SEDIMENTOLOGY OF MODERN
ALLUVIAL FANS, BAJA CALIFORNIA
MEXICO

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By

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ABSTRACT

Five modern alluvial fans in Baja California have been examined in terms of their sedimentary characteristics.

Three of the fans are located in Sierra Juarez. They are composed of very coarse boulders up to 5 m in diameter. The coarseness of these boulders is related to the joint weathering of the granite plutons which comprise the source area. The transport process is debris flows which are probably triggered by one of the few but intense summer rainfalls. The two other fans are less coarse and largely formed by sheetflows.

Five alluvial-fan derived facies are defined. Two of them; facies A and C, represent debris flow in which the main clast-dispersion mechanism is thought to be dispersive pressure generated by particle collisions. Two more; facies B and D, represent debris flow in which the main clast-dispersion mechanism is thought to be matrix-strength. Finally, facies E represents sheetflow deposition.

A remarkable ancient analogue to Sierra Juarez alluvial fans shows that given the same tectonic and climatic setting, similar debris flow processes would take place.

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INTRODUCTION

1.1 STATEMENT OF THE PROBLEM:

1.1.1 The Alluvial Fan Environment:

Alluvial fans have been recognized by several authors as one of the most conspicuous sedimentary facies associated with tectonic activity (Dickinson, 1971).

Tectonic activity is responsible for crustal mobility, which generates high relief mountains in relatively short periods of geologic time. As an example, the Laramide orogeny in 40 M.Y. created a high relief along most of the west coast of the American continent, i.e. the cordilleran mountain system (Damon, 1979).

The geomorphological response to crustal mobility, is erosion and sedimentation. Climate has also a main role in determining the main erosional and sedimentary processes. But still, as pointed out by Ahnert (1970), it is relief and not climate that mainly controls the rate of denudation and supply of sediment.

The drainage nets of basins in high relief mountains tend to converge in a single trunk stream towards the lowest point of the drainage basin. Where the stream becomes unconfined, deposition of the erosional products spreads out over a surface forming a segment of a cone, which is known as an alluvial fan (Fig. 1.1). A series of coalescing fans forms extensive bajada deposits. A wide variety of deviations from a well-shaped fan morphology are likely to occur (Bull, 1977).

The alluvial fan surface is dissected by a main channel running from the apex towards the toes of the fan in any one radial direction. The depth of the channel decreases downslope until it intersects the fan surface and becomes braided. The point where this takes place is known as the intersection point, and is usually located in the middle reaches of the fan. In the upper fan, deposition of the coarsest material takes place in levees, along the main channel walls. Below the intersection point, gravel bars dominate the braided channel, and on the fan toe shallower braided pebbly to sandy channels are still the main distributary system. A sandflat and mudflat are found below the area of the fan toes and are the ultimate receptors of the finest fraction of the sediment. These deposits accumulate in the playa, which occupies the center of most

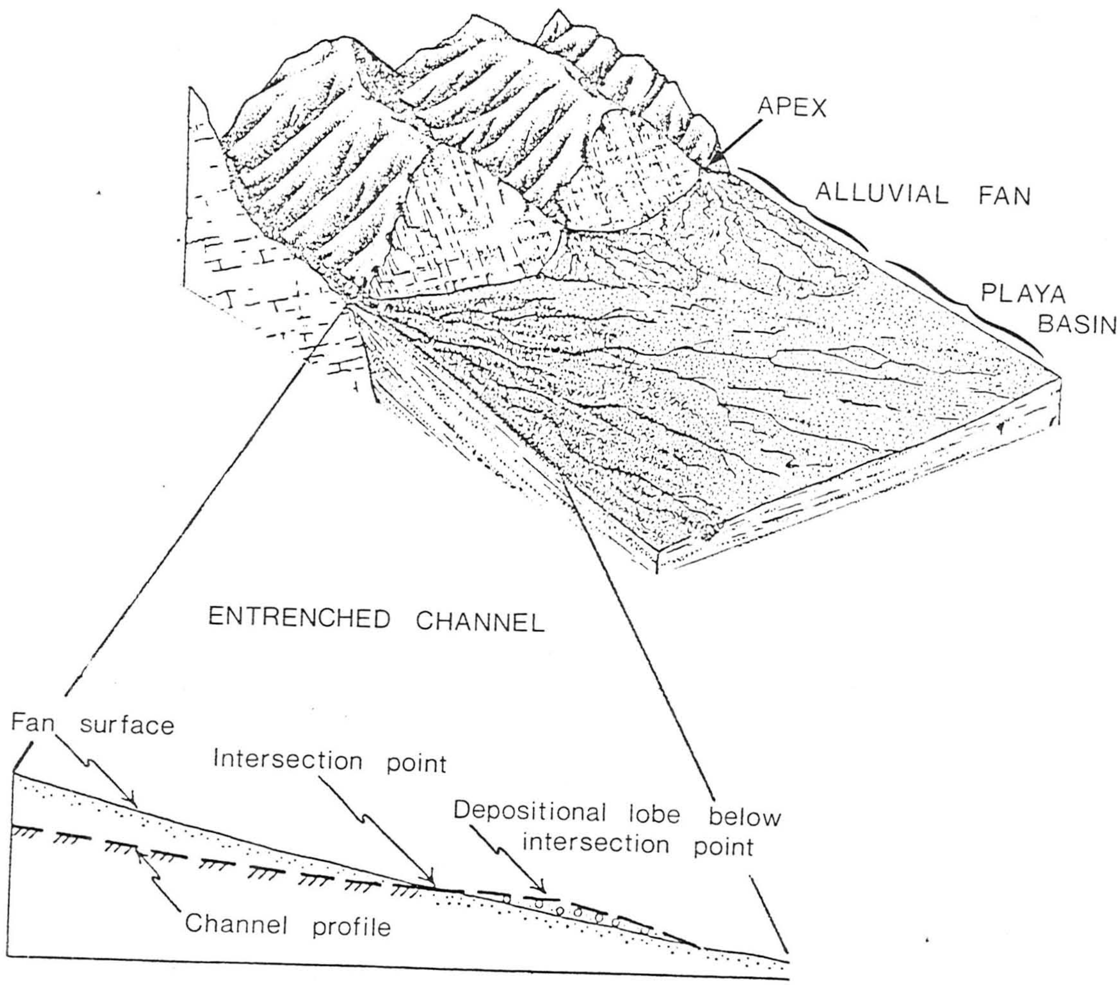


Fig. 1.1 Block diagram of alluvial fan morphology. Note that unentrenched fan surfaces are smaller than entrenched fans, where the net deposition of debris has been "shifted" downstream, just after the dissected channel bed meets the fan surface at the intersection point. (After Bull, 1977 and Hooke, 1967).

alluvial basins (Bull, 1977).

Recent alluvial fans have been reported in a variety of settings, in humid and in arid climatic regimes. However, in arid and semiarid zones, the lack of abundant rain and poor development of vegetation and soils not only enhance the direct control of morphology on sedimentation, but the sedimentary features have a greater chance to remain undisturbed or reworked by processes other than the ones directly involved in their genesis, than in more humid environments.

In desertic environments, provided that loose sediment is available for transport in a steep drainage basin, and that an intense enough precipitation occurs, sediment is moved over the fan surface by several types of flows, namely; debris flows, stream flows or mudflows. Debris flows are one of the most common types of deposit that comprise alluvial fans (Bull, 1964, 1977; Denny, 1965; Blissenbach, 1954).

1.1.2 The Problem:

Most of the alluvial fan literature describes fans in the arid and semiarid regions of the southwestern United States, and is focussed mainly on the geomorphological features of these fans. Only a few experimental studies of some alluvial fan processes (debris flows) are available (Johnson, 1970; Hooke, 1968). Sedimentologists, however, are interested in constructing an alluvial fan facies model based on the systematic documentation of a large number of alluvial fan deposits. Construction of such a model should begin with recent fans, where dissections of the fan surface (such as active channels, fault scarps, or man-made pits) allow detailed description of the vertical sequence of its facies. Later, comparison with fans previously studied elsewhere, and with ancient analogues from the geologic record, will allow completion of the alluvial fan facies model.

The prime difficulty in describing alluvial fan facies is the "structureless" nature of the conglomerates that comprise most of the alluvial fan deposits. Isolation in outcrop of individual depositional events is extremely difficult, due to the lack of lateral continuity of a typical debris flow deposit. Features such as imbrication, crude stratification and grading do not necessarily have the same physical and mechanical meaning in debris flow as in streamflow conglomerates.

1.1.3 The Study:

The present study provides a detailed description of the sedimentology of five alluvial fans located within a small area in northern Baja California, where the tectonic, climatic and geologic framework can be considered uniform, and yet the sedimentary characteristics of the fans, particularly the grain size, is very variable.

Observations of these five fans are compared with those on ancient fans in Wyoming described in the literature and with observations made of Triassic alluvial fan facies in New Brunswick, made in the field. Comparisons with well known alluvial fans in Death Valley and elsewhere are also considered.

1.2 LOCATION AND GENERAL DESCRIPTION OF THE STUDY AREA:

1.2.1 The Sonoran Desert:

The Baja California Peninsula, part of Sonora, southwestern Arizona and southern California comprises the southernmost desert of North America; The Sonoran Desert, (Fig. 1.2; Crosswhite and Crosswhite, 1980).

Topographically, Baja California is an integral part of the North American cordillera. It is regionally known as the Peninsular Range Province, and consists of an up-lifted and west-tilted crustal block topographically higher in the

