

DRAINAGE EVOLUTION IN THE ATACAMA DESERT OF NORTHERNMOST CHILE

CEDRIC MORTIMER

Inst. Geol. Sciences, Overseas Division, 154 Clerkenwell Road,
London EC1R 5DU.

RESUMEN

Los diferentes estilos de drenaje, en el Norte Grande de Chile, se clasifican en grandes grupos basados en un origen común. En todos los grupos se considera que la extrema aridez del clima ha producido todos los procesos fluviales con lentitud.

Los perfiles de los cauces largos que llegan a la costa desde la Cordillera de Los Andes difieren, según su posición geológica, su aporte de agua, su edad y su ajuste relativo al nivel marino actual. Los cauces que han producido una incisión de hasta 2.000 m son posteriores al comienzo del Mioceno Superior. El más complejo de los cursos de agua de esta categoría es el río Loa, que se ha formado mediante la unión de varios segmentos cuyos orígenes fueron independientes y complejos.

Los valles, que descienden de los Andes y terminan en la depresión longitudinal, están entre las principales quebradas de la categoría anterior y son además una continuación de la superficie deposicional occidental de la depresión. Aguas arriba, la parte oriental de la depresión es observable como una terraza alta con incisiones de quebradas de hasta 1.000 m de profundidad. Tales quebradas se originaron al mismo tiempo que sus contrapartes del grupo anterior, pero no han sufrido una conversión al nivel marino básico y, por lo tanto, su incisión es menor. Hacia las cabeceras, la erosión es activa en ambas categorías de cauces.

En el sur de la región, existen largos cauces de poca pendiente sin incisión de quebradas. Tales cursos de agua actúan como niveles de base local hacia un pediplano regional.

En las partes donde tales cauces se conectan con la costa, caen al mar con una fuerte convexidad. Las porciones superiores de los canales son del Mioceno Medio, de acuerdo con la edad del pediplano al cual controlan. Estos cauces han sufrido pocas modificaciones desde hace algunos millones de años, a excepción de la región inmediatamente vecina a la costa. La recesión hacia el este de los acantilados, durante la última parte del Terciario, produjo un descenso relativo del nivel de base, cuyo efecto aún no se ha transmitido muy lejos tierra adentro.

Los cauces de drenaje, que sólo se extienden sobre distancias cortas, son empinados y, en su mayor parte, convexos. La progresiva recesión de la línea de costa y la erosión de los acantilados hacia el este, han impedido la formación de tales cauces. Un sollevamiento de la costa plio-pleistocénico, a escala local, ha permitido que la degradación subaérea afecte los bordes de los acantilados, que alcanzan una altura máxima de 2.000 m.

El drenaje interno es común. En la Alta Cordillera de los Andes, debido al volcanismo, existe un bloqueo de los cursos de agua y los tributarios tienen perfiles de agradación. Los cierres tectónicos son también comunes. Algunas de las cuencas internas mayores están actualmente fracturadas pero siguen actuando como niveles de base. Otras cuencas encerradas pierden agua a lo largo de las fallas. Frecuentemente se observan depresiones menores originadas por diferentes fenómenos, incluyendo la deflación.

El agua del drenaje era dirigida, antes, por los eventos tectónicos, a cuencas cerradas, excepto en el sur, donde un nivel de base marino dio origen a una peniplanicie miocena. Los cauces que, en el norte, se conectan con el mar, se desarrollaron durante el Neógeno. Estos cursos y aquellos posteriores, cercanos a la línea de costa, han establecido el proceso inicial de erosión hacia el nivel del mar. La inferencia es que el fallamiento y otros procesos geomorfológicos endógenos están, momentáneamente, inactivos pero no existe ninguna razón fundamental para que ello sea así.

ABSTRACT

The various styles of drainage in northernmost Chile are categorized into broad groups which are based upon common origins. Within all the groups, the extremely arid climate is considered to have rendered all fluvial processes to be very slow.

Long channels which reach the coast from a source in the Andes differ, in bed profiles, in a manner which depends upon their geological position, water supply, age and adjustment to the present marine level. Such channels, which have achieved an incision of as much as 2,000 m are not older than early Upper Miocene. The most complex water course of this category is that of the Rio Loa, which has formed through the union of several segments which have had independent and complex origins.

Valleys descending the Andes and terminating in the longitudinal depression lie between the major canyons of the previous category, and they are continuous with the western depositional surface of the depression. Upstream the eastern surface of the depression can be followed as a high terrace with up to 1,000 m of canyon incised into it. Such canyons originated at the same time as their longer counterparts of the previous group, but have not suffered a conversion to a marine baselevel and are consequently less incised. Headward erosion is active in both this and the former category of channels.

In the south of the region there are long low gradient channels without canyon incision. Such watercourses act as local baselevels to a regional pediplain. Where such channels connect to the coast they fall to the sea with a strong convexity. The upper portions of the channels are Middle Miocene in accordance with the known age of the pediplain which they control. They have undergone little modification in the past few million years except in the immediate coastal region. Cliff recession eastwards during the latter part of the Tertiary caused a relative lowering in the baselevel, the effect of which has not yet been transmitted far inland.

Drainage channels which only extend a short distance inland are steep and, for the most part, convex. Progressive recession of the shoreline and erosion of the cliffs towards the east have inhibited the formation of such channels. Limited and local Plio/Pleistocene coastal uplift has permitted subaerial degradation to affect a cliff edge which reaches a maximum height of close to 2,000 m.

Internal drainage is common. Volcanic blocking of water courses occurs in the High Andes, and the contributing streams have profiles of aggradation. Tectonic closures are normal. Some of the larger internal basins are now breached but still act as local baselevels. Other enclosed basins lose ground water by percolation along faults. Smaller depressions frequently occur and have formed from a variety of phenomena, including deflation.

Drainage water was formerly largely directed by tectonic events into enclosed basins, except in the south where a marine baselevel gave rise to a Miocene pediplain. Channels connecting to the sea in the north have developed within the Late Neogene, and these and later nearshore watercourses have established the initial process of erosion towards sea level. The inference is that faulting and other endogenic landforming processes are momentarily tranquil, but there is no fundamental reason why this should be so.

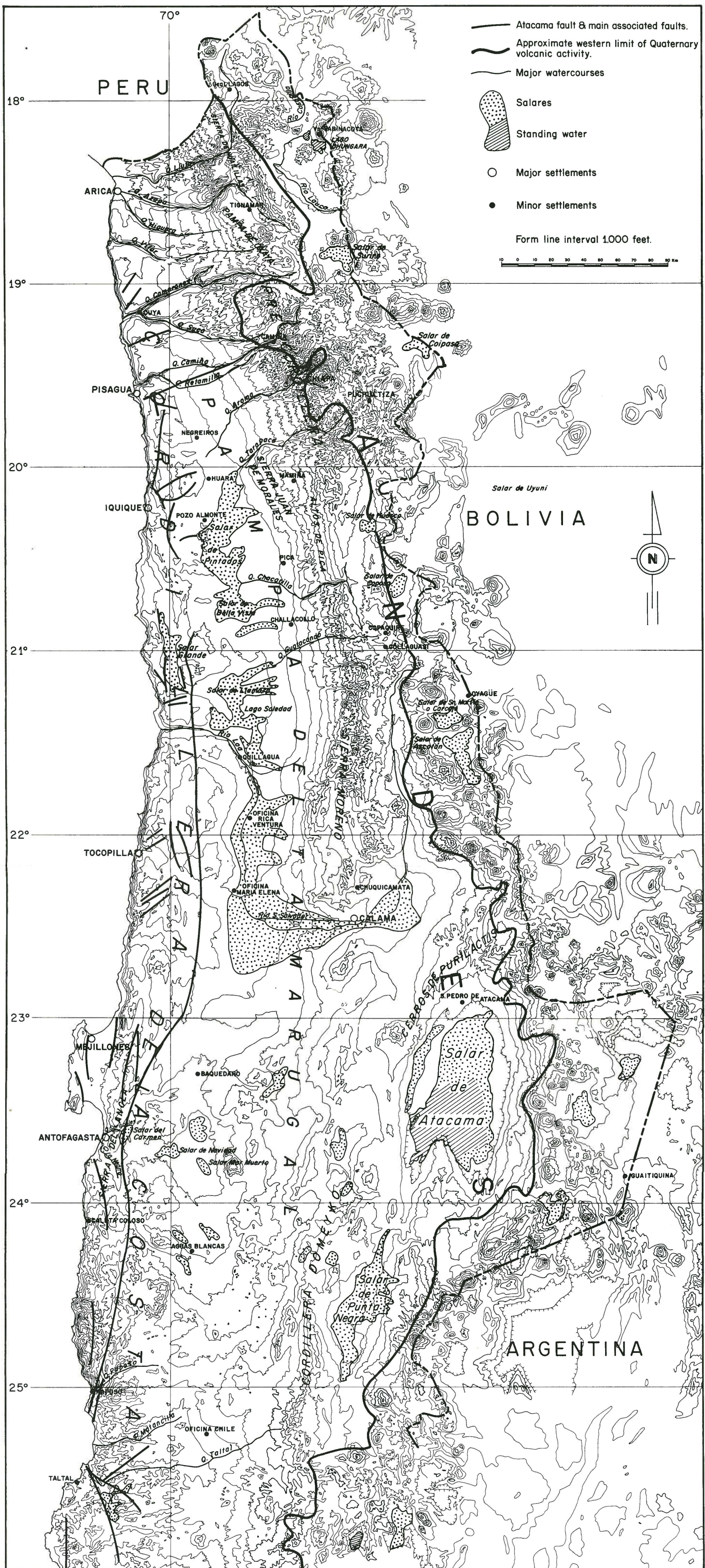
INTRODUCTION

GENERAL PHYSIOGRAPHY

The area lying between 17°30' Lat. S and 26°30' Lat. S, roughly that part of northern Chile between the towns of Arica and Taltal, is known locally as the Norte Grande and constitutes the heart of the Atacama Desert (Fig. 1). The region is divisible into three longitudinal (NS) physiographic provinces which, from west to east, are the Cordillera de la Costa, the Pampa del Tamarugal and the Andean block.

The Cordillera de la Costa is a subdued, block faulted mountain range which rises to more than

3,000 m a.s.l., although its summits usually lie about 2,000 m a.s.l. The western boundary of the range is an abrupt cliff which falls either to a terraced littoral selvedge or, more rarely, directly to the sea. The eastern boundary of the coastal mountains interfingers with the alluvial surface of the Pampa del Tamarugal which is a depositional basin lying topographically lower in its western tracts than the Cordillera de la Costa. The Pampa in the northern part of the region is a single unit which rises eastward from its boundary with the coastal mountains up into the Andean flanks. In



the south, however, the Pampa is a composite unit consisting of small, interconnected basins lying between longitudinal sierras. The Pampa and the Andes meet in the Precordillera, a loosely-defined transition zone at between 2.000-3.000 m a.s.l. The Andes proper rise above this level, with erosional and volcanic summits lying at between 4.000 and nearly 7.000 m a.s.l. East of the main western cordillera of the Andes lies the Altiplano plateau.

