric Administration.

The following are translations from Spanish to English.

bahía	bay
cerro	hill, mountain
cordillera	mountain chain
costa	coast
duna(s)	dune(s)
hoyada	hollow
laguna	lake
nevado	mountain
pampa	plain
playa	beach
puerto	port
punta	headland, point
quebrada (abbreviated as "Q.")	dry wash
río	river
señal	signal

Figure 15. Wind-etched furrows in sandstone, which slopes gently to the north towards Río Piura (at top of picture). Individual shrubs are as high as 2 m. Foreground is about 0.2 km across.

Figure 9. Coppice dunes. Shrubs are as much as 2 m high. Foreground is about 0.2 km across.

Figure 1. Beyond storage zone of Pampa las Dunas Erg, showing sand recycling into ephemeral tributaries of Río Chao. View is west, across south-bank tributaries. Relief shown is about 200 m.

Figure 2. Storage zone of Quebrada Grande Seca Erg. View is northeast. Relief shown is about 150 m.

Figure 3. Transfer zone of Quebrada Grande Seca Erg, showing trains of barchans typical of zone. Individual barchans are tens of meters wide and several meters high. View southwest.

Figure 5. Synoptic view of Ica Erg Complex, showing typical platform ergs and fields of yardangs; yardangs are concentrated on both sides of lower Río Ica valley at right. North at top. (Photograph 42008, taken by hand-held camera of Earth Observation Experiment, Shuttle Mission STS 41-G, October 1984, altitude 352 km.)

Figure 8. Parabolic dunes (light colored). Minimum length of individual lobes here is 0.5 km.

Figure 7. Giant compound barchans. Note secondary barchanoid ridges on their tops. Pur-Pur Dune is at bottom; trains of smaller barchans calve away from its horns. Part of Mapa aerofotográfico (mosaico preciso) de Chao-Virú-Moche (Hojas 30, 35) [Aerial photomap (controlled) of Chao-Virú-Moche (quadrangles 30, 35)], 1942, Servicio Aerofotográfico Nacional del Peru.

Figure 4. Pampa de Coyungo Erg, looking south toward its source area—beaches of small bay in lee of rocky headland. Foreground of photograph 2 km across.

Figure 6. Typical mountain ergs. Cerro Copara in foreground is 700 m high; Cerro Blanco in background is 400 m high. View is north.

Figure 10. Zibars mapped as part of platform erg sand unit (pl) in corridors between linear dunes of Ocucaje Erg. North at top. Vertical aerial photograph 18975, Servicio Aerofotográfico Nacional.

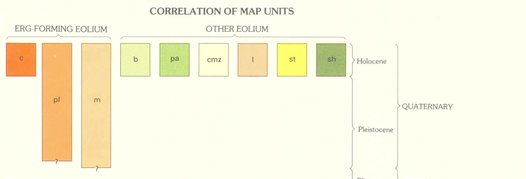
Figure 11. Lomas on marine terrace 200 m above sea level. Lomas are as much as 400 m high and 6 km long. North at top. Vertical aerial photographs 1052, 1054, and 1056, Servicio Aerofotográfico Nacional.

Figure 14. Cerro Hueco la Zorra, a yardang that is the erosional remnant of a river terrace. The yardang is 50 to 100 m high and 2 to 4 km long. View is south. Note sand streamers at base of yardang. Foreground is about 1 km across.

Figure 12. Sand streamers. Alternating light and dark ripples are several meters wide; overlying transverse ripples are a few centimeters high. These streamers are on a terrace within a field of yardangs, some of which are visible in distance.

Figure 13. Multilobate sand sheet. Individual lobes are several kilometers wide and tens of kilometers long. North at top. Vertical aerial photographs 22059, 22061, and 23306, Servicio Aerofotográfico Nacional.