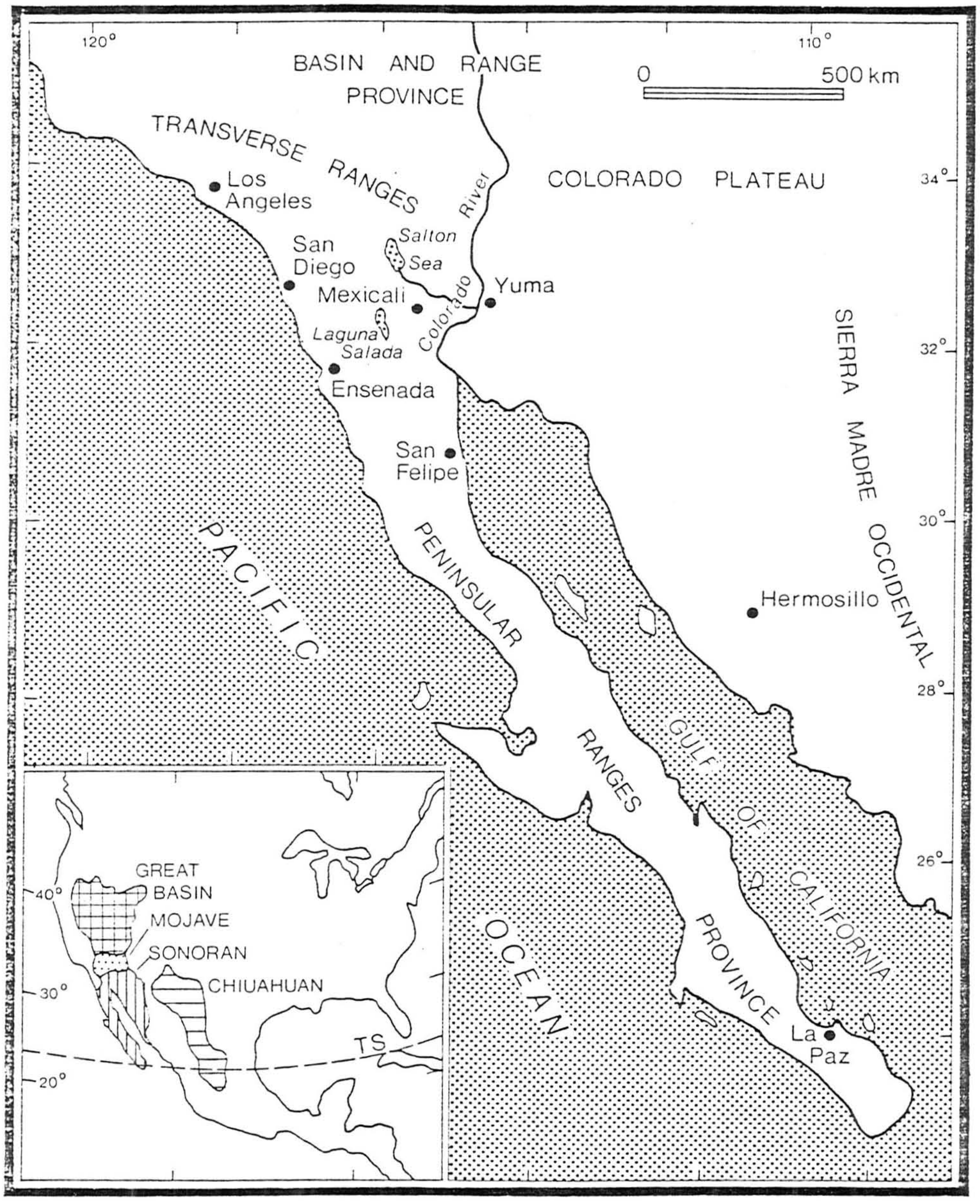
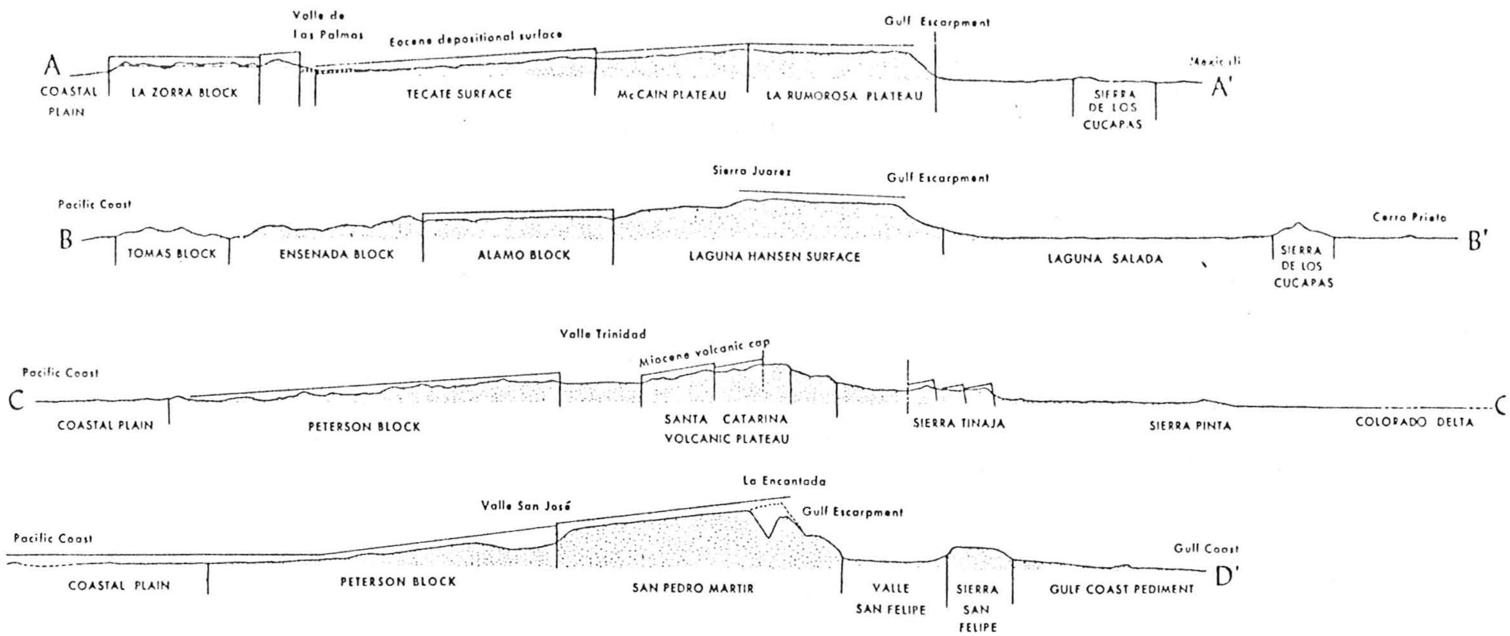


Fig. 1.2 The Sonoran desert. Location and physiography.

North (where it reaches elevations of 1500 m) than in the South (Fig. 1.3). This 1600 km long range is broken into several elongate and subparallel batholiths by major north-west trending faults. The best known of them corresponds to the San Andreas Strike-Slip fault system. Both the Peninsular Ranges and The Gulf of California Trough are abruptly truncated against the Transverse Ranges in southern California where the Basin and Range Province commences. The peninsular batholith consists of Late Mesozoic calc-alkaline granitic rocks which are intruding older metamorphosed rocks (Allison, 1963; Larsen et al., 1958).

The semiarid climate of the Sonoran Desert is mainly controlled by the presence of the Gulf of California. Precipitation decreases from 17 cm/yr in La Paz (the southernmost tip of Baja California) to about 8 cm/yr in the Salton Trough. Rainfall is strongly influenced by season and topography; the peninsular ranges isolate the Gulf of California from the influence of the Pacific Ocean. Parallel to the east side of the Gulf lies the equally high Sierra Madre Occidental. The trough of the Gulf of California is enclosed between these two uninterrupted physiographic barriers. Roden (1963) regards the Gulf as a large evaporation basin which at its southern end is in open communication with the Pacific Ocean. In the winter time,

Fig. 1.3 Selected topographic profiles of the Peninsular Ranges at the study area. Note the westward tilting of the block and the increase of height towards the south. (From Gastill *et al.*, 1975).



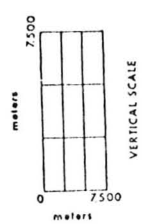
TOPOGRAPHIC PROFILES

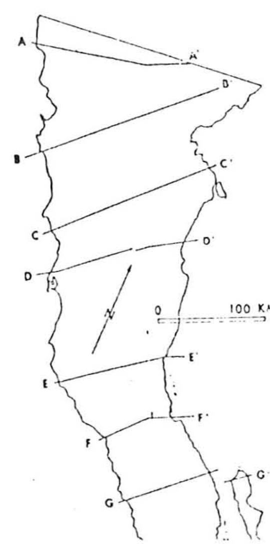
FOR THE STATE OF

BAJA CALIFORNIA

VERTICAL EXAGGERATION 2.5

HORIZONTAL SCALE





northwesterly winds are channelized along the east side of the Gulf, leading to precipitation which increases with altitude and decreases northwards. In the summer time, the wind pattern reverses, blowing southeasterly along the west side of the Gulf. There is very little, if any precipitation at the head of the Gulf, and precipitation increases southwards (Fig. 1.4A). Other sources of precipitation are hurricanes coming from the east Pacific with the peak of intrusion into the Gulf occurring in September (Fig. 1.4B; Roden, 1963).

1.2.2 The Salton Trough:

The Salton Trough is the most important sedimentary basin of the Sonoran desert. It is an elongate basin of extreme tectonic complexity and one of the most seismically active areas of North America (Fig. 1.5; Crowell and Sylvester, 1979).

The Salton Trough is bounded to the west by the 1-2 km high Peninsular Ranges, to the north by the Transverse Ranges, to the east by several northwest elongated blocks beyond which lies the Colorado Plateau, and to the south by the Colorado delta beyond which is the Gulf of California.

The alluviated floor of the Salton Trough is largely below or at sea level. The center of this playa basin is

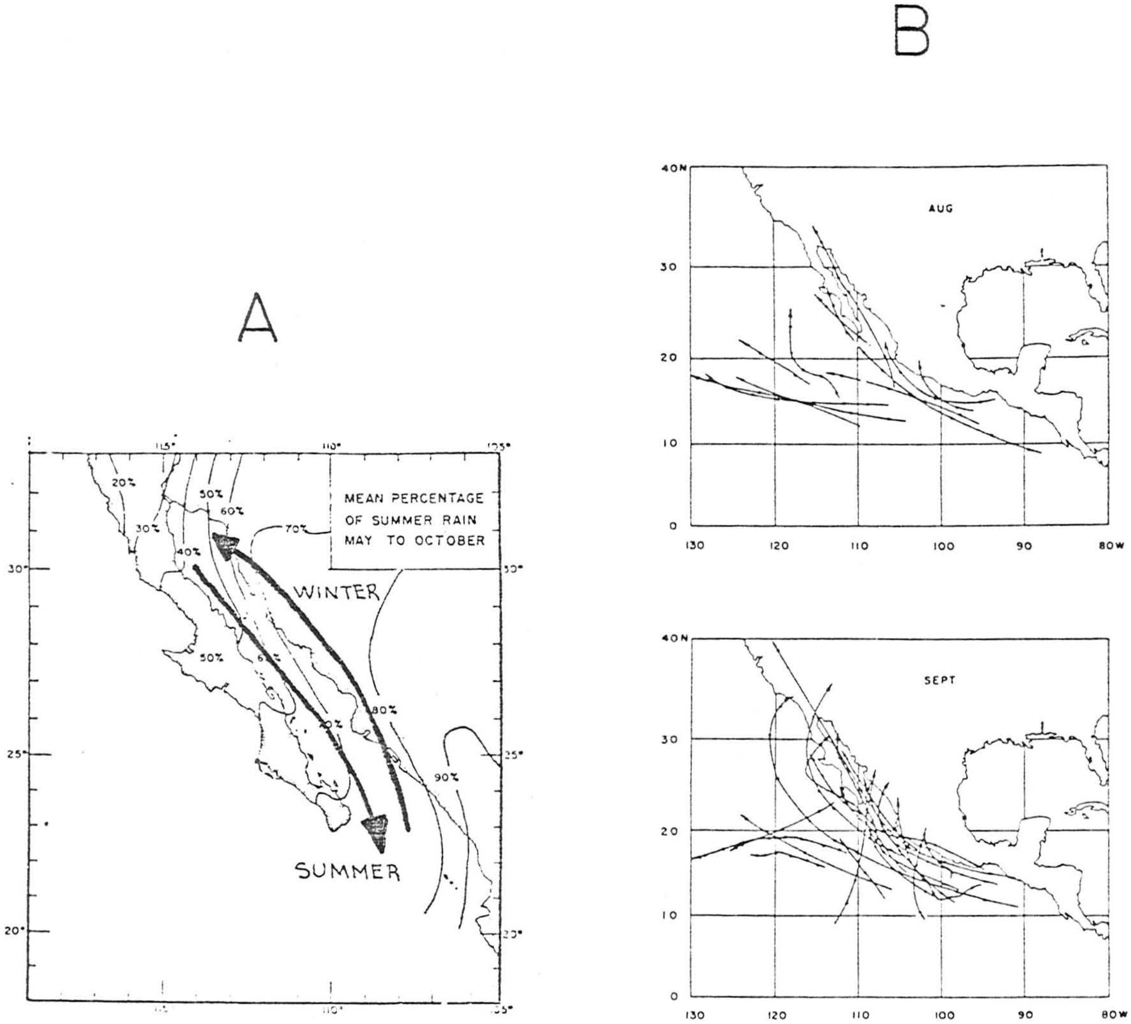


Fig. 1.4 A Seasonal reversal of wind direction in the Gulf of California, and associated rainfall. Note the seasonal difference between summer and winter mean percentage of rain. (After Roden, 1964).

Fig. 1.4 B Paths of northeast Pacific hurricanes entering the Gulf of California in August and September. (After Roden, 1964).

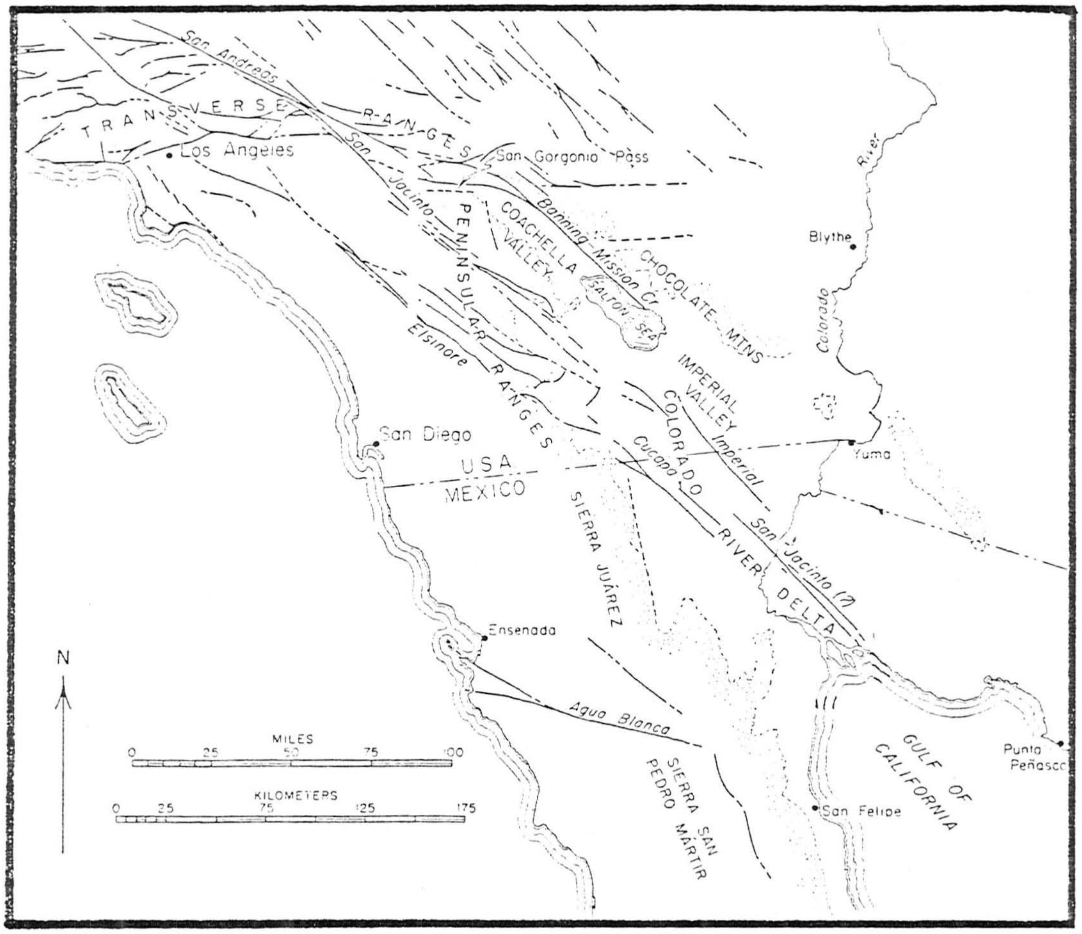


Fig. 1.5 The Salton Trough and its tectonic context. Note the NW-SE orientation of main faults, ranges and long axis of the basin. The study area lies in the southern portion of the basin. (After Kovach, 1962).

occupied in the northern part by the Salton Sea (permanent since 1905) and in the southwest part by the ephemeral Laguna Salada.