The geology of northern Chile has been broadly outlined in the works of Brügger (1950); Zeil (1964); Muñoz (1956); Ruiz *et al.* (1965), and Cecioni (1970). In addition, the Instituto de Investigaciones Geológicas has published regional geological maps. As a preamble to the development of the regional drainage however, the Cenozoic events have been recently examined by Rutland (1971) and Mortimer *et al.* (1974).

The central Andes began to form in the Cretaceous with uplift of the Mesozoic sediments and volcanic rocks which had been deposited peripheral to the western margin of the South American continent. A proto-Andean divide was established some distance west of the present Western Cordillera, during the late Cretaceous and the Paleogene, the erosion of the original mountain mass produced vast thicknesses of molasse sediments in that area now occupied by the Altiplano. The ultimate result of this erosion was the development of a Lower Tertiary regional erosion surface which is still locally preserved in the Cordillera de la Costa, and as the sub-alluvial floor of the Pampa del Tamarugal.

At the end of the Paleogene the regional planation surface was faulted to from the basis of the present topography. The Cordillera de la Costa was uplifted relative to the Pampa del Tamarugal, and block faulting formed enclosed basins within the coastal mountains. During the Lower Miocene the Pampa del Tamarugal began to fill with sediment derived from the uplifting Andean region to the east, and volcanic eruptions, which commenced at this time and continued until the present, covered the Andean area with rhyodacitic flows. These flows and intercalated sediments were deposited over eastward dipping reverse faults developed during the Andean uplift. Consequently the superficial deposits were periodically warped throughout the Neogene by movement along these structures.

The main phase of aggradation of the Pampa area and the Andean flanks ceased at the close of the Middle Miocene. Andesitic volcanism dominated the geological events of the Andean region during the Late Neogene.

In the coastal region the immediate littoral area subsided during the Pliocene and subsidence probably occurred throughout the Tertiary. This subsidence allowed marine abrasion to truncate the Cordillera de la Costa and to develop the high cliff. Slight positive movements have since produced the terraced selvedge of northern Chile.

Other changes within the Atacama Desert during the Upper Miocene and Plio-Pleistocene have directly involved the evolution of the present drainage characteristics, and these events form the subject of this paper.

In studying the channel and basin forms it has been possible to take morphological information from the 1:100.000 maps published by the Instituto Geográfico Militar, although a complete map coverage was not available, particularly east of 69°00' Long. W. Aerial photographs of a scale not less than 1:60.000 were, however, available for the whole region, and some of these are reproduced as illustrations.

CLIMATIC SETTING

Parts of northern Chile are very probably the driest places on earth, although reliable long-term precipitation records have not been kept. Rainfall measurements over a period of 35 years in Arica revealed an annual average of 0,6 mm (Alemyda, 1949); Fuenzalida (1966) reports an annual average for the same town as 1,1 mm over the 20 years up to 1960. Rainfall increases with distance south and with altitude. Taltal, situated on the coast at 25°25' Lat. S, has suffered a 20 year average of 25,1 mm p.a. (Fuenzalida, 1966), whereas Almeyda (1949), revealed a short 10 year average annual precipitation of 273 mm at General Lagos in the Andes east of Arica.

The extreme aridity means that plant growth is virtually absent away from the river valleys and below about 3.000 m. Precipitation in the Andes is comparatively high, but the cold climate and the elevation ensure that the vegetation is stunted. The coastal fog or "camanchaca", which is the result of a strong coastal air temperature inver-

sion caused by upwelling cold water on the east of the northward-flowing Humboldt Current, permits some vegetation to survive on the western edge of the coastal mountains. The lack of rainfall also means that almost all the drainage chan-

nels in the most arid, western part of the Atacama Desert have an ephemeral flow. When they carry water, as they do every few years, the water is exotically derived from exceptionally heavy precipitation in the high Andes.

DRAINAGE DEVELOPMENT

MAJOR TRANSVERSE VALLEYS WHICH REACH THE SEA FROM A SOURCE IN THE CORDILLERA OR PRECORDILLERA.

Channels of this type are "quebradas" which are spectacularly incised transversely across the longitudinal topographic elements. All but one of these watercourses cross the Cordillera de la Costa north of Pisagua (about 18°20' to 19°35' Lat. S). The southernmost and longest channel of this type is the Río Loa, whose mouth lies at 21°25' Lat. S. The valleys are all incised into the Tertiary volcanic and sedimentary rocks which mantle the Andean flanks and fill the Pampa del Tamarugal. The basal member of this fill, only seen in the Arica region, is an Upper Paleogene-Lower Neogene conglomeratic sequence, the Azapa Formation (Salas *et al.*, 1966). This is overlain by intercalated continental sediments and ignimbrite flows of the Oxaya Formation (Salas *et al.* 1966). Further south, at about the latitude of Iquique, the lateral equivalent of the Oxaya Formation is the Altos de Pica Formation (Galli and Dingman, 1962). The uppermost member of the sequence is a gravel deposit which forms the depositional surface of much of the Pampa del Tamarugal. This widespread deposit is named in the immediate Arica region as the Diablo Formation (Tobar *et al.*, 1968). Along the extreme western edge of the Pampa the Diablo Formation, and its lateral equivalents are often overlain by or interfinger with muds, diatomaceous earths and saline deposits, all resulting from a ponding effect created by the barrier of the Cordillera de la Costa. The upper conglomerates of the Pampa are locally replaced in the Andean region by a sequence of sediments and ignimbrites which overlies disconformably the Oxaya or Altos de Pica Formations, and is known in the Arica region as the Huaylas Formation (Salas *et al.*, 1966).

The age of the Tertiary succession is locally

known with some precision. Lower Miocene radiometric ages have been obtained from the Oxaya Formation and its lateral equivalents (Salas *et al.*, 1966; Mortimer *et al.*, 1974), whereas Mortimer *et al.* have shown that the uppermost conglomeratic members of the Pampa del Tamarugal were deposited prior to the early Upper Miocene, probably in the Middle Miocene. The conglomerates of the Diablo Formation, its lateral equivalents on the surface of the Pampa del Tamarugal, and the sediments in the underlying successions were deposited as piedmont gravels at the foot of the eroding Andes. All the deep canyons incised into the Pampa or the Andean slopes must therefore have been established after the early Upper Miocene when sheet depositional conditions changed to those of channel incision.

The reasons for the initial establishment of the channels are not clear. Throughout the Lower and Middle Miocene the Pampa del Tamarugal was characterized by sheet deposition of coarse clastic sediments, this situation changed sometime after about 9 m.y. ago (Mortimer *et al.*, 1974), and channel formation began. The two possible causes of this fundamental change are a climatic change, a tectonic upheaval, or both.

Tectonic steepening of the regional slope of the Andean flanks took place throughout the Neogene, and a critical inclination favouring channel development may well have eventually been achieved.

There is, however, some evidence to suggest that the tectonic influences were not paramount. During the sheet deposition phase there was monoclonal warping of the superficial sediments lying above fundamental bedrock structures. Such warping produced considerable local deformation of the eastern slopes of the Pampa del Tamarugal. However, although the local steepening of gradient was very marked, several hundred meters of relief being generated in places, no channel de-

velopment took place. Instead, succeeding sheet deposition tended to level-off the irregularity in the smooth depositional surface of the Pampa. Therefore progressive steepening of the Andean front was only a contributory factor to the initiation of channel formation.

There was very probably a climatic change which altered the erosional and depositional balance of the area. Although arid conditions are known to have existed in northern Chile throughout much of the Cenozoic (Brüggen, 1950; Mortimer *et al.*, 1974) it would be difficult to envisage a more intensely arid climate than the one which presently exists, and the deposition of sheets of coarse debris must have required more rainfall than is provided by the present climate. The desiccation in the climatic regime may have been temporarily reversed during the glacial phases of the Pleistocene, when the snowline in the Andes was lower (Hollingworth and Guest, 1967; Damuth and Fairbridge, 1970), and mudflows, probably consequent on seasonal snowmelt, were transported via the "quebradas" to be deposited on the western edge of the Pampa del Tamarugal. Once established, the "quebradas" would tend to be self-perpetuating, and return to the earlier sheet deposition would not occur in spite of reversal in the trend of climatic change.

The channel development was further inspired by a number of subsequent events reflected in the form and environment of each river channel. The differences between the channels are significant, and the channels are discussed in subgroups below.

The "quebradas" Lluta, Azapa and Higuera.

The watercourses of this subgroup reach the sea immediately north of Arica, where the Cordillera de la Costa is not present. Unlike the other channels with which they are classified, the Lluta, Azapa and Higuera valleys reach the sea without negotiating a coastal barrier (Fig. 1).

The headwaters of the Lluta and Azapa are found within the high Andean area, whereas the Higuera heads high on the western Andean flanks. The profiles of the "quebradas" Azapa and Higuera are shown in figure 2. Topographic data were not available to allow a profile of the Río Lluta valley to be constructed, but field observations confirm that the valley form is essentially similar

to that of the channel of the Río Azapa.

Although the profile for the Quebrada Azapa is incomplete (Fig. 2), the thalweg in the lower and middle courses is smooth and gently concave. The river is incised about 200 m into the depositional surface of the Pampa near the coast, and the incision increases upstream to an observed 1.500 m some 70 km inland, although the canyon depth reaches approximately 200 m in crossing the Sierra de Huailillas axis. Further upstream, in the high Andes, the canyon depth decreases towards the headstreams. The canyon sides in this valley, as in most channels of this type are normally inclined at over 45°, and are commonly vertical where the lithology of the canyon walls is favourable.

The Higuera canyon is, like that of the Azapa, incised about 200 m into the Pampa del Tamarugal surface near to the coast (Fig. 2). The dissection upstream, however does not exceed 400 m, and about 50 km from the coast the valley incision begins to decrease. The valley floor is barely incised 75 km from the coast, although dissection increases upstream of here towards the source in the Pampa de Oxaya. The lower and middle parts of the thalweg profile of the Quebrada Higuera are gently concave (upwards), but upstream of 75 km from the coast the valley floor steepens in gradient, and the profile in the upper valley is gently convex.

The essential difference between the channel form of the Quebrada Azapa (and Lluta) and that of the Quebrada Higuera, is considered to have resulted because the former channel crosses the Sierra de Huailillas-Pampa de Oxaya ridge, taps water sources in the high Andes and has achieved a much longer profile. The Quebrada Higuera by contrast, is restricted to the Andean flanks.