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

ERG-FORMING EOLIUM

[Ergs ("sand seas") generally isolated from one another by stream valleys. Listed in order from most complete eolian system (consisting of source area, transfer zone, and storage zone) at least complete system (consisting of storage area only)]

c — **Sand of coastal ergs (Holocene)**—Mineralogically immature; composition in source area ranges from quartz arenite to lithic arenite (Potter, 1986), but degree of sorting according to size and mineralogy during transport inland is unknown. Forms at least 25 ergs, one to several kilometers across, distributed discontinuously along narrow coastal plain. Coastal ergs are independent, three-part systems consisting of source area, transfer zone, and storage zone against westernmost Andean foothills (figs. 1–4). Bedforms are (1) foredunes and linear dunes adjacent to beach in source area; (2) barchan trains and sefis in transfer zone; and (3) densely crowded barchanoid and transverse ridges on steep, west-facing slopes of coastal hills and Andean foothills in storage zone. Bedforms change abruptly due to differences in availability of sand and sharp changes in gradient. Two to three successive pulses of sand accretion are indicated by overlapping bedforms in storage area; light-toned bedforms commonly overlap increasingly darker dune sand from earlier pulses. Sand recycled by both fluvial and marine transport. Overall sand budget either positive or in steady state (if rate of fluvial recycling is in dynamic equilibrium with rate of sand accretion)

pl — **Sand of platform ergs (Holocene and Pleistocene)**—Quartz sand mixed with unknown amount of lithic fragments and heavy minerals. Most ergs cut off from supply areas by tectonic uplift, thus consist of only two parts, transfer zone (where ergs are tens of meters thick) and storage zone (where ergs are possibly hundreds of meters thick and more than 25 km² in area; fig. 5). Ergs in Ica Erg Complex merge into one another. Bedforms include barchan trains and sand sheets in transfer zone; zibars and parabolic dunes on proximal edges; linear dunes, large barchanoid ridges, and star dunes in storage zone. Overall sand budget probably increasing; locally, ergs may be in steady state or loosing sand

m — **Sand of mountain ergs (Holocene to Pliocene?)**—Of uncertain mineralogic composition. Present occurrences in storage zones only (fig. 6), completely or partly cut off from former source areas and transfer zones by marine regression and tectonic uplift from Pliocene to present time. Present and past degree of sorting inland from coast unknown. Ergs tens to hundreds of meters thick, several square kilometers in area. Larger bedforms include megaripples along Andean valley slopes, barchans, barchanoid ridges, linear ridges, and star dunes in central parts of erg. Sand being slowly removed by mass wasting and avalanching down steep valley slopes to ephemeral-stream channels below, transported downstream by occasional flash floods, and carried up coast by longshore drift. Therefore sand budget of each erg probably negative

OTHER EOLIUM

Mineralogically immature sand (Holocene)— divided into:

b — **Barchan sand**—Ranges from quartz arenite to lithic arenite (Potter, 1986). Forms giant compound barchans as wide as 1 km, tens of meters to more than 100 m high, such as Pur-Pur Dune 30 km south of Trujillo (fig. 7). Giant compound barchans commonly topped by smaller secondary barchans. Trains of smaller, simple barchans calve off horns and extend many primary-barchan widths downwind. Fields of giant barchans form in shallow depressions in western part of Sechura Desert. Advance of giant barchans very slow (about 1 m/yr) because of large sand volume (Simons and Ericksen, 1963). All giant barchans undergoing deflation: Pur-Pur Dune cut off from its source area since prehistoric time by irrigation in valley of Río Virú; other giant barchans supplied with sand from ocean beaches and upwind deflation surfaces only episodically. During El Niño downpours, wave erosion severely degrades barchans standing in depressions inundated by flood water from nearby ephemeral watercourses. Faster moving, calving barchans also excavate sand from primary barchans. Thus sand budget of each giant barchan is negative

pa — **Parabolic dune sand**—Partly stabilized by ambient air and ground moisture and sparse vegetation. Individual dunes 0.10 to 1.0 km long, 100 to 200 m wide, tens of meters thick (fig. 8); long axes are oblique to coastline, parallel to direction of effective sand transfer. Leading edges of front lobes and steep, outer dune sides commonly stabilized by grass or shrubs; front lobes overlap, indicating two or more pulses of sand advance. Commonly in large, elongated, multilobate, partly vegetated coastal blowouts south and southeast of Sechura Desert; rarely in dune trains, as in southern part of Cerro Huaricangana platform erg south of Ica Erg Complex. Forms small dune fields adjacent to beaches or estuaries where sand supply plentiful; fields are discrete eolian systems, independent of much larger coastal ergs. Sand budget generally positive, because cultivated fields stabilize sand and prevent fluvial recycling