1.2.3 The Study Area:

The study area is divided into 3 sites, in the southernmost portion of the Salton Trough (Fig. 1.6).

i) The Laguna Salada Playa basin is elongated in shape, 80 km long by 16 km wide. It is bounded on the west by Sierra Juarez and to the east by Sierra Cucapas. To the north it is in narrow communication with the Salton Trough, and to the south it is in open communication with the head of the Gulf of California. The outskirts of Sierra Juarez are bordered by a series of very coarse alluvial fans. Two of them were studied: La Poderosa and Las Palmas fans (Fig. 1.6).

ii) Sierra Cucapas is a north-west elongated batholithic block, 1200 m high, and dissected by more than 5 north-west trending faults formed in the very recent past (Fig. 1.6). Alluviation is more extensive on the east side of Sierra Cucapas, where coalescing alluvial fans form an extensive bajada that overlies the recent sediments of the

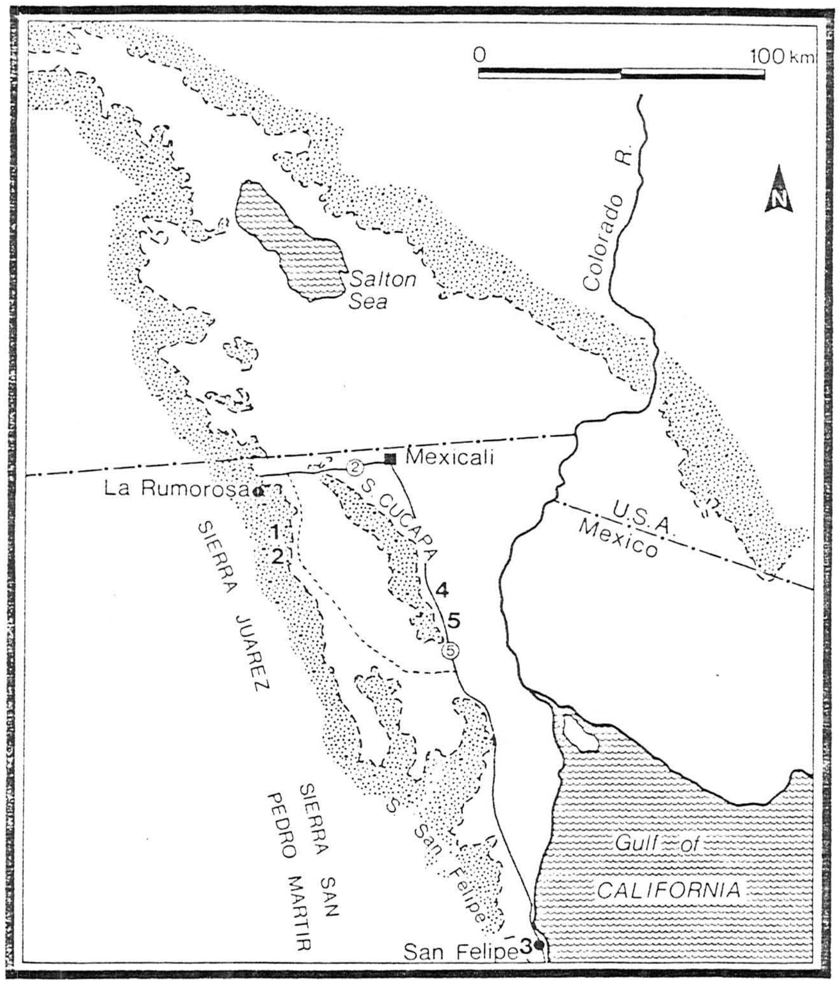


Fig. 1.6 The study area. Location of the alluvial fans: 1.- La Poderosa; 2.- Las Palmas; 3.- San Felipe; 4.- La Puerta and 5.- El Pantano.

Colorado delta. Two individual fans were studied in this area. La Puerta fan is located at the southeastern end of Sierra Cucapas. El Pantano fan is located in the southernmost block adjacent to Sierra Cucapas, locally called Sierra del Mayor.

One more fan is located in Sierra San Felipe (an extension of Sierra Juarez) in the vicinity of San Felipe Village.

All five fans have the same type of granitic calc-alkaline source rocks in their drainage basins, except for La Puerta fan which, in addition, has a small amount of metamorphic source rocks. The grain size varies greatly from the fans located in Sierra Juarez (La Poderosa, Las Palmas and to some extent San Felipe) to those located in Sierra Cucapas.

Debris flows are by far the dominant sedimentary processes involved in the formation of these fans.

CHAPTER 2

GEOLOGIC BACKGROUND

2.1 REGIONAL AND LOCAL TECTONIC HISTORY:

The Baja California Peninsula has been affected by the intense circum-Pacific crustal mobility. The present topography is the result of tectonism today and in the recent past (Ernst, 1981). The nature and intensity of such a crustal mobility is associated directly with the subduction of oceanic plates west of the continental margin, and the evolution through time of different types of margins. Dickinson (1981) has divided the tectonic evolution of the California continental margin into four main stages (Fig. 2.1).

1.- A rifted Atlantic-Type margin evolved through the late Precambrian and early Paleozoic leading to the formation of the Cordilleran miogeocline.

2.- A complex Japanese-type margin with offshore island arcs developed in the late Paleozoic and Mesozoic;

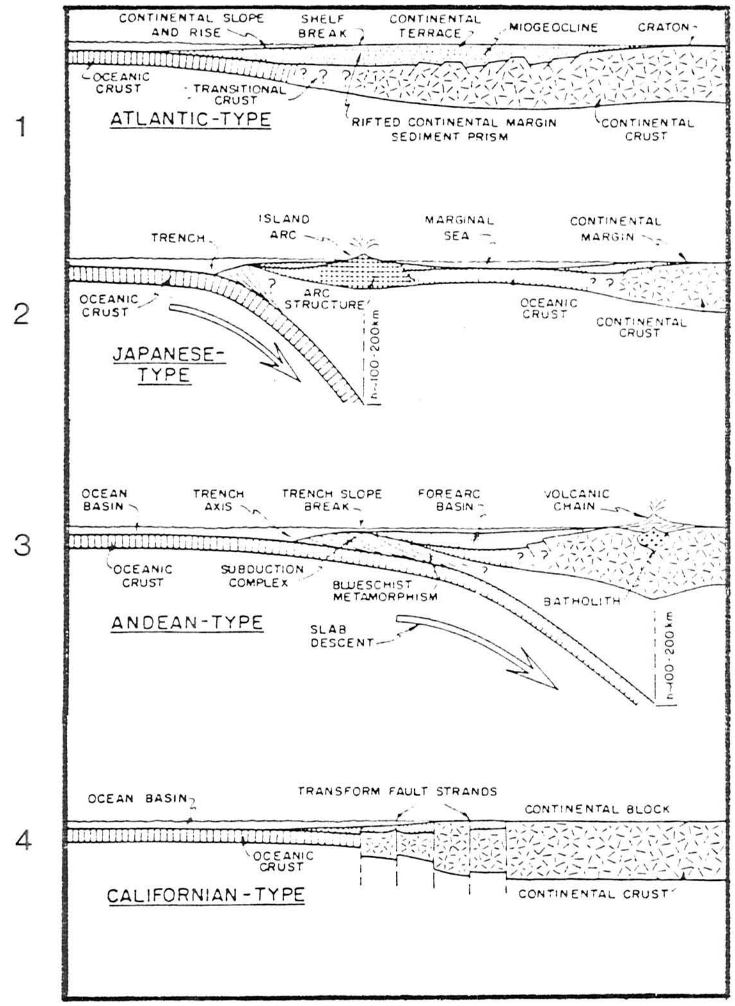


Fig. 2.1 Tectonic evolution of the California continental margin. (After Dickinson, 1981).

during this tectonic regime, the Antler and Sonoma Orogenies took place.

3.- An active Andean-type margin, with a trench along the edge of the continent existed in the late Mesozoic and early Cenozoic. This tectonic regime originated the Laramide Orogeny.

4.- The present Californian-type margin dominated by strike-slip faults developed along the San Andreas transform fault system.

In the last 28 M.Y. the San Andreas fault system has migrated inland from its original position at the edge of the continental slope (Fig. 2.2; Dickinson, 1981: Crowell and Sylvester, 1979).

Extensional effects of the San Andreas system have recently developed a series of pull-apart basins like Death Valley (Burchfiel and Stewart, 1966), the Salton Trough and Laguna Salada (Dickinson and Snyder, 1979).

These pull-apart basins are most active today: the average spreading rate is about 10 cm/yr in the Salton Trough, which implies a net extension of 1 km each 10,000 yr (Elders et al., 1984).

The sedimentation history in the Salton Trough has been fluvio-marine in the recent past and is alluviation at the present time. The alluviated floor of the Salton Trough and

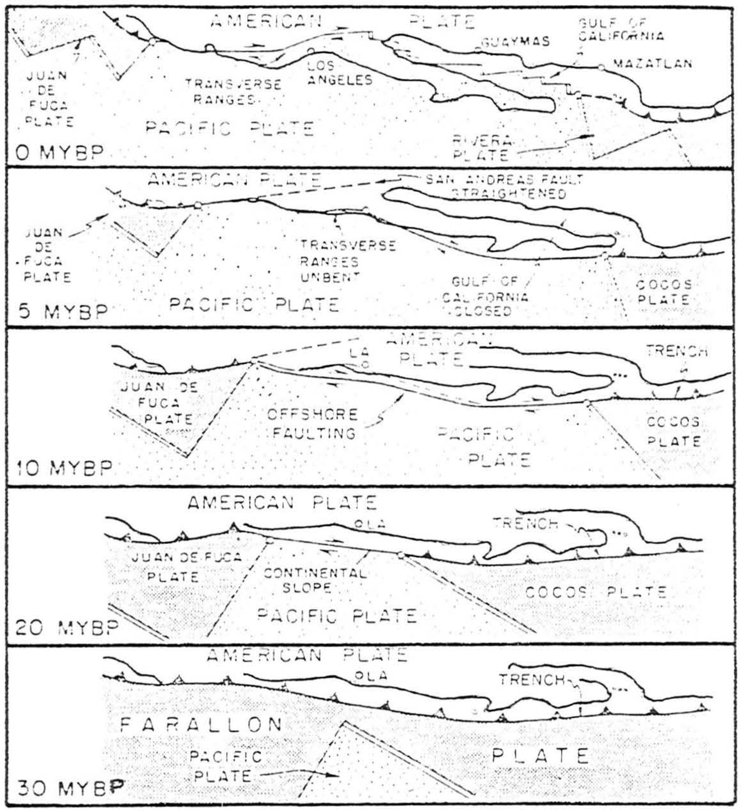


Fig. 2.2 Inland migration of the San Andreas system and the rift of Baja California from mainland Mexico. Note the recent creation of "Pull-apart" basins in the Gulf and in the Salton Trough. (After Crowell and Sylvester, 1979).

Laguna Salada has remained at or near sea level in the past 4 M.Y. This nearly steady state balance between subsidence of the playa and erosion-sedimentation from the steep bordering mountains reflects the unique tectonic framework of the study area (Crowell and Sylvester, 1979).