It is considered that development of all three channels in this subgroup followed cessation of the sheet deposition. They were established as Andean flank streams consequent upon the regional slope and, since the barrier of the Cordillera de la Costa is not present immediately north of Arica, their mouths were crowded towards the available marine baselevel. Their flow was, and is, like all the other north Chilean rivers, almost exclusively exotic to the desert environment of the western and central parts of the country, being derived from rainfall and snowmelt in the uppermost courses.

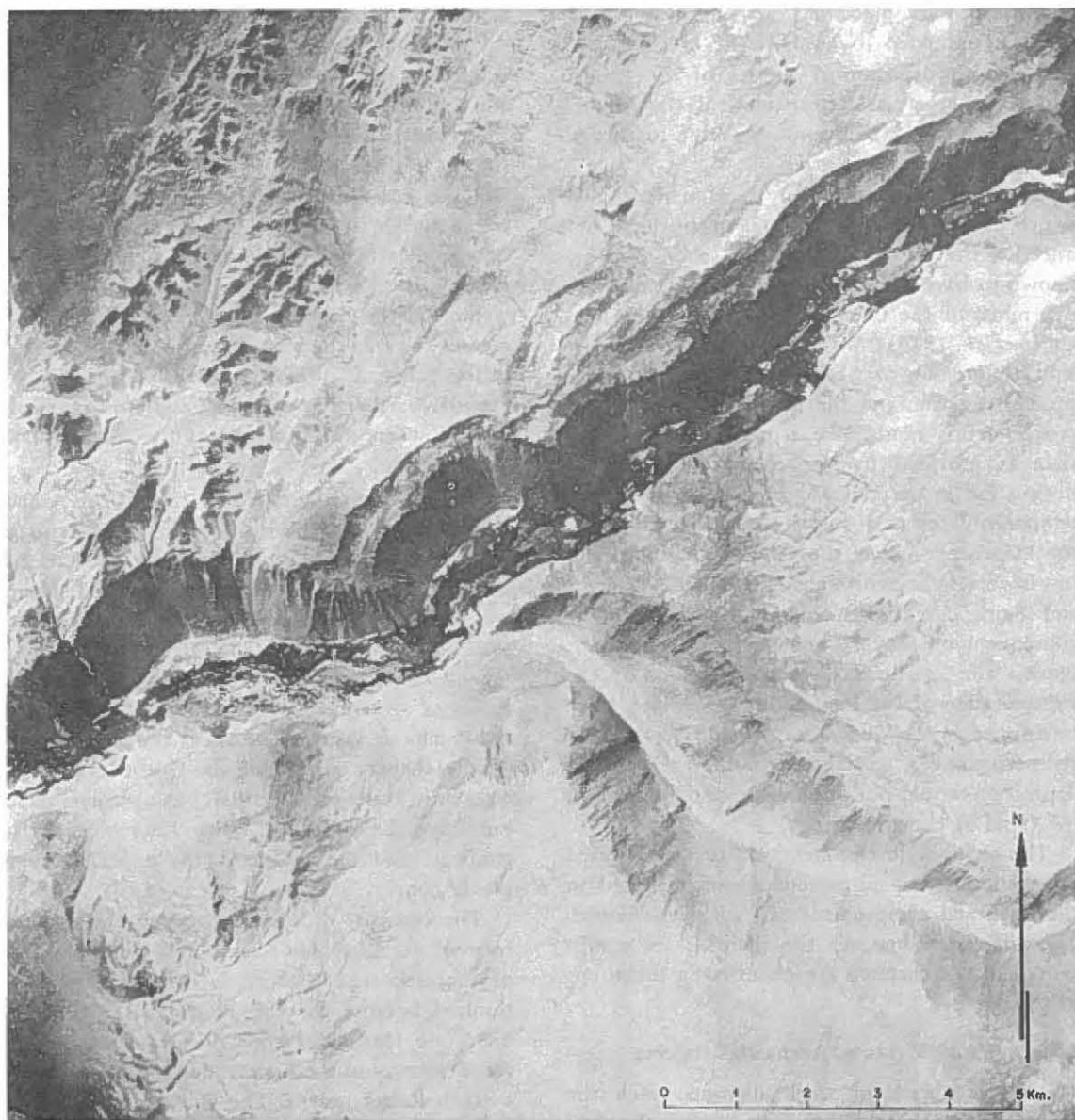
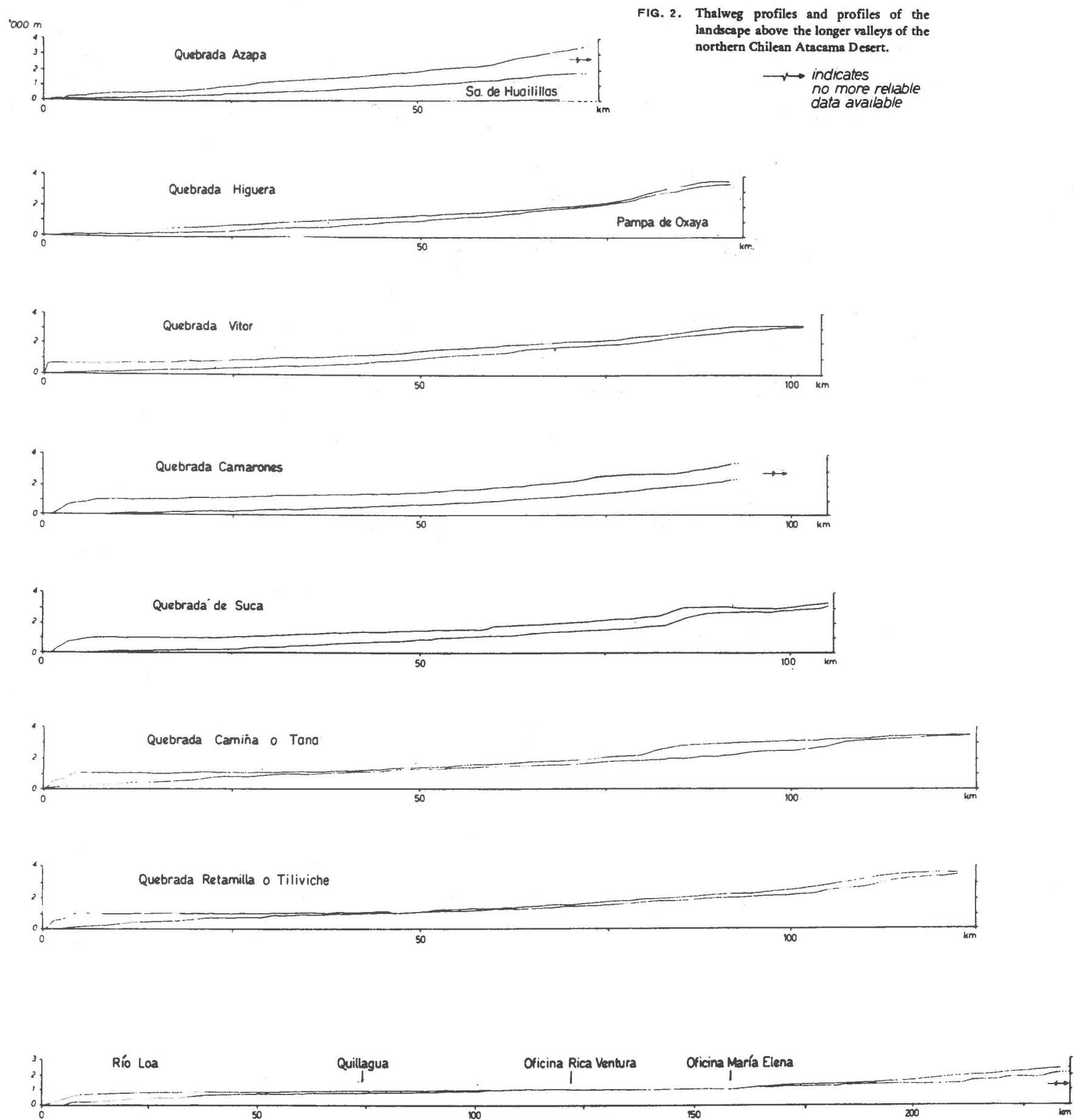


PLATE 1. Convergence of the quebradas Camarones and Suca at Cuya, showing the deep, steep-sided valleys incised into the surrounding subdued topography of the Pampa del Tamarugal and the eastern edge of the Cordillera de la Costa. (Hycon 26357).

Steep canyon sides were therefore developed and tributary formation was inhibited. Erosion at the heads of the canyons eventually enabled the "quebradas" Lluta and Azapa to breach the Sierra de Huailillas-Pampa de Oxaya divide, and to considerably lengthen their profiles, and augment their flow through the capture of drainage in the high Andean plateau. This capture may well have been

assisted by overspill westwards of the drainage of the Tignamar basin, which was infilling with sediment during the late Tertiary. The Andean plateau drainage had already been captured prior to deposition of the uppermost part of the Huaylas Formation, since this formation infills valleys cut through the Sierra de Huailillas-Pampa de Oxaya divide, implying a minimum Pliocene age for the initiation of capture.



The Sierra de Huailillas-Pampa de Oxaya divide was further tectonically emphasized after the river capture, and the ríos Lluta and Azapa were able to maintain their channels antecedently to the positive movements, their canyons being correspondingly deepened to their present spectacular depths. Water from the upper, captured high Andean, parts of their courses ensured that any irregularities in the river profiles was rapidly eradicated. The capture created a new baselevel for the Andean plateau drainage, and powerful headward erosion, initiated along the Río Tignamar and the new upper reaches of the Río Lluta, is still actively proceeding (Pl. 2).

The Quebrada Higuera never extended eastward of the stratovolcanic complex surmounting the Pampa de Oxaya divide, consequently its flow remained ephemeral and insufficient to allow rapid elimination of profile irregularities. The concavity of the uppermost part of the thalweg is very probably tectonically induced, reflecting late Tertiary positive pulses which affected the Pampa de Oxaya ridge (Salas *et al.*, 1966).

The "quebradas" Vitor, Garza, Camarones and Suca.

The "quebradas" of this subgroup differ from those previously described in having their lower courses incised in the Cordillera de la Costa. The Quebrada Vitor is joined on the right flank of its lower reaches by the Quebrada Garza. The profiles of the two channels are similar, and that of the Quebrada Vitor is reproduced in figure 2. Maximum canyon depth of about 650 m in these two "quebradas", occurs in their shared lower course immediately east of the coast. The same order of incision into the surrounding topography is maintained in both valleys as far upstream as their upper reaches, which lie in the Precordilleran region. The profiles are smoothly concave in their lower and middle courses, but some minor irregularities are apparent in the uppermost parts of the valleys.