cmz — **Sand in coppice dunes, vegetation mounds, and zibars**—Makes up dunes less than 10 m high. Coppice dunes are temporarily stabilized as triangular wedges in lee of vegetation clumps (fig. 9); largest field in eastern and central Sechura Desert. Vegetation mounds are drift sand fixed by vegetation; large mounds common along Pan American Highway south of Pisco Erg where vegetation is fed by ground water. Zibars are low-relief dunes lacking discernible slip faces (Cooke and Warren, 1973, p. 309; Nielson and Kocurek, 1986); best developed in Ica Erg Complex, also in corridors between long linear dunes in Ocucaje platform erg (fig. 10) west of Río Ica. Coppice dunes and zibars seem to be in steady state; vegetation mounds in various stages of accretion or erosion, depending on local sand flux

l — **Loma sand**—Underlying and stabilized by loma vegetation that receives only a few millimeters of rainfall per year (fig. 11). Exhibits faint soil profile. Restricted to areas of frequent garúas. Lomas common in central Peru, but only larger ones with sand substrate mapped. Loma vegetation includes associations of algae, lichen, moss, theropytes, and several species of the rootless monocot *Tillandsia* (Koepcke, 1961; Müller and Müller, 1974). Bedforms subdued or lacking where sand is stabilized by algal crust, but stepped lomas (lomas escaloderas) common in south-central Peru. Lomas are sensitive climatic indicators, but interactions between loma sand and vegetation need further study before loma sand budget and advances or retreats of loma vegetation can be determined

st — **Sand and granules of sand streamers**—In yardang fields. Poorly sorted by creep and saltation; in straight or slightly curvilinear bands (streamers) parallel to wind direction; overprinted by transverse ripples (fig. 12; see also fig. 14). Streamers consisting of sand are light and streamers consisting of granules are dark. Streamers of alternately light and dark ripples are one to several meters wide and several hundred meters long. Streamers occur at several places (not mapped) between Huarmey and Chimbote in northern Peru, where they were first named "sand streams" and described by Simons and Ericksen (1953), but they are best developed in lower Río Ica valley in corridors between yardang fields on wind-swept and wind-modified terraces. This valley location has daily alternation between intense sea breeze and more subdued land breeze; resulting effective transfer of sediment not known but probably slightly landward. Sand streamers probably among most stable eolian bedforms

sh — **Sand of sand sheets**—Locally drifting, sparsely vegetated in places. Sand sheets multilobate, occur in bands of 5 to 15 subparallel straight sheets 10 to 20 km long, 0.1 to 10 km wide, but no more than 20 cm thick (fig. 13); locally, many pebbles and rocks on desert floor protrude through sheets. Found near coast where garúas are frequent, but are independent of coastal ergs. Sand sheets located in south-central Peru west of Río Ica and in western Sechura Desert. Source areas are deflated surfaces nearby. Several episodes of sand advance indicated by overlapping sand lobes; younger, overlying lobes lighter in tone. Sand budget of young sheets positive; that of old sheets stabilized by loma vegetation in a steady state, but sheets may lose sand to downwind desert surfaces at all times. Time of reconstitution not known

Contact

Dune trains—Schematic; primarily barchans; movement inland from coast

Yardang or yardang field—Includes some sand streamers

Boundary of furrowed area

Pan American Highway

INDEX MAP SHOWING PERU AND VICINITY

SCALE 1:1 000 000

ONLY 500- AND 2000-M CONTOURS SHOWN

GEOLOGIC MAP OF MAJOR QUATERNARY EOLIAN FEATURES, NORTHERN AND CENTRAL COASTAL PERU

By

Eileen M. Haney and Maurice J. Grolier

1991

INTRODUCTION

The longest west-coast desert in the world stretches for 5,600 km along the Pacific coast at the base of the Andes. The southern part, in Chile, is known as the Atacama. The northern part, in Peru, has no formal name and is here referred to as the "coastal desert." From its northern part (the Sechura Desert) to its south-central part, the coastal desert contains sand deposits that are unusual in several ways. First, the climatic setting of the coastal desert is relatively simple—rain falls only during periodic El Niño storms (described under Climatic Setting) and thus can be disregarded as an erosional agent, and ceaseless winds blow from the southeast. As a result, patterns of sand transportation and deposition are also relatively simple. Second, dune fields and ergs are abundant and differ according to age, terrain, latitude, and distance from source area. Their diversity provides a sample base large enough to develop general models of depositional patterns, including those of transportation from the source area to the storage area, of bedform development, and of relations between different terrains and the dune fields. Third, because dune fields are of different ages, the stages of their development can be studied. Thus, the coastal desert provides a unique opportunity to study the results of differing eolian processes in a varied area, which is reasonably accessible via the Pan American Highway.