2.2 SOURCE AND NATURE OF DEBRIS:

Superficially, alluvial fans in Laguna Salada closely resemble those of Death Valley and elsewhere in southern California. But closer inspection reveals an outstanding difference in grain size. This is due, in part, to the petrography of the source. In Death Valley, metamorphic, igneous and sedimentary material is being eroded into sand, pebbles and cobbles; boulders larger than 1 m in diameter are not a significant fraction of the size distribution (Denny, 1965). In Laguna Salada, the granitic batholith and a few metamorphic (but no sedimentary) materials are being eroded into very coarse rounded boulders, up to 4 m in diameter, together with cobbles, pebbles and sand. The immediate questions are, why is the debris so coarse, and why is it relatively well rounded when the distance from the source does not exceed 10 km?

The batholith of Sierra Juarez, as many others in the deserts of southwestern U.S., are distinctly armoured by naked boulders. Many physiographers have pointed out that this type of landscape is the product of continuing near-surface weathering effects in well-jointed rock. Under the present armour of more or less spheroidal boulders (Fig. 2.3), a second crop is assumed to be in formation through a concentration of chemical weathering at joint intersections, which tends to round the apices of original plane-faced blocks (Oberlander, 1972).

2.2.1 Joint Origin And Boulder Production:

Joint patterns of many batholiths display a close geometric relationship with the local and regional tectonic framework (Balk, 1937). Some joints are related to the upward doming and lateral extension of plutonic masses, either during emplacement or subsequently, as a result of isostatic readjustment (Bott, 1956).

The spacing of the joint system is basic to the evolution of the boulder assemblage. The closer the joints, the smaller the boulders and the larger the area exposed to weathering. For closely spread joints production of granitic sand is also very large compared to production of boulders. But the most common situation in areas of high tectonic activity is that of widely separated joints, commonly as

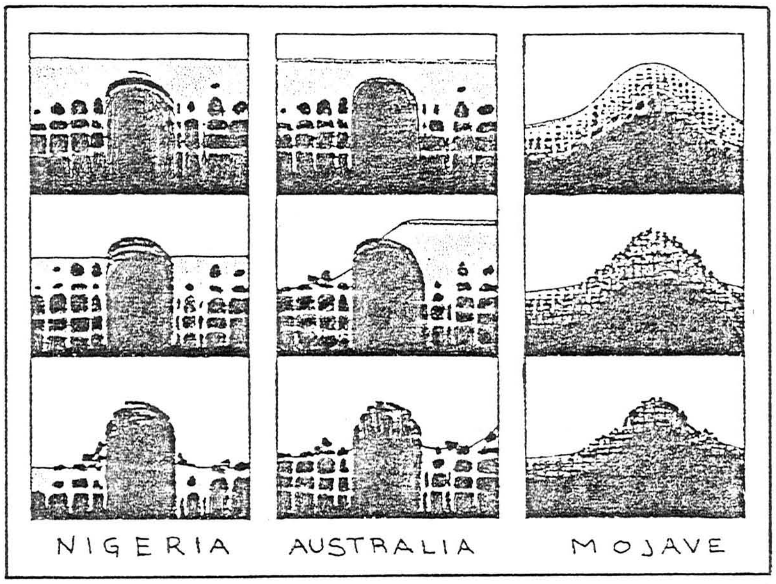


Fig. 2.3 Evolution of pluton residuals in different geomorphic conditions. Note that the Mojave type represents the downward limit of chemical weathering. (After Oberlander, 1972).

much as 2-4 m apart. In this case, the joint blocks are sufficiently large to allow their cores (or "kernels") to resist prolonged weathering (Twidale, 1971). Clearly, the spacing of the joint net has a direct influence on the size of the boulders, through the duration and effectiveness of weathering. The petrology and structure of the local bedrock also have a significant effect. Twidale (1971) has reported the variation within the Palmer outcrop in Australia. Here, gray granite forms boulders 20 cm in length which are relatively weathered but only a few meters away, blocks twice as large formed of a coarse pink granite have been greatly disintegrated.

2.2.2 The Influence Of Climate:

Evidently, the role of the joints in the subsequent formation of boulders, is to act as "moisture traps" which will ensure a differential weathering. The arid deserts like the Mojave, are good examples of boulder-armour landscape, but the source of moisture is difficult to explain. Oberlander (1972) suggested that such a landscape was first developed during a semiarid climatic regime which no longer exists. Oberlander did not explore the lines of inquiry that this statement opens up. How much moisture does a joint system require to develop a boulder drape, and what other factors control the rate of joint disintegration?

Roth (1965) conducted systematic measurements of temperature and water content on the surface and at several internal positions within an outcrop of quartz monzonite in the Mojave Desert. The maximum range observed was from 49 to 8 ^{o}C with temperature gradients in the rock of 15 to 4 $^{o}C/cm$. These data and the coefficients of expansion of the constituent minerals suggest that temperature variations alone are not important in rock disintegration. Water content of the rock, on the other hand, increases towards the inside of rock fissures, ranging from 0.05 to 0.15%. Griggs (1936) conducted an experiment where a granite block was subjected under dry conditions to heating and cooling daily cycles representing 244 years, but no alteration was observed. When the same experiment was repeated with the addition of sprayed moisture, rock alterations were observed in a much smaller number of cycles.

Unfortunately, rock temperature and moisture content in other deserts has not been consistently studied and their variation with time, topography and depth remain unknown. But the importance of humidity conditions in hot desert environments can be clearly appreciated in coastal deserts, where not only is moisture available but the sea provides a source of airborne salts. Many of these coastal deserts, like the Sonoran desert itself, are surrounded by high mountain chains. Hollerman (1975) has observed that there is evidence for altitudinal increase in moisture retention, in cavernous hollows (the same can be applied to joints). Dragovich (1967) has shown (in the Australian desert) that relative humidities are consistently higher than in the air outside.

In these examples, the principal role of increased relative humidity is that it promotes the direct precipitation of moisture onto rock surfaces during the night in joint spaces, particularly in those where moisture supply from other sources is either infrequent or unavailable (McGreevy and Smith, 1982). The role of salts in weathering involves not only physical and chemical changes but the rate and nature of rock breakdown can also be affected.

Even if these control factors have not been quantified, their influence in Laguna Salada region can be clearly distinguished. Air photographs (Fig. 2.4), reveal that joint systems occur predominantly in the highlands, where scattered conifer flora indicates cooler temperatures. Hastings and Humphrey (1969) report a mean annual temperature range of 7° to 24° C in La Rumorosa (Fig. 1.6) where precipitation is considerably higher (6.4 to 2.2 cm/yr) than in the valley (2.8 to 0.7 cm/yr). No

Fig. 2.4 Source of coarse boulders in the Sierra Juarez alluvial fans. Note the NW-SE trend of the joint system on the batholith surface. The space between joints determines the size of the boulders. Steep chutes on the drainage basin facilitates boulder removal during the short but intense rainy season.

relative humidity data are available but the Gulf of California, a large evaporation basin itself, is likely to provide extra humidity to the surrounding highlands and associated intermontane basins.

Closer inspection of Fig. 2.4 reveals that boulder armour occurs in the upper steeper ($>35^{\circ}$) walls of the drainage basins, suggesting that gravity instability may rapidly increase as erosion proceeds. This provides a suitable framework for flow generation to occur during intense rainstorms, followed by evolution of the next "crop" of boulders.

2.3 THE ALLUVIAL FAN MORPHOLOGY:

Alluvial fans are derived from a source area with a drainage net that transports the eroded material of the source area to the fan apex in a single trunk stream.

The plan view of the fan-shaped deposit has contours bowing downslope. Overall radial profiles are concave upwards. However, many alluvial fans are not fan-shaped because they are restricted by adjacent larger fans, or they may be coalescing forming extensive bajadas (Blissenbach, 1954; Bull, 1964).

The main channel is the connecting link between the erosional and depositional parts of the system, and is a dominant influence on the fan morphology. Changes in main channel slope, depth and width affect the fan surface slope, and the loci and mode of deposition on the fan surface. Fans vary greatly in size, from less than 10 m to more than 20 km in length (Bull, 1977).

2.3.1 Factors Affecting Alluvial Fan Morphology:

Hooke (1967) studied artificial fans under controlled experimentation in the laboratory. Deposition during a single simulated runoff event was generally localized. One part of the fan may build slightly higher than the surrounding conical fan surface. Such "highs" commonly develop below the intersection point, that is, the point where the main channel merges with the fan surface. Braided streams crossing the intersection point deposits tend to shift laterally into adjacent lower areas. Gradual migration of the intersection point in this way, in addition to more abrupt diversions of the main channel nearer the apex, are responsible for shifting the locus of deposition. The experiments of Hooke suggest that over a period of several simulated runoff events, shifting of intersection points results in deposition of a relatively uniform layer of sediment over the entire fan surface. Various researchers (Beaty, 1970; Bull, 1977; Pierce, 1974) and Hooke himself have demonstrated this process is applicable to natural alluvial fans.

2.3.2 Segmented Alluvial Fans:

Bull (1964) described the nature of segmented alluvial fans commonly occurring in arid environments. In segmented fans, deposition at any particular time is concentrated on the active channel, thus deposition is considered to be uniform only on the active channel. Segmented alluvial fans originate by apex incision. Hooke (1967) considered a fan to be apex incised only if overbank flooding by water flows was likely to occur less than once in a few decades. Water flows tend to erode the active channel in debris flow deposits.

Despite the apex incision, some debris flows may exceed the channel depth, overflow, and deposit broad sheets of debris on the fan surface above the intersection point. However, in some alluvial fans the apex incision is too deep and wide for overbank deposition to take place.

Hooke's (1968) experiments show that a large number of water flows are required to incise debris flow - dominated alluvial fans, furthermore he observed that most water flows were scarcely able to transport any of the armoured channel particles. Hooke suggested that after a long period of time without overbank deposition, sedimentation eventually results in backfilling of the active channel above the intersection point, forcing the subsequent debris flows to follow the easiest path toward other steeper parts of the fan.

2.3.3 The Intersection Point:

The intersection point on laboratory fans studied by Hooke (1968), commonly occurred near midfan (Fig. 1.1) probably because stream flow deposition predominates near the fan toe and occurs without further down fan migration of the intersection point, while debris flow deposits predominate near the apex. Thus the average radial position of the intersection point should be related to the relative importance of debris flow and/or stream flow processes in transporting debris to the fan.

2.3.4 Alluvial Fan Slope:

Field and laboratory data presented by Hooke (1967, 1968), Bull (1964, 1977) and Denny (1965) suggest that fan slope is controlled primarily by grain size and by the nature of debris-transporting processes. Thus, fan slope is largely determined by the nature of the source area. Fan slope tends to be steeper on debris flow dominated fans than in stream flow dominated fans.

An increase in discharge with drainage area is probably responsible for the decrease in fan slope with increasing drainage area. This means that fan slope depends on discharge; smaller discharges will deposit sediment primarily near the apex, while larger discharges will deposit more sediment near the toe. The actual slope that the fan assumes will be determined by a balance between these tendencies (Hooke, 1967).

2.3.5 Alluvial Fan Area Equilibrium:

Many alluvial fans in arid and semiarid zones are found in enclosed basins containing an aggrading playa, where the silt and clay fractions are deposited. There will be a tendency for the rate of deposition on the playa to equal that of the surrounding fans. Hooke (1968) points out that if the playa were too large with respect to the volume of material supplied to it per unit time it would increase in thickness more slowly than adjacent fans. The fans would encroach upon the playa, thus decreasing its area and increasing its rate of thickening, so long as the volume of sediment supplied per unit time remained constant.

This process will continue until the rate of increase in thickness of the playa equated that of the bordering fans. This model assumes that playas are currently aggrading, and this seems to be true for many modern playas. For instance, Death Valley, the Salton Trough and Laguna Salada have a playa thickness in excess of 6 km and all of them are of Pliocene to Recent age. This shows that an alluvial fan - playa equilibrium theory is plausible, since deposition is a relatively fast and continuous process when considered on a time scale of thousands of years.

CHAPTER 3

THE NATURE OF DEBRIS FLOW

Debris flows are mass flows composed of highly concentrated mixtures of sediment and water: there is generally a wide range of sediment grain sizes, the flows are initiated on high slopes (generally steeper than 10°) but move out onto slopes that may be lower than 5°, and movement is relatively slow (generally "walking speed"). Debris flows consisting largely of mud are often called mudflows: mud is prominent, mixed with coarse grains in the fine-grained matrix ("slurry") of many debris flows, but debris flows that contain little mud are also common. Debris flows are generally decimetres to metres in thickness and have a well-defined front. Like other mass flows, they are episodic and most deposition takes place after the flow has come to rest.

In this thesis, only coarse grained subaerial debris flows will be described. The mechanism by which debris flows move and support the larger clasts in the flow is controversial, and will be discussed later in this chapter.

A summary of the most interesting field observations of debris flows is described in the next sections in order to set an appropriate framework of reference for the following chapters.