The "quebradas" Camarones and Suca also have a shared near-shore canyon, incised about 1,000 m into the coastal mountains and the Pampa del Tamarugal (Pl. 1, Fig. 2). Upstream in the Quebrada Camarones, the thalweg profile remains smoothly concave and the amount of incision increases very slightly upstream. Reliable data

in the east are not available, but the headwaters of these "quebradas" are in the Altiplano. The thalweg profiles of the Quebrada de Suca, though smoothly concave in its lower course, becomes more irregular in its upper portion. In the Quebrada de Suca, the amount of incision into the surrounding topography drops from 1,000 m near the coast to about 500 m some 60 km inland. Further east it increases in depth locally before shallowing towards the uppermost part of the channel on the Andean flanks.

In this area the Cordillera de la Costa acted as a barrier to drainage from the east during the Neogene, as a result, the sedimentary fill of the Pampa del Tamarugal was deposited along the eastern edge of the coastal mountains. As the level of the sediment rose, the western extension of the Pampa slowly encroached on the Cordillera de la Costa. At the same time, coastal subsidence led to truncation of the Cordillera de la Costa by marine abrasion (Mortimer, 1973; Mortimer and Saric, 1972) and a high cliff was formed. Eventually, the sediment accumulation overtopped the coastal mountains and reached the cliff. Water draining from the east had previously found baselevel in the Pampa del Tamarugal, but following the overspill to the west there was a rapid downcutting towards the newly-acquired marine baselevel, and the lower courses of this subgroup of channels were established. Channels on the cordillera flanks, established following the change in regime from sheet deposition to drainage incision, became rapidly connected to the new channels across the Cordillera de la Costa, and the river profile ultimately became adjusted to the new situation. The thalweg profiles of the "quebradas" differ. Most distinctive is the Quebrada Camarones, in which a deep incision is maintained well into the Andean range. This is the only channel in this subgroup to head in the Altiplano region. The longer profile was probably achieved through capture of Andean drainage by headward erosion, in the same manner that the "quebradas" Lluta and Azapa were lengthened. The resulting increased flow and longer profile permitted this "quebrada" to deepen more than similar channels heading in the Andean flanks. In the upper part of the Quebrada de Suca there is a strong convexity which is also reflected as a flexure in the topography above the river. The monoclin flexure

of the Tertiary succession, also apparently deformed the long profile of the "quebrada".

The "quebradas" Camiña and Retamilla

The "quebradas" Camiña (or Tana) and Retamilla branch from the Quebrada Tiliviche inland from Pisagua (Fig. 1); they are considered to have established their shared Quebrada Tiliviche section by overspill of drainage from the Pampa del Tamarugal in the same manner as the subgroup of channels immediately to the north. Both "quebradas" show convex, irregular lower profiles (Fig. 2). Some 750 m of incision near the coast gives way upstream to virtual convergence with the depositional surface of the Pampa del Tamarugal some 40 km inland. Further upstream the Pampa surface and the thalweg profiles diverge, and are humped at the top of the Andean flank slopes. This is particularly noticeable in the Quebrada Camiña (or Tana). Although both channels head in the Altiplano, neither shows the same degree of dissection as seen in the "quebradas" Lluta, Azapa or Camarones.

It is considered that the "quebradas" Camiña and Retamilla demonstrate an earlier stage in the establishment of a marine baselevel than is seen in valleys further north. The convex upwards lower profile suggests either that overspill of the Pampa drainage across the Cordillera de la Costa is relatively recent or that insufficient flow in the quebrada systems has inhibited the thalweg profiles from achieving equilibrium with the marine baselevel. The virtual coincidence of the Pampa del Tamarugal depositional surface with the "quebrada" bottoms just inland from the Cordillera de la Costa shows that the Pampa at this level has only just ceased to be the base to which the upper parts of the river profiles were adjusted. The upper courses of the "quebradas" Camiña and Retamilla are interpreted as post-deposition of sheet gravel and until their linkage to the sea by the gorge across the coastal mountains, they reached baselevel in the Pampa del Tamarugal. They were able to erode eastwards and capture some of the channels in the high Andes, but since the effects of the new marine baselevel have not yet been transmitted upstream, the canyon incision into the Andean flanks is much less than in other "quebradas" which have similar capture characteristics.

The humping of the topography above the uppermost part of the canyon profiles is considered to be caused by similar tectonic activity to that observed near the source of the Quebrada de Suca, and the distortion of the thalweg profiles in the upper reaches of both the Retamilla and Camiña canyons is probably attributable to the same cause. The knick point in the Quebrada Camiña thalweg profile is however, some distance east of the tectonic dislocation of the Pampa surface, and it is tempting to suggest that the knick point has migrated upstream of its original position.

The Río Loa

The Río Loa, some 400 km in length, follows a tortuous route flowing south to Calama then west down the upper slopes of the Pampa del Tamarugal, north to Quillagua, and finally west again in a gorge cut across the Cordillera de la Costa (Fig. 1).

The deepest incision of the river into the surrounding topography is about 700 m in the immediate coastal area (Fig. 2). Further upstream the depth of the canyon decreases. Upstream of Quillagua the depth of the canyon is never more than about 250 m and generally much less. It was not possible to make a complete profile of the river because of the lack of topographic data east of about 69°00' Long. W.

The available section of the profile demonstrates a convexity in the canyon across the coastal mountains downstream from Quillagua. Further upstream the degree of convexity lessens where the river channel lies on the western border of the Pampa del Tamarugal. Upstream of Oficina María Elena the river flows east-west across the Pampa del Tamarugal, and the profile is gently concave until the eastern border of the Pampa; here a number of humps are encountered in the bed profile of both the Río Loa and its tributary the Río San Salvador. Further east the bed profiles are unknown, but there is at least one more major knick point just downstream from Calama.

Brüggen (1950) noted high terraces and salt deposits in the Quillagua area of the Pampa del Tamarugal, and suggested the former existence of an extensive lake which originally included the area of the present basins of the Salar de Llamara and Salar Grnade. He concluded that the canyon of the Río Loa across the Cordillera de la Costa

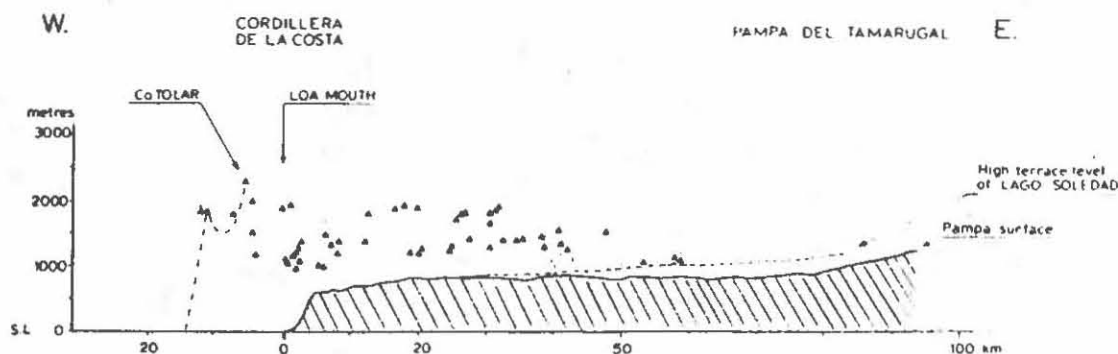


FIG. 3. (Δ = summit heights north and south of Loa mouth). Summit levels in the Cordillera de la Costa adjacent to the mouth of the Río Loa, compared with the former level of the Lago Soledad. The coastal cliff in this region reaches to near 2,000 m a.s.l. below Cerro Tolar south of the river.

formed during the Pleistocene, when the Lago Soledad, overfilled with glacial meltwater, spilt over the coastal mountains to the sea and rapidly produced a deep channel.

The former presence of a semi-permanent lake in the Quillagua region is indicated by the limestones and diatomaceous earths which form the upper part of the Pampa sedimentary accumulation termed the Loa Formation (Hollingworth, 1964). However, saline and gypsiferous terraces of the former lake which lie above the Salar de Llamara rise about 250 m from west to east in a distance of approximately 50 km (Fig. 3). Further south, east of the Oficina María Elena, the highest beds of the Loa Formation rise about 250 m in a 30 km east-west transit of the Pampa del Tamarugal. The terraces and the lacustrine sediments are inferred to have been horizontal, and therefore the Pampa del Tamarugal, at least in this region, has undergone tectonic tilting to the west. The summit heights in the Cordillera de la Costa in this region rise markedly towards the coast, and an impressive cliff height of nearly 2,000 m occurs just south of the Río Loa mouth. Prior to the westward tilting, this increase in summit height westward must have been accentuated (Fig. 3). This tilting, which resulted from Neogene subsidence of the coastal region coupled with tectonic relief generation near to the Andean axis, displaced the lake waters towards the sea. As a result, a marine baselevel was achieved, followed rapidly

by the drainage of the Lago Soledad and later development of the nearshore canyon. The convex profile of this part of the Río Loa suggests that, like the lower courses of the "quebradas" Camiña and Retamilla, the channel upstream is still not adjusted to a marine baselevel. Hollingworth (1964) and Rutland (1971) comment on an old mouth of the Río Loa immediately north of the present river mouth. This is herein considered to be a small channel or basin infilled by continental sediment truncated by the cliff recession. Several similar features occur in the cliff-top further north, and all phenomena predate the origin of the Río Loa.

As waters of Lago Soledad were displaced towards the coast they were also displaced westward into the previously empty tectonic basin within the Cordillera de la Costa now occupied by the Salar Grande. The saline terraces of the Quillagua region indicate that the Lago Soledad was saturated with salt, and it is suggested that pure halite deposits in the Salar Grande were formed through complete evaporation of decanted saline solutions, rather than from a continuously evaporating arm of the Lago Soledad as Brüggén (1950) suggested.