The eolian features of the coastal desert are confined to a strip between the shoreline and the Andean foothills. This region is newly emergent and tectonically unstable. People, water, and irrigated fields are found primarily where the narrow flood plains of mountain rivers cut across the desert to the sea. Most of these rivers are intermittent, and farming and irrigation are regulated by the supply of water from the mountains. The river valleys, as well as the low, typically dry deflation basins in the Sechura Desert and elsewhere in northern Peru, are periodically inundated by El Niño rains. The effect of El Niño is strongest in the north and weakens in the south, allowing observation of the effect of differing amounts of precipitation on eolian processes.

The map shows the areal distribution of major eolian deposits, gathered under the generic term "eolium," and of the principal wind-eroded landforms. The 500- and 2,000-m topographic contours relate the ergs and smaller dune fields to overall Andean relief. The Continental Divide, the crest of the Western Cordillera (Cordillera Occidental), is shown to give regional perspective; its various segments and major peaks bear their Peruvian names.

We gained first-hand knowledge of the coastal desert of Peru during field expeditions in 1971, 1973, and 1978. Field work included ground reconnaissance of eolian features followed by a flyover to gain an aerial perspective. We acquired thousands of ground and oblique aerial photographs in the field. We supplemented the fields of view by studying topographic and geologic maps and hundreds of vertical aerial photographs. Thus we studied almost all map units and major landforms on the ground as well as on photographs. The exceptions are zibars, which were not recognized at the time, and some of the mountain ergs, which were hidden by fog during parts of the ground and air reconnaissance.

CLIMATIC SETTING

The four conditions for the existence of a sandy desert are met to an unusually high degree in coastal Peru: (1) aridity, (2) persistent winds; (3) an inexhaustible supply of sand from coastal beaches, channels of ephemeral streams, and barren ground under constant deflation; and (4) a lack of vegetation, which is controlled by aridity. The first two conditions are climatic and are discussed below.

The aridity index (Budyko ratio) for the mapped area ranges from 50 in the north to 150 in the south (Henning and Flohn, 1977). These values are the ratios between net radiation at the surface and precipitation. Ratios larger than 1 indicate radiation in excess of available moisture; ratios greater than 1.5 are considered significant indicators of potentially arid conditions; ratios in excess of 20 indicate hyperaridity, the condition of all parts of coastal Peru. However, lack of precipitation does not mean lack of moisture, nor does it indicate excessive heat. Frequent heavy fogs (garúas) and perpetual cloud cover, which is formed at the inversion layer between cold and warm air masses, provide some moisture to coastal Peru and keep its temperatures below 28 °C year round (Johnson, 1976).

Winds are dominantly southeasterly, paralleling the coast and the Andes (Johnson, 1976). In the south, around Lima (lat 12° S.), these winds parallel the coast at nightime and in winter, and they are westerly in the morning in summer. Farther north, near Trujillo (lat 8° S.), wind directions have a more easterly component, changing from south-southeast in the morning to south-southwest in the afternoon. Nearshore winds in the coast have a slight onshore component, but they are not real land-sea breezes. Wind speeds range from between 4 and 8 knots around Lima to 13 knots around Chimbote (350 km northwest), averaging 10 knots along the entire coast. Winds are generally stronger during the second half of the year. In the coastal desert, prevailing southeasterlies show a pronounced curvilinear pattern as they move inland, changing to southerlies, southwesterlies, and westerlies. This pattern can be observed in the orientation of individual dunes and dune fields (Rich, 1942, fig. 267; Craig and Psuty, 1968, p. 52–59).