3.1 COARSE CONCENTRATED DEBRIS FLOW (CDF):

The best and perhaps the only well documented occurrence of this type of debris flow has been reported by Okuda *et al.* (1980) from the Disaster Prevention Research Institute, Kyoto University in Japan. Debris flows in the Japanese Alps occur several times a year; observational systems equipped with several video cameras and measuring devices have documented debris flow characteristics for over 10 years.

In the Kamikamihori fan, a debris flow frontal lobe was sampled for clast size distribution whose diameter was larger than 10 cm. Fifty percent (by weight) of the clasts was between 0.1 and 1.0 m, 30% was between 1.0 and 2.0 m and 20% was between 2.0 and 3.0 m. The mode (by number) was composed of 10 to 20 cm clasts, while the matrix was composed of 94% sand and pebbles and 6% silts and clay (Okuda *et al.*, 1980).

Annual precipitation amounted to 2000 to 3000 mm. A heavy rainfall of 7 mm in 10 minutes significantly increased the probability of debris flow occurrence. A rapid rise of ground water level in the channel surface and sudden appearance of surface runoff along the canyon were often found immediately before the debris flow initiation.

The main source of debris was the canyon armoured floor, where the slope ranges from 13 to 32°. Debris flows initiated in slopes as low as 20°. Debris flow occurring in the upper reaches of the canyon rarely reached the fan apex, but they stopped in the canyon bed in the form of unstable piles of debris. Since the amount of silt and clay was minimal, the slurry played a minor role in preventing friction forces between clasts, and collisions between clasts was by far the dominant mode of flow motion (Fig. 3.1).

Velocities rarely exceeded 5 m/sec on the fan. The frontal lobe velocity seemed to depend upon the scale of the flow (i.e. the height of the snout, therefore on the maximum clast size) and upon the concentration of boulders and cobbles controlling the apparent viscosity of the flow. Description of those who actively observed the flows provides a better understanding of this type of debris flow:

> "the frontal lobe, of a few tens of metres long, came running down containing many large rock blocks and broken trees, and next, a fast current of muddy water containing many cobbles and pebbles followed the frontal lobe, and last, shallow water current with

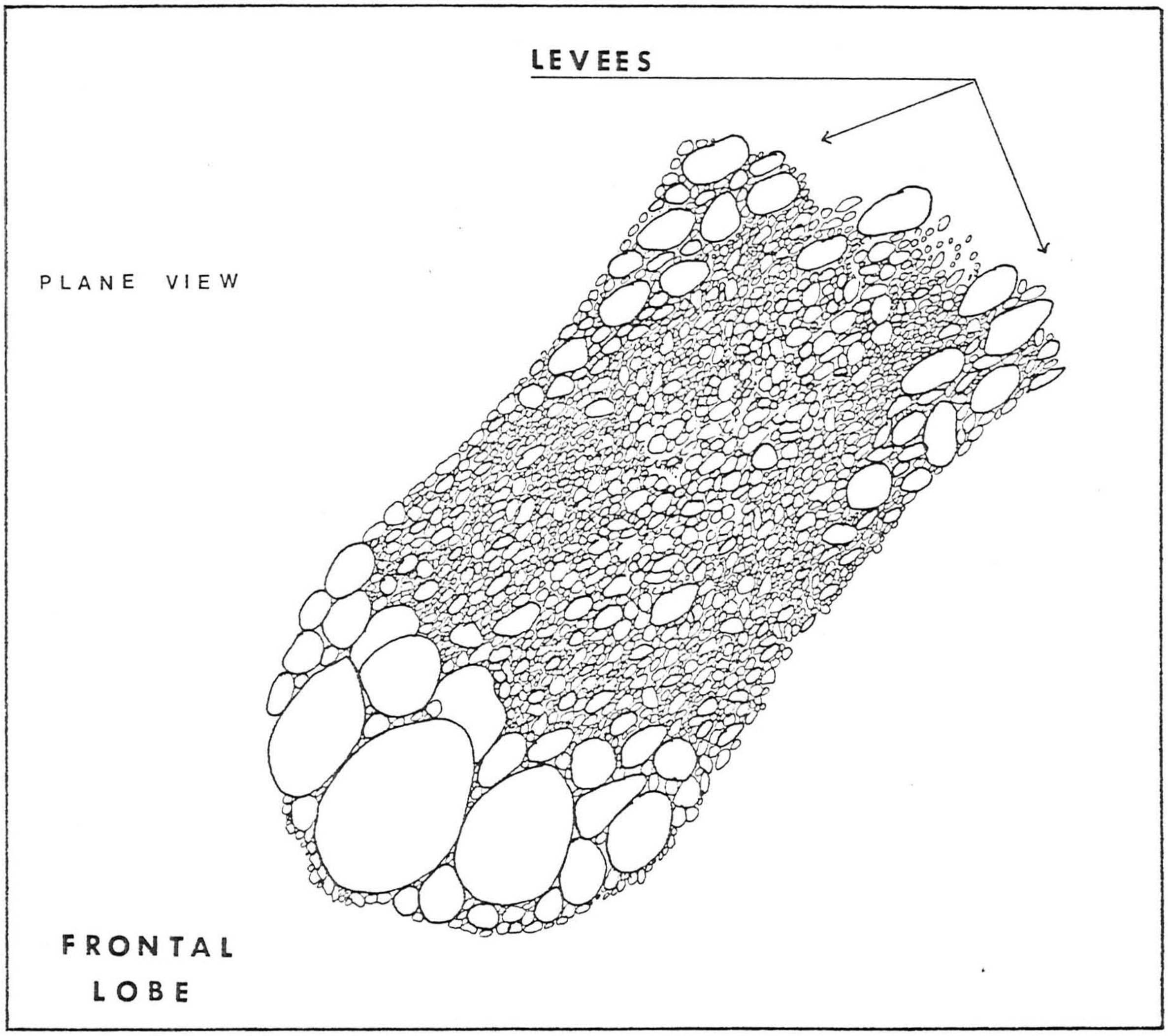


Fig. 3.1 Idealized diagram of a coarse concentrated debris flow. The coarsest boulders concentrate in the frontal lobe, whereas less-coarse boulders segregate on the levees. Note that all clasts are in contact with each other generating a dispersive pressure force which supports the coarsest clasts.

> pebbles, sand and mud in high concentration continued to flow for several hours."

Due to the orientation of the research (towards prevention of disasters), post-depositional descriptions of the sediment are rarely reported.

3.2 COARSE DISPERSED DEBRIS FLOW (DDF):

The best, although not the only well documented occurrence of this type of debris flow has been reported by Curry (1966) in the Tenmile Range, Colorado. His descriptions are very similar to those of Denny (1965) and Johnson (1970), in semiarid regions of southern California.

Vegetation was relatively rare in the debris flow area of the Tenmile Range.

Sixty percent of the debris matrix material was finer than 50 mm. 29% was finer than 2.0 mm. Less than 9.9% was silt size and only 1.1% clay size. Water content in a fresh debris flow matrix averaged 9.1% by weight. Individual angular boulders were as large as 80 cm.

A heavy rainfall of 2450 mm in 24 hr triggered the debris flows of July 30, 1961. The event was characterized by a series of pulses or waves of debris.

The main sources of debris were talus cones of previous rockfall avalanches shedding onto the canyon floor, where slopes ranged from 33° to 25°. Debris flows initiated on slopes ranging from 25° to 7.5°.

Individual flows occurred as a series of lobate pulsations; the largest of them lasted for one hour. The boulders in the flow were dispersed far enough apart in the matrix so that there were few collisions between them (Fig. 3.2).

Velocities ranged between 15 m/sec near the apex, to 1 m/min in the lower fan. Some pulses that reached the lowest part of the fan, easily breached natural levees 60-80 cm high and continued to flow slowly over the armoured surface.

The eye witness reports:

> "It was my impression that the flow pulse resulted from the triggering effect of a shock wave traveling through a talus cone lying at the angle of repose and that, along the course of the upper half of the debris flow, the velocity of the flow pulses appeared to be incorporated into the surge front. Material immediately in front of the flow was usually pushed up the outside of the mud-lubricated surge front to the top of the flow mass or pushed around the side of the frontal lobe, perhaps to be carried for a short distance but eventually forming well-defined natural levees. In the lowest part of the fan and in the meadow below it, the flow continued to move over the armoured surface without incorporating new debris, but deposited the largest levees, up to 1 mt high."

Johnson (1970, pg. 438) described a nearly identical event produced by rapid snow melt in the San Bernardino Mountains of southern California. The waves or surges

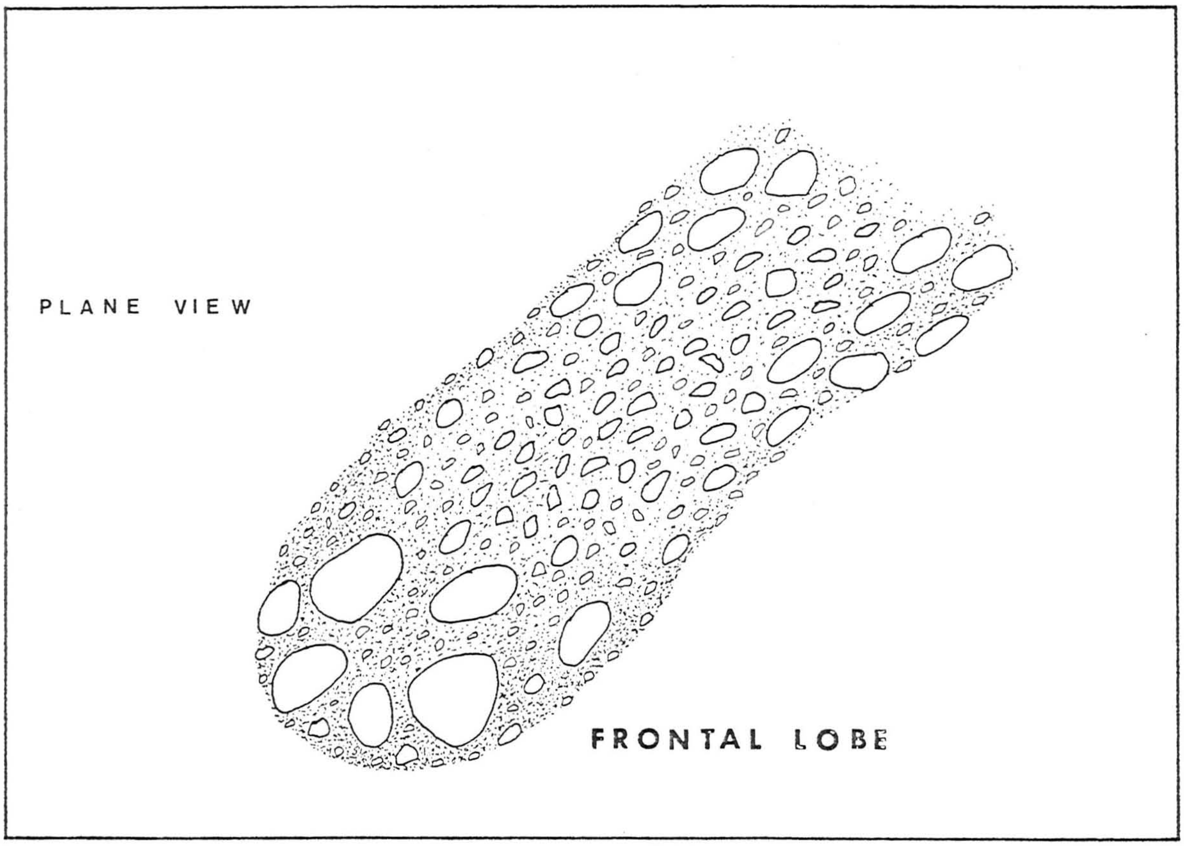


Fig. 3.2 Idealized diagram of a coarse dispersed debris flow. Some of the coarsest clasts may concentrate on the frontal lobe. Note that the fine-grained matrix-mixture is supporting the dispersed clasts.

appeared every 10 to 20 minutes during 10 days. It is interesting to note that this type of event, characterized by muddy water flow followed by a debris surge which in turn is followed again by more diluted muddy water, produced deposits which are likely to be remobilized in shallow braided channels. In this way all of the matrix may be washed out, so only the last pulses of the event are likely to be preserved in their original depositional mode.

3.3 THE STRENGTH OF DEBRIS FLOW:

Water by itself, is a fluid that has no strength. But even minute amounts of clay are enough to provide the clay-water mixture with rheological properties such as strength and cohesion. These are two important properties that contribute to retard the sinking of particles suspended in the slurry and reduce the internal angle of friction of the bulk material to a low-value.