At Quillagua the channel of the Río Loa is incised into the surface of the Pampa del Tamarugal by about 100 m. Upstream, however, the incision decreases, and at Oficina María Elena, 75 km further upstream, the river is in virtual coincidence

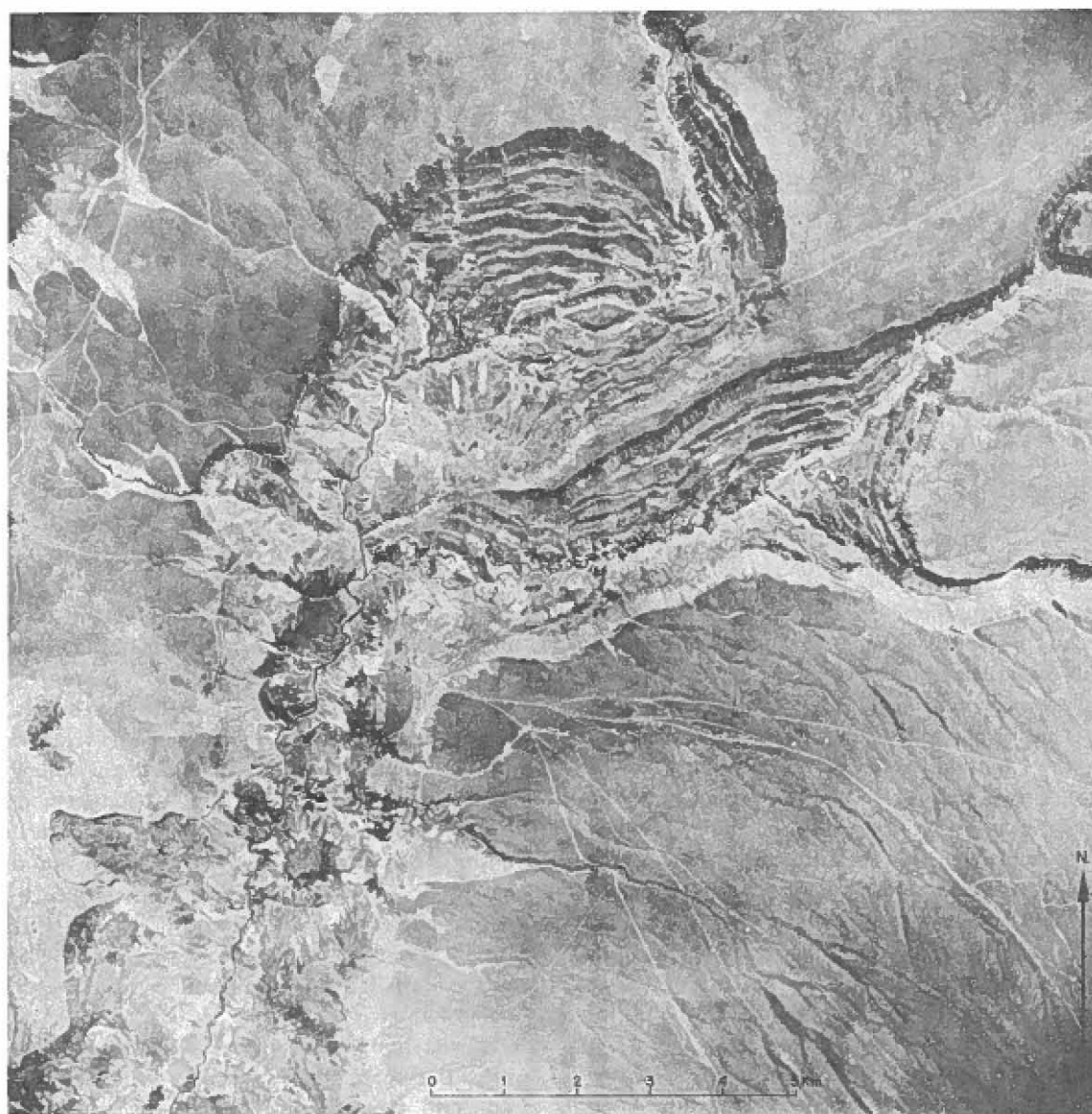


PLATE 2. Present-day headward erosion at General Alcérreca in the upper Río Lluta seen as mass-movement collapse of the valley walls. (Hycon 9129).

with the Pampa surface, where the influence of the marine baselevel has not worked this far upstream.

The development of that part of the Río Loa valley aligned NS along the edge of the Cordillera de la Costa (Pl. 3) resulted from drainage of the old lake. As the lake level fell subsequent water delivered to the basins channelled itself along the junction between the Pampa and the coastal mountains. This was both the lowest part of the Pampa and the region where the water table was closest to the surface.

Upstream of Oficina María Elena the Río Loa descends the Pampean slopes from east to west. The incision of the valley into the Pampean slopes increases with altitude, but does not exceed about 200 m, and the thalweg profile of the channel is very irregular. This pattern is mirrored in the Río San Salvador tributary channel.

The diatomaceous earths and freshwater limestones which form the upper part of the Loa Formation extend from the Quillagua area southwards and eastwards up the eastern slope of the Pampa del Tamarugal into the Calama basin. Dissection

of these sediments is marked, adjacent to the Loa valley on the Pampean slopes. If the lacustrine sediments were deposited nearly horizontally, the 1,500 m of relief between the western Pampa del Tamarugal and the Calama basin must have been largely tectonically generated during the late Neogene. They occupy a wide area of the Calama basin, but are here sub-horizontal, and much less dissected than on the eastern slopes of the Pampa del Tamarugal. Thomas (1967) has mapped the Loa Formation in the Calama basin, and its area of deposition narrows markedly towards the west above the Pampean slope.

It is proposed that the lacustrine sediments of the Loa Formation were originally deposited in a semi-permanent lake which covered the Quillagua region of the Pampa del Tamarugal and locally extended at least as far east as the western edge of the Calama basin. The lake was later tectonically differentiated into two areas, the Pampa and the Calama basins. Thereafter deposition continued independently in each basin. Lacustrine sedimentation may not have occurred in the Calama basin until after its relative uplift.

It is considered that rudimentary overspill drainage from the Calama basin, combined with the consequent drainage on the tectonically created Pampean slopes caused the dissection of the sediments already deposited in this latter region. The two largest channels which were developed became respectively constituent sections of the Río Loa and its tributary, the Río San Salvador. The tectonically produced slope was steepened progressively in the late Neogene, and the irregularities present in the Río Loa thalweg profile between Calama and Oficina María Elena are considered to reflect both the repeated tectonic disturbance in this area, as well as the short time which this section of the river has had to grade its bed.

The Calama basin (2,500 to 3,000 m a.s.l.), drains through a narrow gap to the west via the rivers Loa and San Salvador. Though these rivers cross the basin in steep sided gorges cut through the Loa Formation, they are little incised and can be interpreted as the result of recent re-establishment of a drainage connection towards the west. This would have largely drained the lake in which the upper beds of the Loa Formation accumulated.

Water flowing eastward, in many streams from the line of volcanic cones lying NE of the Calama

basin, encountered the structural block of the Sierra de Moreno and was diverted south along the direction of the regional slope. This formed the largest single source of surface water entering the basin, and it must have soon connected with the incising streams draining the Calama basin towards the west, thereby becoming established as the upper course of the Río Loa. The Calama basin however, remains locally a region of internal drainage, being fed by many small streams descending from the Andes.

The Río Loa is hence considered to be a heterogeneous channel which has resulted from the union of several independently originated sections.

VALLEYS WHICH HEAD IN THE CORDILLERA OR PRECORDILLERA AND TERMINATE IN THE LONGITUDINAL DEPRESSION.

There are a great many channels which head in the Altiplano or Andean flanks and terminate on the surface of the Pampa del Tamarugal at altitudes around 1,000 m a.s.l. Such canyons lie between and parallel to the major cross-cutting watercourses, and they are similarly deeply incised into the surrounding topography. Profiles were made of the "quebradas" Aroma, Tarapacá, Chacarilla and Guatacondo (Fig. 4), and these watercourses can be taken as examples typical of the many other similar flank streams. All of the specimen "quebradas" head on or near the Altiplano, and descend to the Pampa del Tamarugal in profiles characterized by a smooth, gentle concavity in the lower and middle course. The upper courses are more irregular, and there is a levelling of the long profile towards the headwaters to produce a marked convexity. The western and central tracts of the Pampa del Tamarugal are continuous with the bed profiles of the quebradas, and the streams are still aggrading the western areas of parts of the Pampa del Tamarugal whilst being the principal source of groundwater within it. Upstream the depositional surface of the Pampa becomes a high terrace and the "quebradas" become more incised into it with altitude, up to a maximum canyon depth of about 1,000 m. The amount of dissection decreases east of the Altiplano border as the plateau maintains an approximate horizontality whereas the river profile continues to rise.

These canyons are considered to have initiated after the cessation of sheet deposition in the Pam-

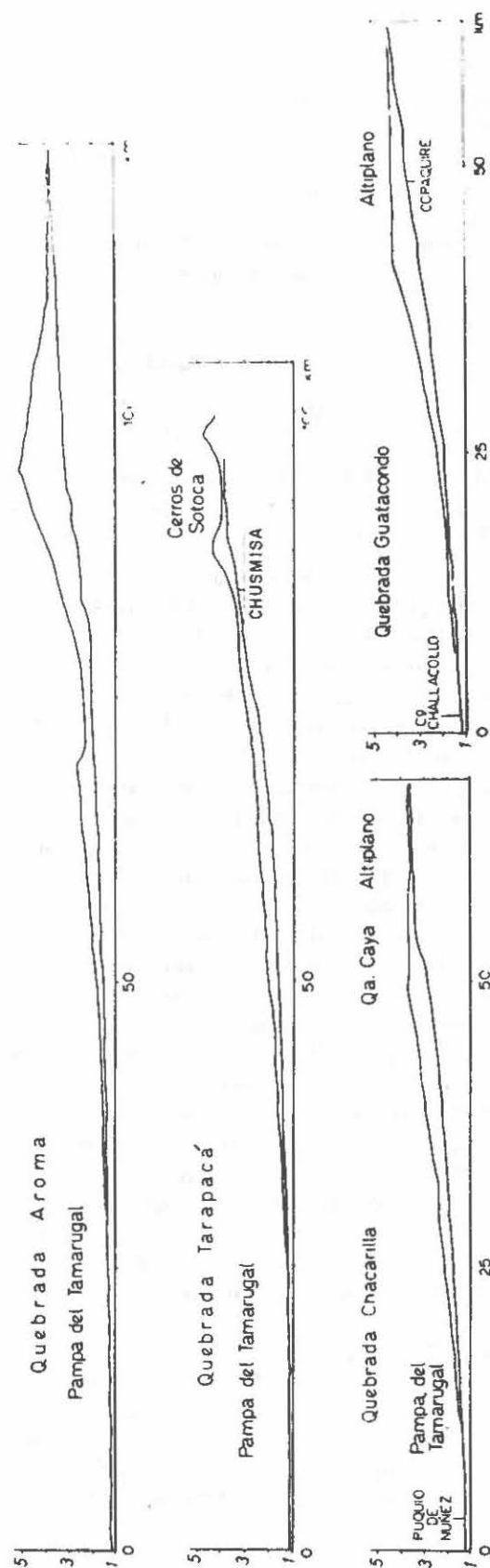


FIG. 4. Thalweg profiles of the quebradas debouching onto the Pampa del Tamarugal, together with profiles of the landscape above the present valleys.

pa del Tamarugal at the same time, and in the same manner, as the higher sections of the major traverse valleys, by a combination of climatic change and tectonic relief generation in, or after the Upper Miocene. They differ from the upper sections of the traverse valleys only in not having been connected to a marine baselevel and consequently have been downcut less than, for example, the Azapa canyon. The "quebradas" Camiña and Retamilla discussed earlier, having only lately made a marine connection, have retained upper bed profiles which were developed in relation to a Pampean baselevel and which are therefore equivalent to the profiles of the watercourses discussed in this section.