An exception to the general direction of the surface winds along the coast is in the platform area south of Pisco (lat 13°43′ S.) that extends southeast to Chala (lat 15°40′ S.) and the Ica Erg Complex. Here the local wind systems (sea and land breezes, El Virazon and El Terral) overshadow the offshore winds. At Pisco, the prevailing wind direction is northwesterly, indicating substantial onshore winds. This condition arises because south of Pisco a coastal mountain range (Cordillera de la Costa) protects the inland areas of the platform from cold marine air. They are therefore warmer than other areas, and they draw in the cooler marine air from the bay at Pisco to the north. Prevailing wind direction is northwesterly from Pisco to Ica. South of Ica, southerly and southwesterly winds, modified by local relief and the northwesterlies just described, are dominant (Johnson, 1976).

The aridity, moist air, and constant low temperatures along the coast of Peru, as well as the persistent southeasterly winds, can be attributed to the unusual circulation patterns of wind and water in the region. Air circulation off the coast of Peru is powered by the persistent high pressure of the anticyclone system of the mid-Pacific. The counter-clockwise rotation of wind around this system is streamlined by the Andes to produce a low-level jet stream parallel to the South American coastline (Lettau, 1978). The resulting southeasterly winds drive cold Antarctic waters northward against the Peruvian coast (Smith, 1981; Thiede and Suess, 1983). Here they well up from depths of 50 to 240 m (Demaison and Moore, 1981) to form a nutrient-rich, cold surface current flowing northward at velocities of 10 to 30 km per day (Zuta and Guillén, 1970; Demaison and Moore, 1981; Scheidegger and Krissek, 1983). The upwelling of cold sea water is particularly strong because the coast of South America projects westward, contacting actively circulating water of the open ocean to very low latitudes (Lydolph, 1957). Because the water is so cold, the adjacent 300-m-thick air layer is perpetually cooled, lacking thermal convection cells and preventing precipitation (Hartline, 1980; Reimers and Suess, 1981). The result is a desert with perpetual wind; almost constant cloud cover at the inversion layer; cold, moist marine air; and frequent fog—but with no rain.

A final factor in ensuring hyperaridity in coastal Peru is the Andes, which rise within a few tens of kilometers of the coast to heights of 4,000 to 5,000 m. They not only channel the coastal winds to produce the jet stream, but they also form an effective shield against tropical air masses from the Amazon basin (index map), which otherwise might interfere with the well-established inversion layer.

Thus, hyperaridity in coastal Peru is ensured by (1) an inversion layer of cold maritime air above the ocean along the coast, which prevents the formation of convection cells and thereby reduces annual rainfall to a few millimeters, and (2) the Andean cordillera, which helps channel the cold air north along the coast and separates the dry environment of the coastal desert from the humid easterlies of the Amazon basin.

In northern Peru as far south as Lima, the main departure from hyperaridity is caused by episodic torrential downpours associated with the onset of El Niño ("The Child," so-called because its arrival at the west coast is commonly at Christmastime). During El Niño events, the high-pressure system over the South Pacific decreases in intensity and sea surface temperatures rise, while corresponding pressure cells in the Indian Ocean fall, and the Indonesian low is strengthened. This pressure change was first observed by Walker and Bliss (1932), and overall the phenomenon is known as the Southern Oscillation. Today, the local effect (El Niño) and the regional event (Southern Oscillation) are usually lumped in the term El Niño/Southern Oscillation (ENSO). During an ENSO, the monsoons fail in Indonesia and the coast of Peru is deluged (Walker and Bliss, 1932; Quinn, 1971; Philander, 1985). ENSO events ranging in intensity from moderate to very strong have been summarized by Quinn and others (1987) on the basis of historic records. They concluded that the average period between all ENSO events has been 3.8 years. Frequent but moderate ENSO events have affected only the northern coastal areas; precipitation has been carried into the southern coastal desert only by very strong events that have occurred, on average, at 50-year intervals. Thus the northern part of the coastal desert has received much more precipitation than the southern part.

The beginning of hyperaridity in the coastal desert was signaled by the onset of upwelling of Antarctic waters. We do not yet know when this ancient upwelling began or its relation to the rise of the Andes. However, evidence of the onset of upwelling and of its fluctuations has been preserved in the sedimentary and fossil record of the continental shelf and slope (Suess and Thiede, 1983). Such evidence indirectly aids in the interpretation of the paleoclimate of coastal Peru during much of the Cenozoic. Recent work on this problem is summarized below.