Rodine and Johnson (1976) tested the strength of clay-water slurries and concluded that they all possess virtually no frictional strength regardless of their cohesion (as high as several thousand dyn/cm^2). Therefore the fine grained matrix, or fluid phase of the flow can be described in terms of cohesion and unit weight. They observed the following regimes:

i) Cohesive regime; the addition of sand to the slurry increased the unit weight proportionally to the volume of sand. The cohesive strength however, remained constant provided that the volume of sand was small compared to the volume of slurry.

ii) Granular regime; if the volume of sand is increased enough to produce particle interactions the strength of the mixture depends on both the cohesive strength of the slurry and the contact friction between particles.

iii) Frictional regime; if the volumetric proportion of slurry (slurry volume) becomes insignificantly small compared to the proportion of sand, the grains will interlock and both the internal friction angle and the cohesion of the bulk material will increase.

It is clear from these observations that the strength of debris flows depend on the particle volume concentration in both the finer grained phase and the coarser grained phase.

When one of the phases predominates, the model of deformation will approach that of the predominant phase (Bingham or Coulomb models) and will define the mechanism of clast support by the flow (Figs. 3.1 and 3.2).

3.4 COMPETENCE OF A DEBRIS FLOW:

The competence of a debris flow is directly related to its strength (Section 3.3). The abundance of coarse clastic material transported by debris flows indicates high competence and therefore suggests high strength, yet the movement of debris flow over gentle slopes suggests low strength (therefore low competence).

Experimental work of Rodine and Johnson (1976) suggested that strength and competence depends on grain concentration as well as packing. Theoretical analysis of various size distributions revealed that clasts, if sufficiently poorly sorted, can comprise as much as 64% of the volume of debris and yet have essentially no influence on the gross strength of the debris flow. In addition, a fluid phase composed of kaolinite and water proved to have essentially zero apparent friction, therefore the apparent cohesion is determined by the water content of the fluid phase. According to this hypothesis, the debris may be virtually frictionless on low slopes provided that interlocking of particles is very low, and since the density of the flow (assuming up to 64% clast content) is nearly equal to the average density of the solid clasts themselves, large blocks may be transported by debris with low strength.

Although not strictly stated in this hypothesis, Rodine and Johnson imply that debris with closer packing and thus a degree of interlocking of clasts will require higher shear stress (i.e. steeper slopes) to flow.

CHAPTER 4

INTRODUCTION TO FACIES:

Four months were spent in the field during the summer of 1983. Work was conducted in two locations: Northern Baja California, Mexico and southern New Brunswick, Canada. Six selected modern alluvial fans in Baja California were studied based on 1:50,000 scale geologic-topographic maps; 1:25,000 scale air photographs photolog mosaics of longitudinal vertical sections photographed in incised alluvial fan channels, and field notes. In New Brunswick, the Maces Bay section of Triassic alluvial fan deposits were studied based on 1:15,840 scale air photographs; photolog mosaic of the 92 m section; field notes amd hand samples.

Since the Triassic alluvial fan facies are only partly analogous to the modern alluvial fan facies in Baja California, a brief section devoted to the Maces Bay facies is presented in Chapter 7.

In the Baja California alluvial fans, the detailed photologs comprise all incised channel outcrops, with the exception of those that had been eroded into a talus.

In addition to the detailed documentation of these fans, other localities described in the literature were visited. These include the alluvial fans in Death Valley and White Mountains California (visited in March, 1983); some debris flow deposits in canyons with no fan morphology in Baja California; and some Pleistocene inactive alluvial fan deposits exposed in coastal cliffs in San Felipe.

All the geologic maps and air photos are presented along with the description of the individual fan facies distribution and interpretation (Chapters 5 and 6) and selected folded-photologs are included in the back cover.

4.1 FACIES DESCRIPTION CRITERIA:

Facies description in this study is entirely based on the photologs. Consistent estimations of sedimentological characteristics such as sorting, packing and texture were done by means of comparison charts (Appendix II). Features such as clast size and imbrication are not direct field measurements. Texture was too variable to be described only as being matrix or clast supported, since a combination of both often occured. Therefore, an area percent scale was used; as an example, a 70 % clast supported texture means that 30 % of the area observed in the photolog is matrix supported.

The boundaries between "beds" are only an attempt to describe separately those parts of a section whose texture was noticeably different from one another. However, they may or may not represent real individual events of deposition.

Slope estimations were derived from topographic maps (Figs. 5.3 and 6.2).

4.3.1 Facies A:

Facies A consists of poorly sorted clasts from 0.8 up to 5.0 m in diameter. They are 60 to 100 % clast supported. The matrix, if any, is relative to the coarsest clast framework, therefore it may consist of poorly sorted boulders, cobbles, pebbles and minor amounts of coarse sand. The coarsest clasts generally exhibit a well developed imbrication in the upflow direction. Inverse grading is present in a few cases (Fig. 1, Appendix III).

4.3.2 Facies B:

Facies B consist of poorly to well sorted clasts, generally within 10 to 40 cm in diameter, In a few localities, a few coarse blocks and boulders may be scattered about the deposit. The texture is 60 to 100 % matrix supported (or 40 to 0 % clast supported). The matrix consists of relatively well sorted clasts, ranging from fine pebbles to mainly coarse sand with a few percent content of fines. Imbrication, grading and stratification are rare (Fig. 2, Appendix III).

4.3.3 Facies C:

Facies C is very similar to Facies A; however, it is distinguished by being 70 to 100 % clast supported, and having little if any matrix, therefore large voids are characteristic. Imbrication, grading and stratification are rare to absent (Fig. 3, Appendix III).

4.3.4 Facies D:

Facies D has exactly the same characteristic as Facies C, but is distinguished by being considerably smaller in terms of grain size. Facies D is mainly composed of cobbles to fine pebbles (Fig. 4, Appendix III).

4.3.5 Facies E:

Facies E is composed of well sorted pebbles and gravels, 80 to 100 % clast supported. Grading is normal and stratification is common, although it is not an internal stratification as in fluvial facies (Fig. 5, Appendix III).

4.3.6 Facies F:

Facies F is used in this study to designate all those fluvial facies occurring in the sandflat area.

CHAPTER 5

SIERRA JUAREZ ALLUVIAL FANS

5.1 INTRODUCTION:

Sierra Juarez is covered on the east side by an alluvial apron ranging from one to three km long measured at right angles to the mountain front. Las Palmas and La Poderosa fans are part of the semi-closed playa basin Laguna Salada (Fig. 5.1A). San Felipe Fan is 120 km south of Las Palmas Fan where the alluvial apron is broader (up to 5 km long) and extends towards the gulf coastal plains (Fig. 5.1B). The characteristics of these three fans along with comparable fans in Death Valley are listed in Table 5.1.

5.1.1 Location and Accessability:

La Poderosa and Las Palmas fans are located 50 km southwest of Mexicali, Baja California (Fig. 1.6). Access to these fans is by Mexican highway 2 West; 500 m past the

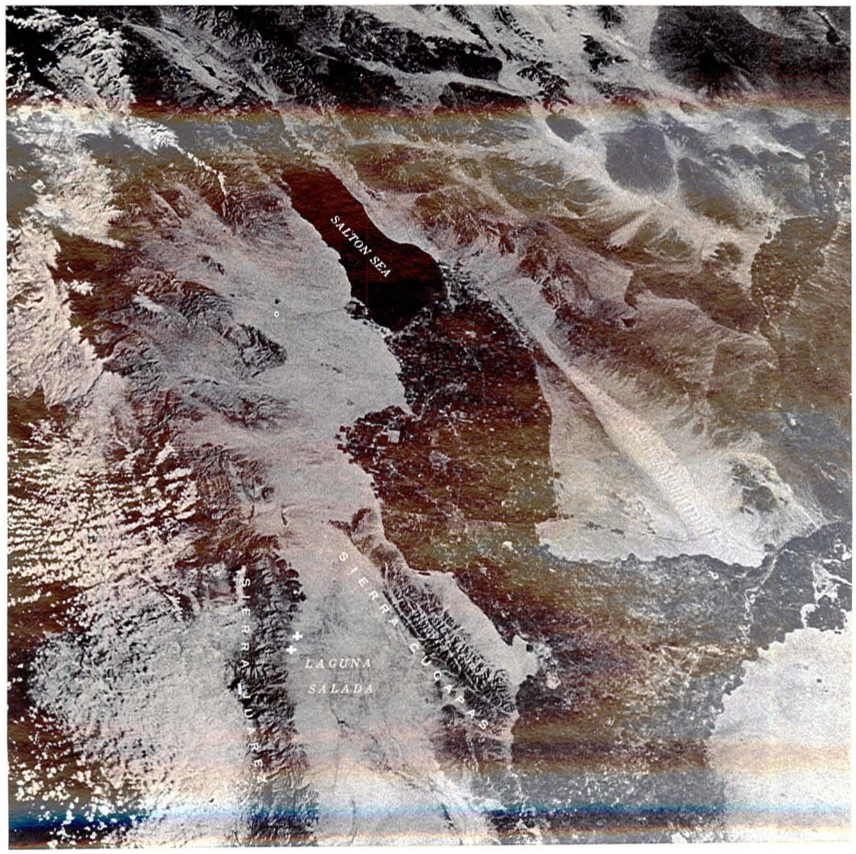
Fig. 5.1 Sierra Juarez alluvial fans.

A: La Poderosa and Las Palmas fans. Note the narrow and steep drainage basins. Distance from summit to mountain front is approximately 10 km^2. The alluvial belt along the west side of Laguna Salada is 3 km^2 in average width.

B: San Felipe fan. Note that the alluvial belt is wider than the fans in Laguna Salada, although the relief of the drainage basin is smaller.

White crosses indicate the position of the fans. Photographs were taken by Apollo 6 (From Hamilton, 1971).

A


SALTON SEA
SIERRA CUCAPAS
SIERRA JUAREZ
LAGUNA SALADA

B

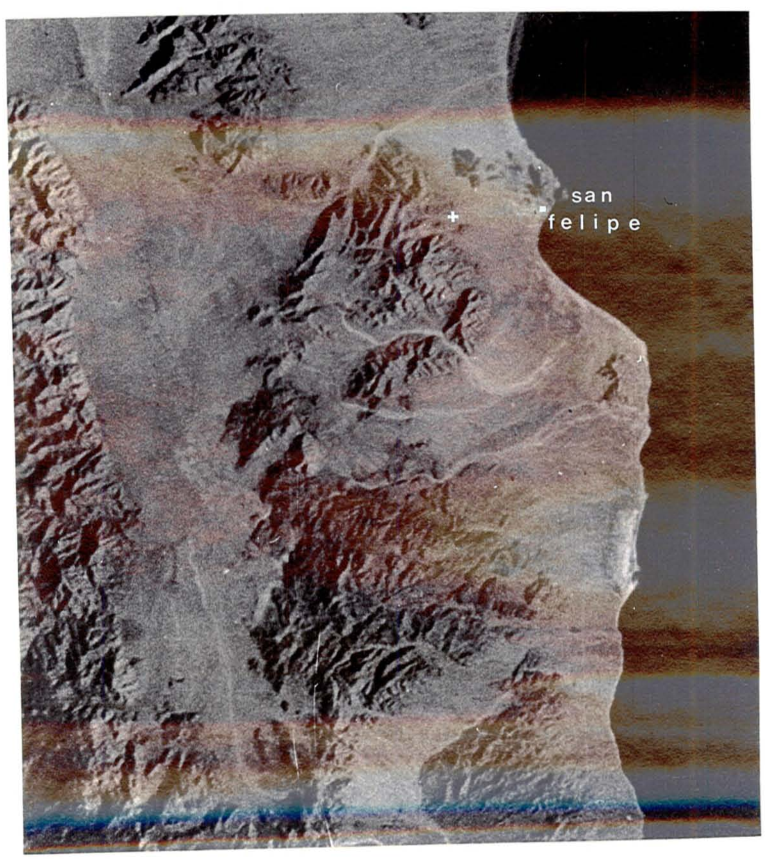

san felipe

TABLE 5.1

Comparable dimensions of the studied fans with other fans in Death Valley, California.

	DRAINAGE BASIN			FAN		
Fan Name	Summit	Area	Relief	Thickness	Length	Area
	m	km^2	m	m	km	km^2
Las Palmas	1380	3.9	1160	220	2.6	2.6
La Poderosa	1400	6.8	1100	300	3.2	5.3
San Felipe	830	7.4	670	160	4.8	10.9
Johnson Cn.	2920	28.6	2273	132	10.4	23.2
Copper Cn.	1867	35.6	1812	146	2.4	3.6
Shadow Mt.	1537	4.4	482	85	9.6	14.3

Death Valley fans data source: Denny, 1965.

gas station El Puerto turn left at "Guadalupe" road sign. This dirt road follows the sandflat belt. There are many side roads to the playa, but the road always keeps to the left. La Poderosa and Las Palmas fans are located 30 km south of the turn off the highway. The only landmark nearby is an abandoned hut. The fans can be then distinguished from the road by their conical shape one adjacent to the other. It is strongly recommended to look for a good firm sand spot to stop beside the road. La Poderosa is the first fan. It is difficult to see the main channel of this fan due to the height of the bushes on the extensive sandflat; however, the canyon is always visible in the mountain front and the channel may be found by trial and error. Once in the fan toes, where 20-30 cm boulders become abundant, follow the channels with the brighest gray-tone boulders, which eventually lead to the active channel. The total distance between the road and the apex can be covered within a 3-hour walk. Las Palmas fan, 5 km south of La Poderosa may be reached in the same way although the walking distance is one hour shorter.