The smooth concave profiles of the lower courses of the "quebradas" of this group indicate that the channel form has here been stabilized. Headward erosion resulting in the capture of some of the Altiplano drainage, combined with the tectonic instability of the Andean front, has created some irregularities in the upper bed profiles. Headward erosion and river capture within the specimen channels is especially noticeable in the higher parts of the Quebrada Chacarilla where a small Altiplano drainage basin has been tapped. The flattening of the upper bed profile (Fig. 4) reflects this headward lengthening of the channel. Tectonically induced irregularities are possibly best represented in the bed profile of the Quebrada Aroma (Fig. 4). The sharp jump in the profile, some 80 km from the "quebradas" mouth, probably resulted from movement along one of the eastward dipping reverse faults which affect this area.

THE SHALLOW VALLEYS OF THE SOUTHERN REGION.

South of about Antofagasta the topography between the coast and the Precordillera is composed of undulating alluviated plains above which rise the smoothly pedimented flanks of "sierras" and isolated mountains. Drainage lines away from the coast occur as washes in the floors of the interconnected basins. The channels are not normally

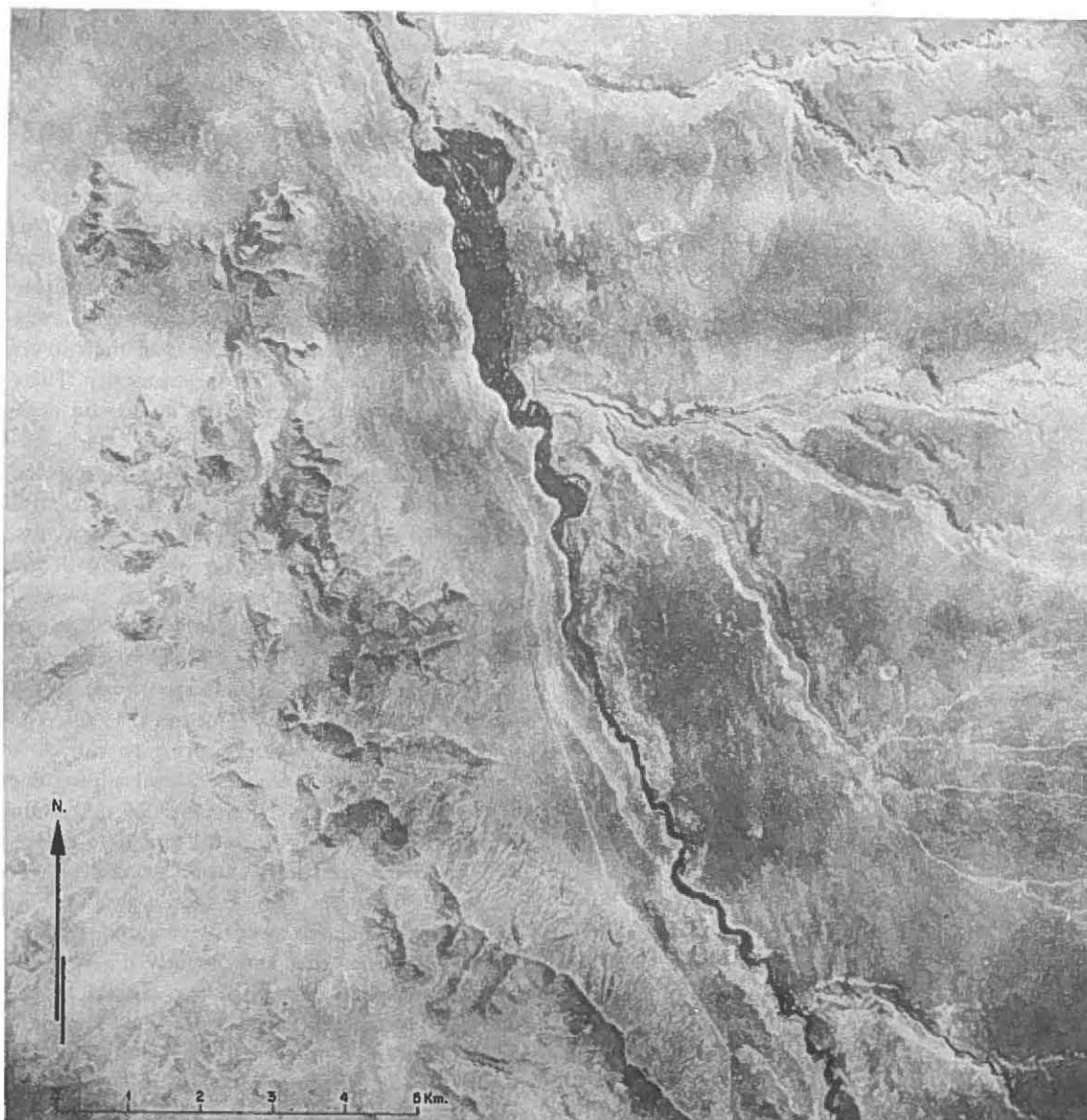


PLATE 3. Approximately NS section of the Río Loa valley along the east edge of the Cordillera de la Costa at Quilagua. The river transverses diatomaceous earths and limestones of the Loa Formation. (Hycon 6552).

incised and act as local baselevels to the alluviated pediments which form part of a regional pediplain (Pl. 4). Only locally, in the watercourses in the Cordilleran flanks, is there any evidence of canyon development and it is slight when compared with the deep channels further to the north.

South of Antofagasta the Cordillera de la Costa acts as a barrier to easterly-derived sediment, and the ephemeral streams descending the Andean flanks in shallow washes are directed northward towards large areas of saline accumulations in the Aguas Blancas area. South of about Paposo how-

ever, a number of long channels which are oriented approximately WSW drain from the coast to the Precordillera. The profiles style of those streamcourses which reach only as far as the central depression is identical to that found in the upper courses of the channels of this group which connect to the coast. The channels reaching the coast have equatable long profiles and those sections of the long profiles in the "quebradas" Tal-tal and Cachina (Fig. 5) are representative of the watercourse of this southern region.

As can be seen from the profile of the upper

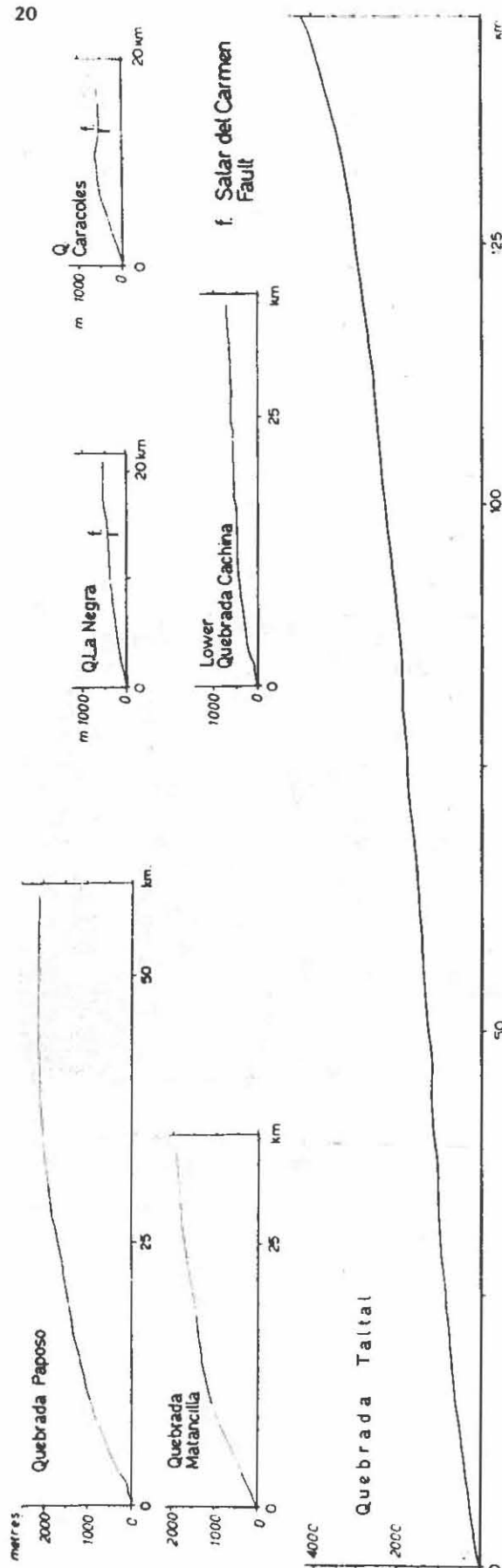


FIG. 5. Thalweg profiles of both long and short quebradas near to and south of Antofagasta.

Quebrada Taltal (Fig. 5) the watercourses descending the Andean flanks do so with a smooth concavity which achieves a minimum gradient of about 8 m/km in the Pampa del Tamarugal. This is a very low gradient for Andean flank streams. Channels which connect with the coast have profiles which steepen markedly westwards away from the longitudinal depression and their lower profiles are marked by a strong convexity. There is some channel incision in the immediate near-shore region.

It is clear from the lack of incision and from the wide valleys of the watercourses in the central and eastern parts of the country, that the hydrological system has achieved equilibrium with the landscape. The regional pediplain (Pl. 4) which dominates the landscape, and to which the graded channels act as baselevel, is a northern extension of the Atacama Pediplain first recognized in the area around 27°00' Lat. S (Mortimer, 1973). The Atacama Pediplain developed prior to the close of the Middle Miocene as a regional adjustment to a marine baselevel. The channels of this group are therefore probably ancient, and have undergone little modification, except in their lower courses, during the past few million years.

The longer channels must have maintained their contact with the coast antecedently during positive structural movements of the coastal mountains relative to the central depression. The manner in which the profiles steepen and the wide valleys become canyons towards the coast indicates that the present marine baselevel does not determine valley style very far inland.

Although the coastal terraces provide indisputable evidence that slight relative uplift of the coast has recently taken place (Pl. 5), the existence of the high cliff testifies that the previous predominant coastal movement was subsidence which permitted considerable cliff recession (Mortimer, 1973; Mortimer and Saric, 1972). The early hypothesis that the cliff is a direct fault scarp (Brüggen, 1950) cannot be substantiated. It is concluded therefore, that the long drainage channels originally graded towards a baselevel some distance to the west of the present shoreline and the change in effective baselevel of the river system has not yet been transmitted far inland.



PLATE 4. The Quebrada Taltal, hardly incised into the pediment cover alluvium lying on the Atacama Pediplain. (Hycon 8205).