GEOCLIMATIC HISTORY

TECTONICS

The rise of the Andes, even when considered to have occurred only since the start of the Triassic and to be restricted to the Peruvian cordillera, is an extremely complex sequence of events. It involved at least three orogenies during the Late Cretaceous, Eocene, and early Pliocene (Zeil, 1979, p. 27–43). These orogenies were accompanied by or interspersed with large-scale volcanism and emplacement and unroofing of batholiths (Cobbing, 1972; Noble and others, 1974). Most important for the coastal desert is the growing body of evidence (Mégard and others, 1984; Tosdal and others, 1984; Alpers, 1987) that the Andes have been a barrier to tropical rains from the Amazon basin and a funnel for southeasterly winds since the middle Miocene. If so, hyperaridity could have begun at any time thereafter, when a strong South Pacific high-pressure cell developed (see Quaternary Climate Changes).

Coastal Peru is tectonically unstable because it is located above the subduction zone between two actively converging plates, the Nazca plate and the overriding South American plate (Shepherd and Moberly, 1981). Although the Peruvian Andes lie along the "ring of fire" that rims the Pacific Ocean, no Quaternary volcanism has occurred north of lat 15° S., where the Nazca Ridge abuts the South American plate (Barazangi and Isacks, 1976; Nur and Ben-Avraham, 1981). However, earthquakes are common, as evidenced by the tremor of May 31, 1970 (Pilaker and others, 1971), which devastated the region inland from Chimbote (at 9° S.). A long-term vertical uplift of the coastline at an average rate of 1.8 cm per year was calculated by Wyss (1978). Sandweiss and others (1981), however, found a single large Holocene uplift of the coastal region between lat 8°30′ and 9°00′ S. Additional geologic evidence of episodic Quaternary uplift of the Peruvian coast includes the raised marine terraces (tablazos) of the Talara-Paita region in northernmost Peru (Richards and Broecker, 1963; Richards, 1967; Richardson, 1969). Farther south, beaches are stranded by prominent wave-cut cliffs. However, simple calculations of uplift based on height of marine terraces above sea level are complicated by sea-level changes. Many marine terraces along the coast of Peru were formed during Pleistocene marine transgressions (DeVries, 1987; Wells, 1987). So far, no realistic rate of uplift through time, based on both eustatic sea-level changes and tectonism, has been calculated.

Crustal instability and emergence along the Peruvian coast are also documented by a growing body of archeological data on pre-Columbian irrigation farming and on its subsequent collapse due to the decrease and even reversal of irrigation-canal gradients (Moseley, 1983). Large-scale irrigation agriculture in coastal Peru began after 900 B.C. (Park, 1983), but "abandoned [prehistoric] canal sections presently run uphill or have gradients that would be inoperable today" (Moseley and others, 1983); tilted buildings are common on archeological sites (Donnan and Ortloff, 1983; also found in Moseley and others, 1983). Sea-level changes or tectonism could account for indications at older dated archeological sites that the shoreline of Puerto de Casma (lat 9°30′ S.) was as much as 3 km inland from its present position until about 2,000 yr B.P. (Pozorski and others, 1983). In south-central Peru, a few kilometers southeast of Peninsula Paracas (13°50′ S.), a raised lagoon floor is surrounded by conspicuous shell mounds and middens that stand 5 m above sea level and have been dated as 3,550 to 3,660 yr old (Craig and Psuty, 1971). However, DeVries (1987) and Wells (1987) found that many shell mounds and middens are still at sea level, stranded by prograding beaches after the Holocene maximum transgression.

In conclusion, Peru has been proven to be relatively young. Volcanism and batholith emplacement, along with uplift and batholith unroofing, had formed a formidible barrier to atmospheric circulation by the middle of the Miocene. Most of the coastal desert is newly emergent because of tectonic uplift and eustatic sea-level changes and associated beach progradation. This terrain formed after the onset of hyperaridity and has not been eroded by water to any significant degree.

QUATERNARY CLIMATE CHANGES

Important factors in evaluating the ages and accumulation rates of the dune fields in the coastal desert are the onset and duration of consistent southeasterly winds, which ensure hyperaridity. Changes in the coastal climate have been caused by changes in the South Pacific high-pressure cell. Should the strength of the cell increase, no El Niño incursions would take place and hyperaridity would be even more pronounced. A decrease in the strength of the cell might permit seasonal or year-round precipitation along the coast. Northward or southward shifts in the pressure cell would change precipitation patterns along the north and south edges of the coastal desert. Unfortunately, evidence for climate change along the coast of Peru is contradictory, subject to multiple interpretations, or insufficient to develop a chronology of climates and their changes during the Quaternary.