San Felipe fan is located 5 km west of San Felipe, Baja California (Fig. 1.6). Access to this fan is by Mexican highway 5 North. Two km out of San Filipe, turn left at "Col. San Pedro Martir" road sign, follow this dirt road until the first "Y" bifurcation and turn left, follow the straight road (bordered by a wire fence) until the "T" bifurcation and turn left. The corner of this bifurcation is a good place to park the vehicle. The apex of the San Felipe fan can be seen towards the southwest from this corner. Vegetation on this sandflat is scattered enough so that the modern washes and channels may be seen and followed. The total distance between the road and the apex can be covered in two hours.

5.1.2 Lithology:

Sediments constituting the coarse-grained fans in the study area are derived directly from the Peninsular Ranges Batholith. Most plutons in the area are of Mesozoic age and intrude metamorphosed stratified rocks of Jurassic and Cretaceous age.

Sierra Juarez, the source rock of Las Palmas and La Poderosa fans is composed of unfoliated granite, granodiorite and adamellite plutons. Very small amounts of boulders are derived from metamorphic rock sources.

Sierra San Felipe is an isolated pluton of unfoliated tonalite and undifferentiated granitic rocks.

The area has been regionally mapped by Gastill *et al.* (1975). Their term "tonalite" is used parallel to "granite" and "granodiorite" to indicate a rock with appreciable quartz content (> 10 percent). "Adamellite" is used for rocks containing less than 10 percent quartz.

5.1.3 Topography:

Sierra de Juarez is a mountain block with rough and steep bedrock slopes. The western boundary is remarkably linear and is fault-controlled (Fig. 1.3).

Drainage is largely controlled by structure, the trends of major drainways are predominantly northeast. V-shaped valleys are characteristic and their steep bare rock slopes comprise about 90 percent of the drainage basin. Slope angles on bare rock drainage basins average 22° but sections steeper that 40° are found at La Poderosa and Las Palmas drainage basins and a maximum of 30° in San Felipe. These slopes are cut in their upper reaches by numerous chutes which direct runoff and facilitate the removal of coarse unstable debris (Fig. 2.4).

5.2 LAS PALMAS FAN:

5.2.1 Morphology:

Las Palmas fan is nearly conical shaped (Fig. 5.2).

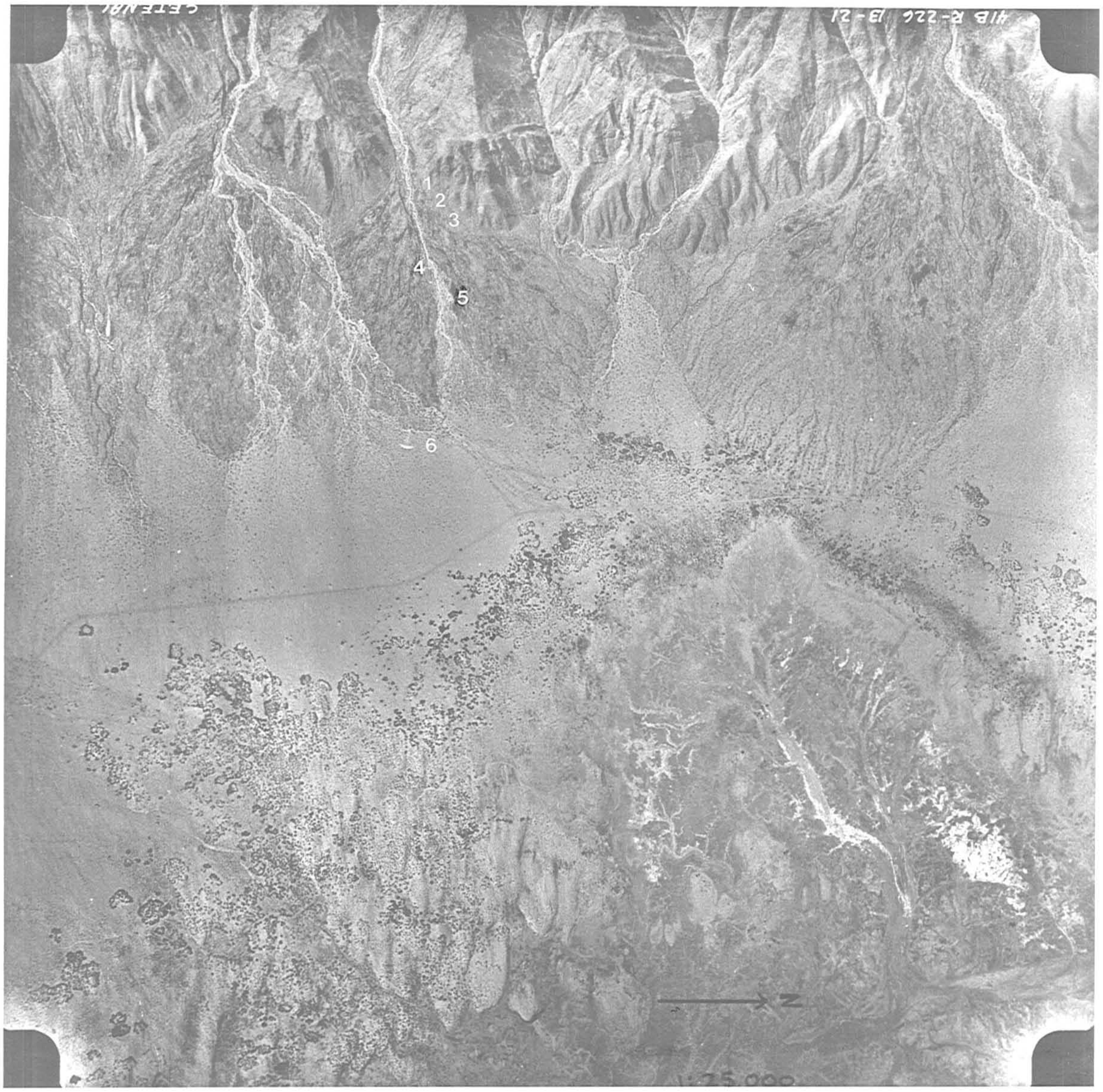


Fig. 5.2 Las Palmas fan. Location of described sections.

The maximum thickness of the fan at the apex is 220 m; the maximum radial distance from the apex to the most distal reach of the toe is 2590 m. The average slope of the drainage basin is 22.3°, the fan surface averages 5.7° and the sandflat surface averages 0.9° (Fig. 5.3A).

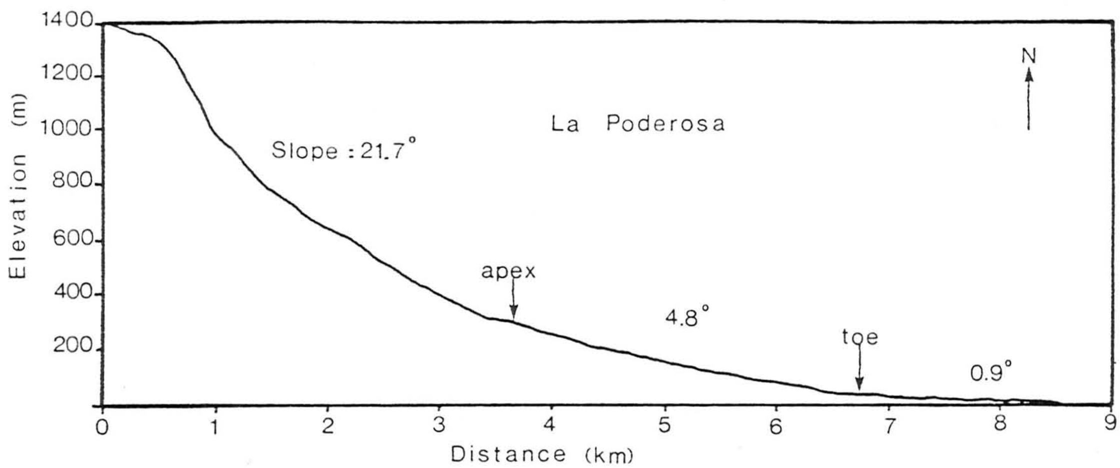
The fan surface area is 2.6 km^2. The surface is longitudinally dissected by a nearly straight main channel oriented NE. At the apex, the main channel is 80 m wide and 3 m deep, and its surface is in turn incised by a narrower, 30 m wide and 4 m deep, active channel.

The active channel merges into the main channel at about 800 m from the apex, and continues for another 500 m before it merges with the fan surface, and becomes moderately braided at the intersection point. The average depth of the channels gradually decreases from 1.75 m at the intersection point to 40 cm at the fan toe, where the braided channels merge with the sandflat and shallow rapidly.

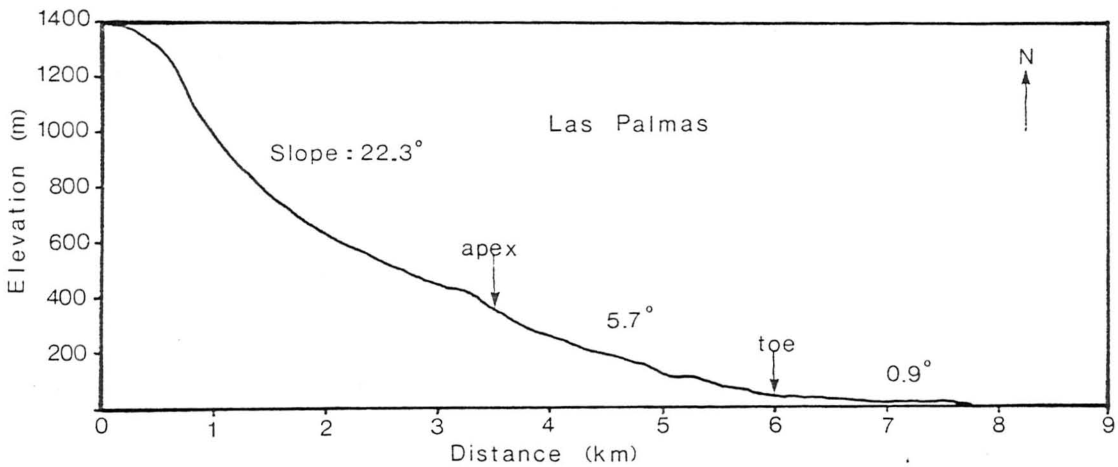
The entire area of the main channel from apex to toe comprises less than 5% of the fan surface, and 90% of the main channel surface area is distributed below the intersection point. This means that the active channel must shift radially rather often in order to maintain a uniform deposition over the whole fan surface.

Relative age of the channels can be clearly

DRAINAGE LINE & FAN ACTIVE CHANNEL CROSS SECTIONS



A



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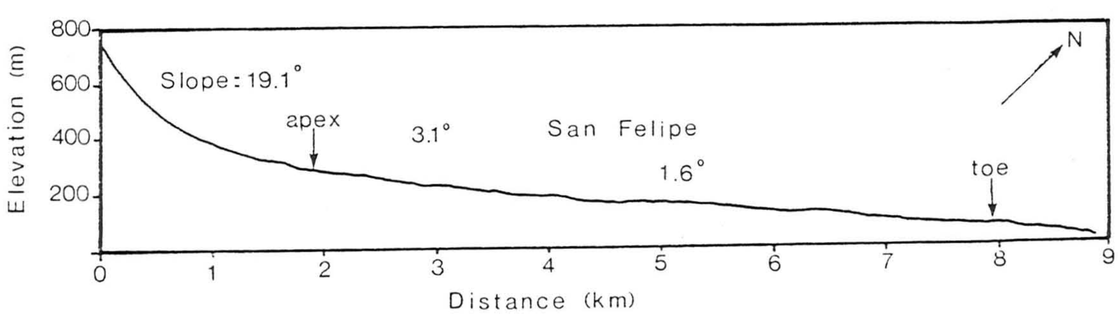


C

Fig. 5.3

distinguished by the nearly white colour of the most recent channel beds. Various hues of brownish-red are due to desert varnish indicate aging of abandoned channels, the oldest being a very dark brown. Las Palmas fan surface is radially incised by abandoned channels which show relative ages that are symmetrical on both sides of the active channel (Fig. 5.2). This indicates that deposition has occurred nearly uniformly throughout the entire fan surface, but particularly past the intersection point.