DRAINAGE CHANNELS RESTRICTED TO THE NEAR-COAST AREA.

North of about Tocopilla the cliff edge is occasionally notched by hanging channels which extend a few kilometers into the Cordillera de la Costa. South of Tocopilla the frequency of such channels increases and their mouths debouch near to sea level. Where they cross a littoral area of marine terraces these stream channels are often developed across piedmont fans. Further south channel length increases, though the profiles of all the

channels remain steep, and most of them exhibit the convex profile characteristic of the westernmost sections of north Chilean rivers. Example profiles of such short channels as the "quebradas" Paposo and Matancilla can be seen in figure 5, plate 5. The channels are the initial expression of incipient erosion of the Cordillera de la Costa towards a marine baselevel. Coastal recession must previously have inhibited their formation whereas recent coastal uplift has allowed subaerial degradation processes to have an effect on the continental margin. The channels must receive their

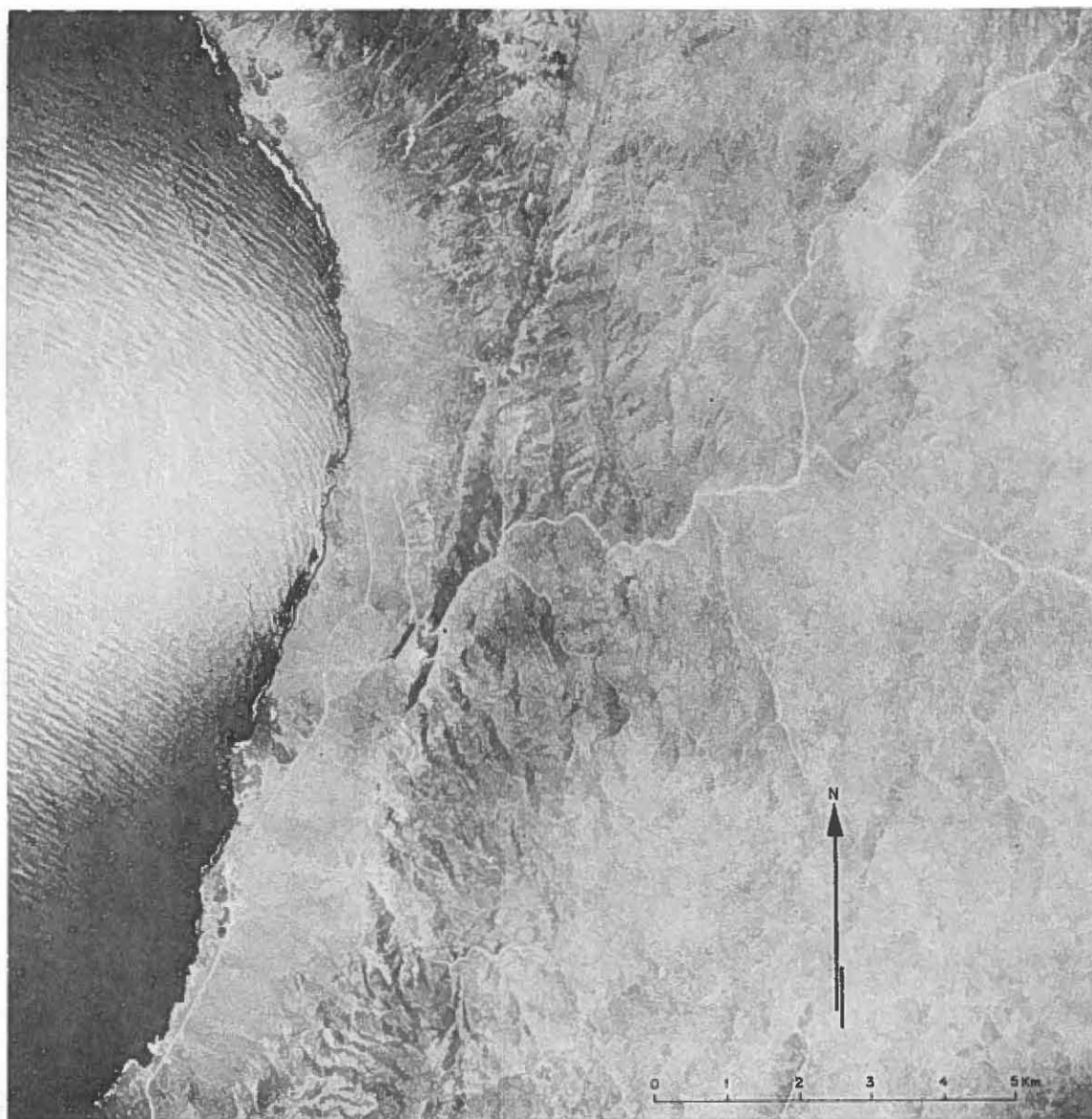


PLATE 5. The coastal terraces and abandoned cliff at Paposo. The Quebrada Paposo (Fig. 5) is followed by the southwestern branch of the road. The strong approximately north-south lineation in the north of the photograph is the trace of a part of the Atacama Fault. (Hycon 24421).

water from rare coastal showers since the number and depth of the valleys increases to the south with rainfall though their ephemeral flow may perhaps be aided by groundwater percolation from inland, and by fog condensation.

Two of the short channels, Quebrada La Negra and Quebrada Caracoles lie inland from Antofagasta and delimit the Sierra del Ancla. The profiles (Fig. 5) illustrate the characteristic convex form,

but the Quebrada Caracoles domes where it crosses the Salar del Carmen (Atacama) Fault. The Quebrada La Negra, lying some 15 km to the south crosses the same fault but has not, apparently, been affected by it. Westerly upthrow on the fault has disturbed the profile of the Quebrada Caracoles, and the internal drainage of the Salar del Carmen region has developed as a result (Pl. 6). The drainage across the fault in the Quebrada

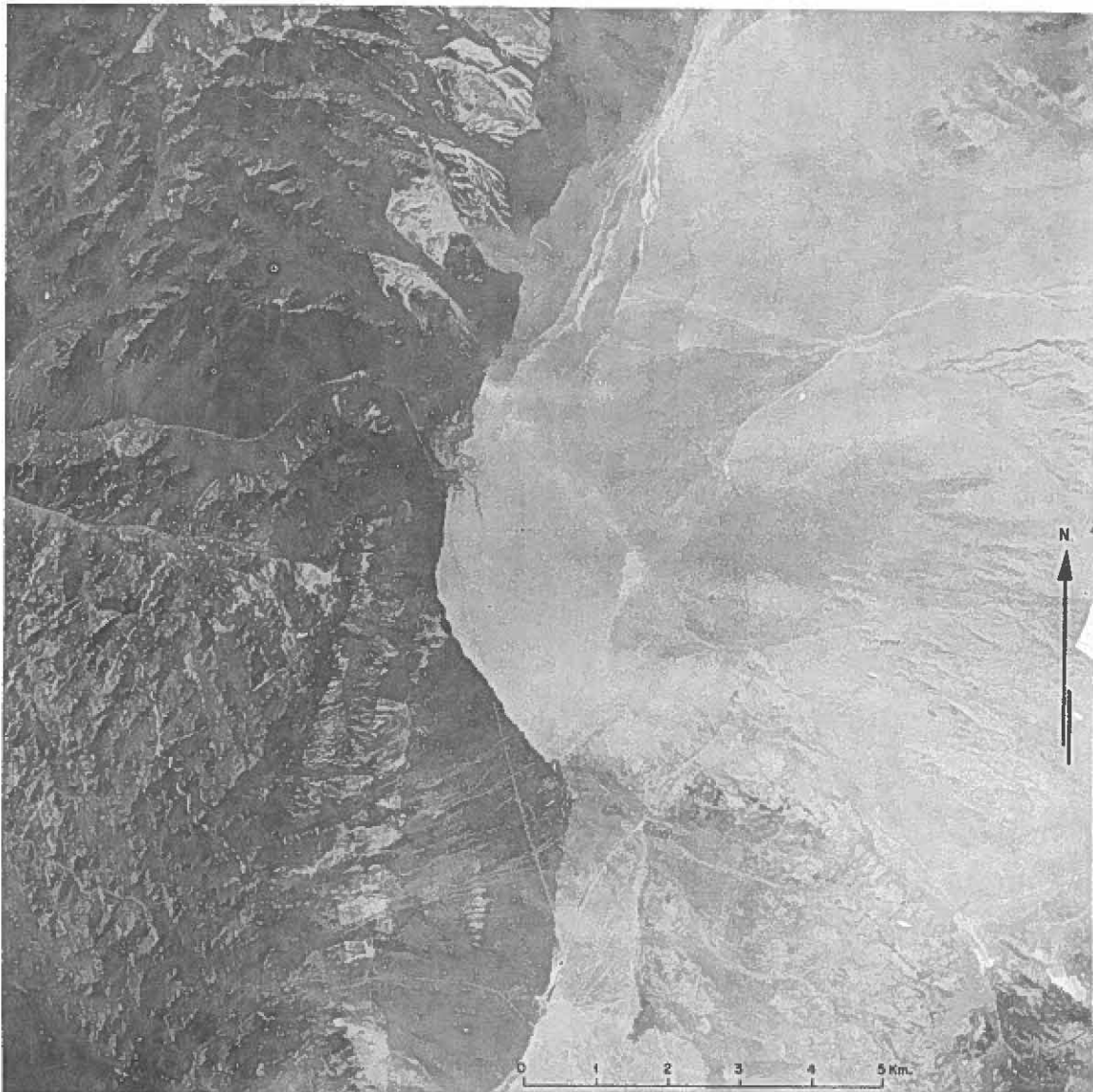


PLATE 6. The Salar del Carmen to the east of the Atacama Fault. The Salar has formed as a result of westerly uplift of the coastal block. The Quebrada Caracoles which once drained the salar area is followed westward by the road. (Hycon 8347).

volcanic and tectonic enclosure of original run-off. The superimposition during and since the Miocene of the andesitic stratovolcanoes has been particularly important in moulding the present form of the enclosed basins in the Andean region. The cones and lava flows have joined and interlocked to produce or modify basins which have subsequently filled with water. The majority of the

La Negra has, however, maintained itself antecedently to the structural changes.

INTERNAL DRAINAGE

Large parts of the northern Atacama Desert are areas of centripetal drainage.

In the Cordilleran and Precordilleran areas, internal drainage basins have originated through the



PLATE 7. The Salar de San Martín (or Carcote) in the high Andes northeast of Antofagasta. The salar has formed following the blocking-off of drainage by lava flows. The rising level of saline deposits has partially submerged a recent cinder cone. The salar is transversed by the Antofagasta-Bolivia railway. (Aeroservice 27-2272).