Much of the evidence for climate change comes from the north coast of Peru, on the edge of the hyperaridz zone. Climate in this region changes abruptly from hyperarid in the south to tropical. Even moderate ENSO events or small movements of tropical storms to the south bring moisture into this part of the coastal desert. Near Talara (lat 4°37′ S.), the late Pleistocene faunal assemblages of the Talara tar seeps include waterfowl, crocodiles, mastodonts, and ground sloths, indicating a more humid regional climate at that time than at the present (Bryan, 1973) and suggesting that the desert was smaller at times in the Pleistocene (Lanning and Patterson, 1967). DeVries (1987) has reported a southward shift of cold-water species since the early Pleistocene, and he suggested that the shift was caused by the onset of ENSO events in the South Pacific. Richardson (1978) suggested that mangrove mollusks, which lived 8,000 to 6,000 yr B.P. at the mouths of the Río Chira and lesser streams near present-day Talara, retreated northward 140 km to Tumbes because of increased Holocene dessication. His conclusions have been challenged by DeVries (1987) and Wells (1987), both of whom established that Richardson's mollusks were restricted warm-water forms that lived in protected bays and estuaries in association with cold-water, open-marine fauna on rocky headlands nearby. DeVries and Wells suggested that these warm-water mollusks were obliterated from the Peruvian coast as Holocene marine transgression and beach progradation filled the marine embayments where they had lived; no climate change is indicated in this scenario. Quinn (1971) argued on theoretical grounds that lower sea levels during glaciations would have enhanced hyperaridity and locked the Southern Oscillation into a high index phase, characterized by extreme hyperaridity and no ENSO events. This view was also held by Damuth and Fairbridge (1970) on the basis of their work in the Amazon basin. Hyperaridity since 5,000 yr B.P., punctuated by periodic ENSO events, is well documented by, among others, Rollins and others (1986), Sandweiss (1986), and Wells (1987). In their summary of the long historical/climatic record of this coast, Quinn and others (1987) concluded that the climate since Spanish colonial times has been hyperarid except during ENSO events. The evidence is therefore not clear that even northern areas of the Peruvian desert have had periods of increased or decreased precipitation during the Holocene, and such evidence would not necessarily apply to the coastal desert south of the zone of frequent El Niño rains.

In the coastal desert south of the range of moderate ENSO events, additional paleoclimatic work is needed. Lanning (1963, 1965) estimated that lomas (defined in Description of Map Units) were once 10 times more extensive throughout Peru, during a wetter climate than today's. However, because lomas are formed under conditions of extreme aridity and intense coastal fogs, their possible extension would have been during a period of hyperaridity, not precipitation. In Chile, a field reconnaissance found intermixed sand dunes and soils and stratigraphically distinct cold-water and warm-water molluscan faunas, which led Paskoff (1973) to suggest alternating wet and dry climates in the past.

Wind speeds and durations in the coastal desert have varied during the Quaternary. Smith (1955a) observed differences in the color and stabilization of sand sheets; for their formation he hypothesized two episodes of intense wind action separated by an interval of decreased winds. Oceanographic evidence based on quartz, opal, and radiolarian assemblages (Molina-Cruz, 1977) indicates that velocities of winter winds were intensified during past cool climatic stages. Oceanographic evidence also suggests that circulation patterns in the South Pacific were maintained during glaciations, but that greater volumes of warm water from the North Pacific may have invaded the southern ocean during climatic optimums (Valencia, 1977; Corliss and others, 1986).

In summary, the formation of eolian deposits and landforms along much of the coast may have been fairly recent in the north, where deposition continues today on a newly emergent terrain, and where the climate may have been wetter than today's until as late as 5,000 yr B.P. In the older desert to the south, hyperaridity may have continued unabated since before the Pliocene, and sand deposition may have been constrained only by sea level. In such a hyperaridz environment, sand blown to a sufficiently high elevation could have been preserved throughout the Quaternary.

CLASSIFICATION OF MAP UNITS AND OTHER FEATURES

ERG-FORMING EOLIUM

Eolium is divided into nine morphostratigraphic units according to bedform type. Because the dune fields and ergs form more than one type, their eolium is divided according to their depositional substrate: the narrow coast, the Ica platform, or the mountains. This classification is based on the premise that further work will reveal additional distinct differences in erg histories according to their depositional substrate. More precise stratigraphic units may eventually be established on the basis of distinctive characteristics of the sand—its mineralogy, sorting, and depositional history—but such distinctions were beyond the range of this study.

In most of the map area, between the Sechura Desert and the Ica Erg Complex, the coastal desert is only a few tens of kilometers wide. It receives some moisture from ENSO inundations, particularly in the north, but their influence is seldom felt south of Lima. In this region where the desert is narrow, sand moves inland from the shore and is deposited in coastal ergs (unit c) where the Andean foothills begin to obstruct the wind, generally below elevations of 500 m (figs. 1–3). These ergs are also found on the southern part of the platform of the Ica Erg Complex (fig. 4). Coastal ergs were photographed in 1939 by Rich (1942, figs. 262, 267, 268, 271–273, 275, 278) and were briefly alluded to as "sand sheets" by Gagliano and Teves (1970).

South of San Vicente de Cañete (lat 13° S.), uplift has partly or completely isolated most sand deposits from their source area. Such deposits (unit pl) are platform ergs; the largest form the Ica Erg Complex on a broad platform that is close to 500 m high and several kilometers inland (fig. 5). The ergs begin on a chain of yardangs developed in a former marine terrace that parallels the coast; this old coastline was probably the source area for the ergs. Three of the platform ergs were described by Gay (1962).

Southeast of the Ica Erg Complex and other platform ergs are the spectacularly high sand deposits (unit m) of the mountain ergs (fig. 6), which climb from 500 m to more than 2,000 m. These ergs are partly or completely cut off from their source area, and they probably formed before uplift isolated them tens of kilometers from the sea and high above it. The modern analog of these ergs is the Tanaca Erg (lat 16° S.) to the southeast, which climbs from close to sea level to 1,800 m within a few kilometers of the shore.

Because the mountain ergs were proximal to the coast before uplift of the Ica platform area, they are presumed to be older than the platform ergs. The preservation of platform and mountain ergs is dependent on (1) multidirectional winds (see Climatic Setting) and (2) lack of significant rainfall even during ENSO events, of which only the strongest reach this far south. Mountain ergs were photographed by Rich (1942, fig. 225), alluded to by Smith (1956b), and described by Gay (1962).

OTHER EOLIUM

In northern Peru, particularly in the Sechura Desert, the relatively high, ENSO-related precipitation and unobstructed winds favor the deposition of sand in several of the map units grouped as other eolium. These units are barchan dunes (unit b) and three vegetation-dependent forms—parabolic dunes (unit pa), coppice dunes, and vegetation mounds; the last two forms, together with zibars (described below) are mapped as unit cmz. Some of the barchan dunes are giant compound forms, of which the most notable is Pur-Pur Dune (fig. 7; Simons and Ericksen, 1953; Simons, 1956; Smith, 1956a, b); brief descriptions of other fields of giant barchans in northern Peru have been given by Smith (1955a, b, 1956a, b). The area has changed little since it was photographed in 1939 by Rich (1942, figs. 272, 274). Barchan dunes also occur in erg source areas and transportation zones. The parabolic dunes (fig. 8) are primarily beach dunes; inland they are stabilized by vegetation. Most are found along the coast south of the Sechura Desert; their only other occurrence is far to the south in the Cerro Huaricangana Erg, 125 km southeast of Ica and inland from the coast. The coppice dunes (fig. 9) and vegetation mounds cover large inland areas, primarily north of Trujillo where vegetation is common, but also south of the Pisco Erg where groundwater-fed vegetation fixes the sand.

Zibars (fig. 10) are mapped with the coppice dunes and vegetation mounds on the basis of their size (less than 10 m high), but in contrast to these other dune forms, they are not vegetation dependent. Because zibars have low angles and lack a slip face, they are difficult to recognize from the ground, although they are visible from the air. They occur only in areas of reversing winds on the Ica platform.

Lomas (unit l, fig. 11) are composed of sand that has been stabilized by mats of *Tillandsia*, by blue-green algae, and by other plants that acquire their moisture from intense coastal fogs. Although their range is thus restricted to the coast, lomas are important