Lakes thus formed are saline due to evaporation (e.g. Lago Chungara, Salar del Huasco, Salar de San Martín (or Carcote), Salar de Coposa and Salar de Ascotán (Pl. 7). Often, however, the lake position is not entirely a volcanic phenomenon. Many lakes and salt flats are in the Altiplano region east of the structurally controlled front range of the Andes (the Sierra de Huailillas-Pampa de Oxaya-Sierra de Moreno-Cordillera de Domeyko axis) and prior to the construction of the late Neo-

gene volcanic pile, the drainage direction was often originally towards the east and unconnected with the Pacific baselevel. The Altiplano area has, throughout the Tertiary, been a vast area of centripetal accumulation of sediment with shifting loci of standing water. It is this drainage which has been locally tapped by the strong streams eroding headwards on the Andean flanks.

Drainage towards the aggrading internal basins on the Altiplano is by streams occupying channels

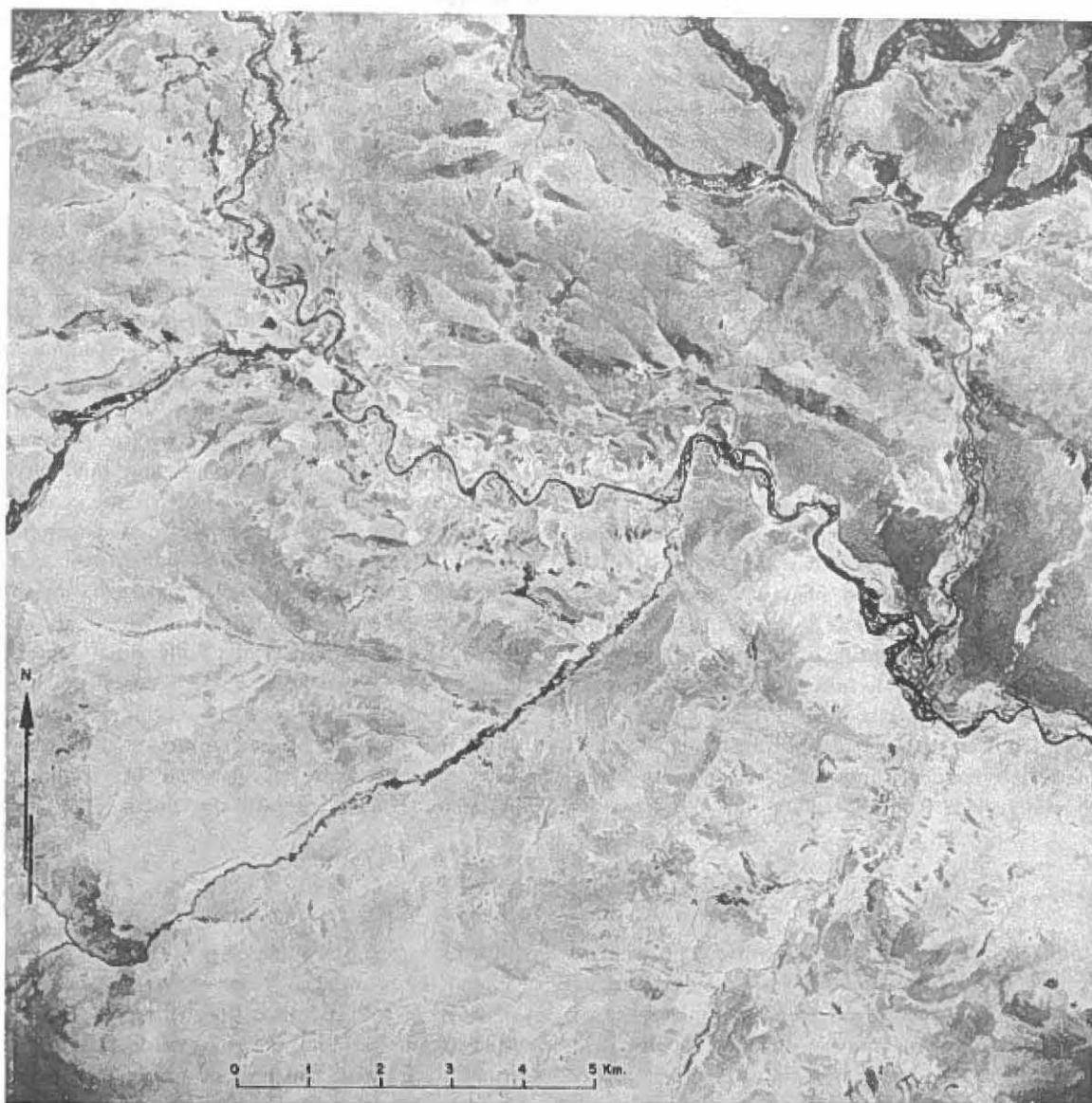


PLATE 8. The mandering Río Lauca flowing south-east in the Altiplano. (Hycon 7296.)

of low gradient and little bed incision, although strong erosion is taking place on volcano flanks. Such streams are normally short, although the ríos Lauca and Cosapilla are notably longer. Much of the Altiplano region east of Arica is drained by the Río Lauca, which flows SE for some 70 km across Chilean territory in a sometimes meandering, sometimes beaded generally shallow channel (Pl. 8). After passing a considerable distance through Bolivia it terminates in the Salar de Coipasa, a small part of which lies in Chile. The Río Cosapilla, which flows northward towards the Río

Desaguadero and ultimately into Lago Poopo is another example of a lengthy stream finding an internal baselevel. Unfortunately there are no topographic data to provide profiles; however, because of the dominantly volcanic aspect of the Chilean Altiplano, the Cordilleran streams are almost certainly very young.

Enclosed drainage basins containing saline deposits which lie west of the Altiplano are tectonically determined. Such basins are typified by the Salar de Atacama and the Salar de Punta Negra (Fig. 1). Centripetal drainage in this region must

have been established with the relative uplift of the Cordillera de Domeyko, and the result was the development of the two largest salt lakes in Chile. These basins collect the run-off from the Andean flanks between 22°30' and 25°00' S, and have probably been doing so since the close of the Paleogene when the structural changes were first effected (Mortimer *et al.*, 1972).

The area of the Pampa del Tamarugal is characterized by drainage which has been ponded since the uplift of the coastal mountains at the Paleogene/Neogene boundary (Mortimer *et al.*, 1974). The Pampa evolved as a huge internal drainage basin, and much of it has only recently achieved a marine baselevel. Many areas, however, continue to collect exotic water and sediment from the Andes and act as a regional baselevel. In the northern part of the Pampa del Tamarugal the Salar de Pintados, Salar de Bellavista and the Salar de Llamara are large areas of saline accumulation where the groundwater is at or near surface (Fig. 1). The Salar de Llamara overflows into the Río Loa and is probably already a fossil feature.

East of Antofagasta, in the Aguas Blancas district, the Salar de Navidad and the Salar Mar Muerto act as baselevels not only to drainage from the immediate Andean region, but also from as

far south as Paposo (Fig. 1), since between Paposo and Antofagasta the drainage is deflected northward by the Cordillera de la Costa. These salars, along with the Salar del Carmen east of Antofagasta (Pl. 6), were probably formed following late Neogene westerly upthrow along the Atacama Fault and associated fault breaks.

The largest quantity of pure halite is found in the Salar Grande tectonic basin just north of the coastal section of the Río Loa discussed previously. Other smaller tectonic basins in the northern part of the Cordillera de la Costa are very numerous, and each constitutes its own drainage system. Some such depressions have a saline floor whereas others seem to lose any water they receive through percolation along their boundary faults. Centripetal drainage basins in the coastal mountains are not common south of Tocopilla possibly because the predominantly unidirectional fault style has not permitted enclosed basins to form, but several small depressions occur at the foot of the Salar del Carmen fault. Such depressions as these have led to the formation of tiny playa basins. Small playas of very local significance, have formed by aeolian action, local tectonic or sedimentary events, and are common throughout the whole of the north of Chile.

OVERVIEW

Until recently the majority of the desert has been isolated from a marine baselevel, and drainage towards local basins has been predominant. Large areas still have no drainage connection with the sea, and many other areas, although connected by channels to a newly-established outlet to the sea, still function as local or regional baselevels to erosion because the channels have not adjusted their profiles to the massive baselevel.

The drainage lines connecting the longitudinal depression with the sea, or the Cordillera with the longitudinal depression have, for the most part, been developed within the latest Neogene. Channels of the southernmost area are of greater antiquity, and even these are not adjusted to the present sea level. The only watercourses to demonstrate any high degree of equilibrium with the present marine baselevel are those in the extreme north

which have captured some of the Altiplano drainage, and the resulting increase of flow has enabled them to more fully adjust their bed profiles. All other streams reaching the coast demonstrate their inequilibrium with the present baselevel by the convexity of their lower profile, and many of them have irregular upper profiles which reflect tectonic changes of the landscape and the inability of downcutting to rapidly eradicate such effects.

The overall impression is that fluvial erosion and channel development have been largely unable to keep pace with other, stronger geomorphological influences. The structural imposition of the basic physiographic units during the Neogene superceded most of a drainage pattern which must have existed in the lower Tertiary, and the resulting tectonic control remained dominant until the

present. Other strong influences have been volcanic outpourings in the high Andes which have modified the drainage pattern. Coastal recession has also had a profound influence on channel and other littoral landform development. The extremely arid climate, has been another factor in inhibiting rapid dissection.

The landscape and drainage style of the southern area was largely established before the close of the Miocene. The lack of Miocene planation in the far north is taken to indicate that in the upper Tertiary as now there was a southerly increase in precipitation. Only relatively recently has there been any tendency for new river systems to become established. The Cordillera de la Costa has been breached in the north and drainage of the longitudinal depression and the Altiplano has locally been captured. Deep canyons have been cut across and peripheral to the Pampa del Tamarugal, and ephemeral streams in the coastal area are beginning to notch the cliff to an extent which reflects the southward increase of rainfall. However, the rate of dissection in the recent geological past is not considered to have been effected solely by climatic or tectonic changes, there has instead

been a lessening in effect of influences which previously inhibited channel formation. Coastal recession seems to have momentarily halted along much of the coast. The production of vast sheets of ignimbritic lava seems to be quiescent, as does the eruption of large volumes of andesitic lava and the formation of stratovolcanoes. The country is notoriously seismically active, but fault movement along the major western longitudinal breaks seems to have waned during the Neogenè, consequently the effects of the slow fluvial processes are now becoming partially established.

The ultimate control of the physiography of the western continental margin of South America is the process of lithospheric plate convergence which has led to the development of the Andean cordilleras and their associated structural and volcanic phenomena. Although this process, insofar as its superficial geological expression is concerned appears to be experiencing a tranquil phase, there is no indication of any major change in the manner of plate convergence, and the endogenic landscape processes could easily be re-established in their former role.

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