The oldest deposits on the fan surface can be distinguished in the air photograph as dark patches beside the abandoned channels. Close inspection in the field reveal that these deposits have been sieved out leaving a wide open fabric. Blocks are up to 8 m in diameter. In the lower fan, sieve deposits are not so coarse, the largest blocks being 1 to 4 m in diameter.

The main characteristic of the older deposits is their very dark desert varnish coating. The boulder surface has been deeply eroded producing a rough and sharp relief which is extremely friable. The wide open fabric has been partially filled by grus derived from the boulders' fragile surface.

The largest of the oldest deposits is located on the central north side of the active channel (Fig. 5.2). It is about 2.5 m high, 30 to 40 m average width and 300 m long.

Textural characteristic are: poorly sorted clast supported; randomly oriented. They can be described as a pile of debris. Deposits of this type account for only about 7 % of the fan surface.

In contrast, boulders found in the main and active channel are well rounded, with a smooth surface texture and bright gray colour. In sites where the active channel cuts through the older deposit, eroded and desert varnish-coated boulders are not found. This suggests that very little reworking is required to "clean" the friable varnish crust from a boulder.

5.2.2 Description:

The following sections are presented in Photolog 5.1. A facies guide is included in Appendix I. Location of described sections is shown in Figure 5.2.

Section 1 is located near the apex. It is 6 m thick and over 30 m long. The slope may not be greater than 4^{o} or 5^{o}. A "void horizon" clearly separates the section into lower and upper parts.

The lower part has a maximum thickness of 2.1 m. The ten largest clasts; ranging from 2.0 to 0.4 m in diameter, are poorly sorted, loosely packed, poorly imbricated and 70 % clast supported. The matrix consists of poorly sorted cobbles and coarse sand. Inverse grading is moderately developed.

The upper part of the section is a complex mosaic of many different conglomerate textures with very little lateral continuity. However, a texture resembling fresh concrete is present in heterogeneous patches randomly distributed throughout the upper part of the section. These patches consists of poorly sorted pebbles and coarse sand supporting boulders up to 1.7 m in diameter.

Section 2 is located in the apex area. It is 7 m high and over 30 m long. The slope may not be greater than 5^{o}. The lower west part is covered by a 5 m long talus. The ten largest clasts, ranging from 5.5 to 2.2 m in diameter, are poorly sorted, loosely packed, six of the ten largest clasts are imbricated in the upflow direction, and 90 % of the area is clast supported. The matrix consists of poorly sorted cobbles and coarse sand. Some of the conglomerate is inversely graded. Large scattered voids are common.

Section 3 is located between the apex and the intersection point. It is 4 m high and over 33 m long. The section can be clearly divided into upper and lower parts due to contrasting textural characteristics. The lower part of the section is 1.0 to 2.0 m thick. The ten largest clasts, ranging from 3.7 to 0.8 m in diameter are poorly sorted, loosely packed, and well developed imbrication, and are 90 % clast supported. The matrix consists of poorly sorted pebbles and coarse sand.

The upper part of the section is 2 to 3 m thick. The well sorted clasts are 0.1 m in average diameter. They are well packed, well imbricated and 90 % matrix supported. The matrix consists of very cohesionless and poorly sorted gravels to coarse sand. The general appearance of this deposit resembles that of fresh concrete.

Section 4 is located near the intersection point, is 4.5 m high and over 30 m long. The lower part of the section consists of several conglomerate bodies ranging from 100 % clast supported boulders on the right side to 100 % matrix supported cobbles and boulders on the left side.

The upper part of the section is 2.2 m thick. The average clasts size is 0.2 m in diameter. Sorting varies from relatively good at the bottom to poor at the top. Matrix-supported texture varies from 100 % at the bottom to 50 % at the top, although a few isolated areas are 100 % clast supported. There is a significant content of elongated clasts parallel to the bed and some of them are imbricated. The matrix consists of well sorted coarse sand with a few percent content of fines as revealed by grain size analysis. There is an overall inverse grading. Very crude stratification is present and consists of changes in both clast size and matrix content percent.

Section 5 is located near the intersection point. It is 2.3 m high and over 20 m long. The slope of various stratified planes on the outcrop may not be greater than 1^{o}. The gemeral appearance of this section is of a crudely bedded conglomerate. The lateral continuity of the beds is not greater than a few meters. In most of the beds the clasts are coarsening downslope.

The ten largest clasts of the crudely bedded material range between 0.3 and 0.05 m in diameter; they are moderately sorted, relatively well packed and 90 to 50 % clast supported. The matrix material consists of poorly sorted pebbles to coarse sand. Inverse and normal grading result from crude bedding.

The easternmost part of the section exhibits a rapid coarsening of the boulders up to 0.7 m in diameter.

Section 6 is representative of the braided channels in the fan toe area. The ten largest clasts range between 0.3 and 0.08 m in diameter; they are poorly sorted, loosely packed, the elongated clasts seem to be parallel to flow direction and some are imbricated in the upflow direction. The texture is 50 %

clast supported; the matrix material consists of gravels and coarse sand. Inverse grading is well developed.

The sandy bodies are generally interfingering with the conglomerates. Coarse sand stratification is well developed; a few imbricated pebbles are common.

5.3 LA PODEROSA FAN:

5.3.1 Morphology:

La Poderosa fan has a well developed conical lobe shape whose axial orientation is towards the south-east. However, a new and smaller lobe is being developed by the present main channel oriented towards the north-east (Fig. 5.4).

The maximum thickness of the fan at the apex is 300 m. The maximum radial distance from the apex to the most distal reach of the toe is 3200 m. The average slope of the drainage basin is 21.7°, the fan surface slope averages 4.8° and the sandflat surface averages 0.9° (Fig. 5.3B).

The fan surface area is 5.3 km^2. It is longitudinally dissected by a lateral main channel oriented northeast. At the apex the main channel has a maximum width of 75 m and is 4 m deep, its surface is in turn incised by

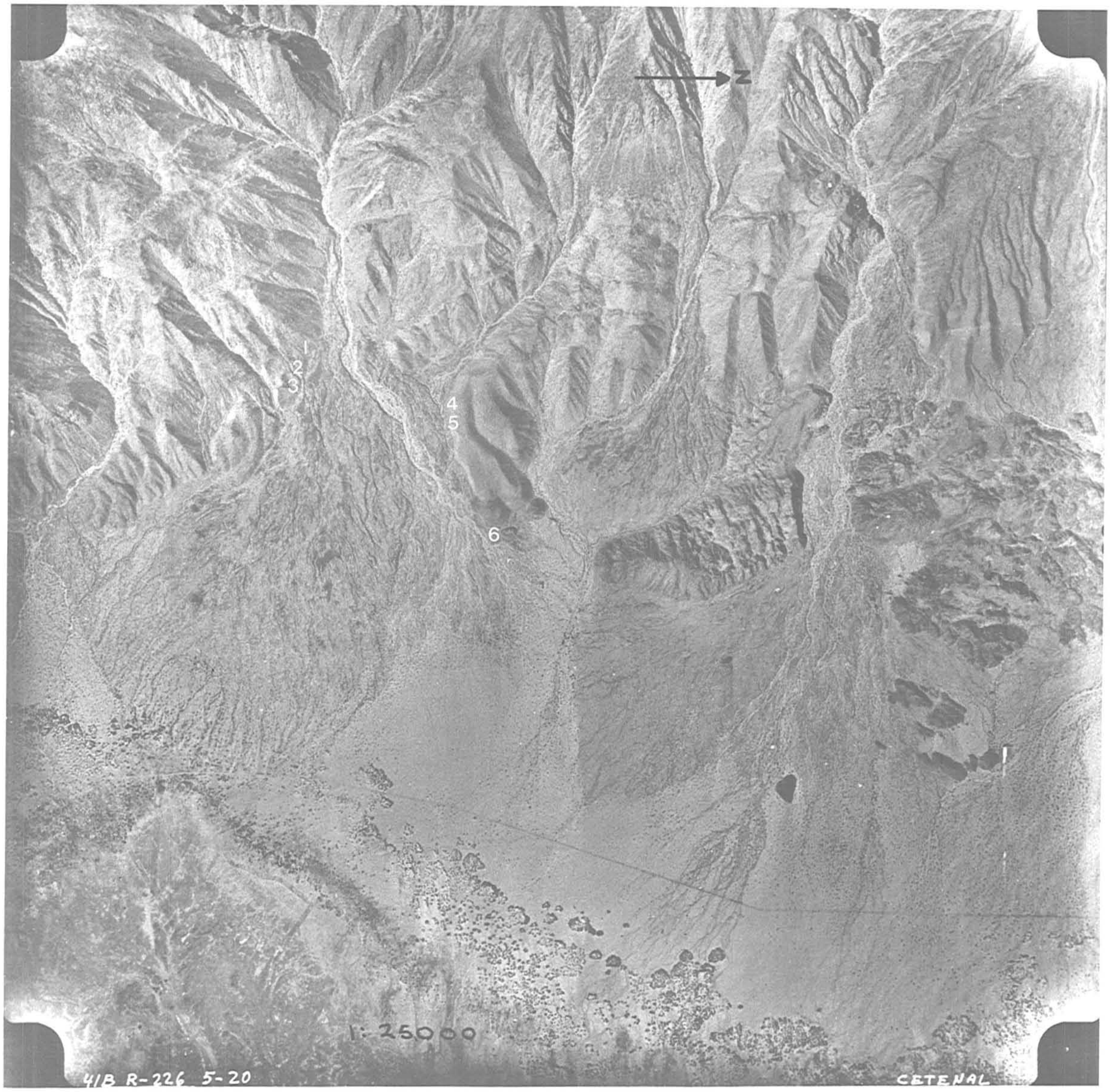


Fig. 5.4 La Poderosa fan. Location of described sections.

braided active channels up to 20 m wide and 2 to 3 m deep. At about 1000 m below the apex, the braided active channels converge into a meandering channel 25 m wide and less than 0.7 m deep. At this point the channel merges to the fan surface and continues for approximately 275 m before it braides out towards the sandflat. The entire area of the main channel comprises less than 7% of the fan surface, and 60% of the main channel surface area is distributed below the intersection point.

The rest of the fan surface area is incised by a web of complicated abandoned braided channels, as deep but not as wide as the main channel. The relative age of these channels can be inferred by the colour of their channel-bed boulders and the "sharpness" of the channel incision, the oldest ones being dark-coloured and shallower with no sharp walls. A general tendency of these abandoned channels to be younger towards the northeast can be distinguished from the air photograph (Fig. 5.4). A fault scarp in the north mountain block and a truncated arroyo suggest that the main channel may be in its present position due to a north-tilting of the fan block.

The oldest deposits on the fan surface can be distinguished in the air photograph as dark patches alongside the abandoned channels. They cover approximately 20% of the fan surface.

5.3.2 Description:

The following sections are presented in Photolog 5.2. A facies guide is included in Appendix I. Location of described sections is shown in Fig. 5.4.

Section 1 is located near the apex. It is 7 m thick and over 50 m long. The slope of the outcrop bedding plane may not be greater than 3^{o}. Upper and lower parts of relatively constant thickness can be distinguished. The upper part is 5 m thick. The ten largest clasts ranging between 4.4 and 1.0 m is diameter are: poorly sorted, moderately packed, and 60 % clast supported. The elongated clasts seem to be parallel to bedding but not imbricated. The matrix consists of poorly sorted cobbles to coarse sand. Inverse grading is well developed, particularly in the three coarsest "clusters" located in the upper part of the section.

Section 2 is a continuation of section 1 in the downslope direction. The middle-central part, which has not been affected by rockslides, is 2 m thick and over 25 m long. The ten largest clasts ranging between 1.7 and 0.4 m in diameter are: poorly sorted, well packed, at least half of the clasts are imbricated in the upflow direction and texture is 95 % clast supported. The matrix consists of

5.4 SAN FELIPE FAN

5.4.1 Morphology:

San Felipe fan has a short conical shape near the mountain front, beyond which it coalesces with extensive bajada deposits (Fig. 5.5). The maximum thickness of the fan at the apex is 160 m. Maximum radial distance from the apex to the most distal reach of the toe is 4850 m. The average slope of the drainage basin is 19.1°, the fan surface averages 3.1° and the sandflat surface averages 1.6° (Fig. 5.3C).

The fan surface area is 10.9 km^2. The surface is longitudinally dissected by a northeast-deflected main channel. At the apex the main channel is 50 m wide and 3 m deep. Other fan surface characteristics are not available.

5.4.2 Description:

The following sections are presented in Photolog 5.3. A facies guide is included in Appendix I. Location of described sections is shown in Fig. 5.5.

Section 1 is located between the apex and the intersection point. It is 3 m thick and over 16 m long.

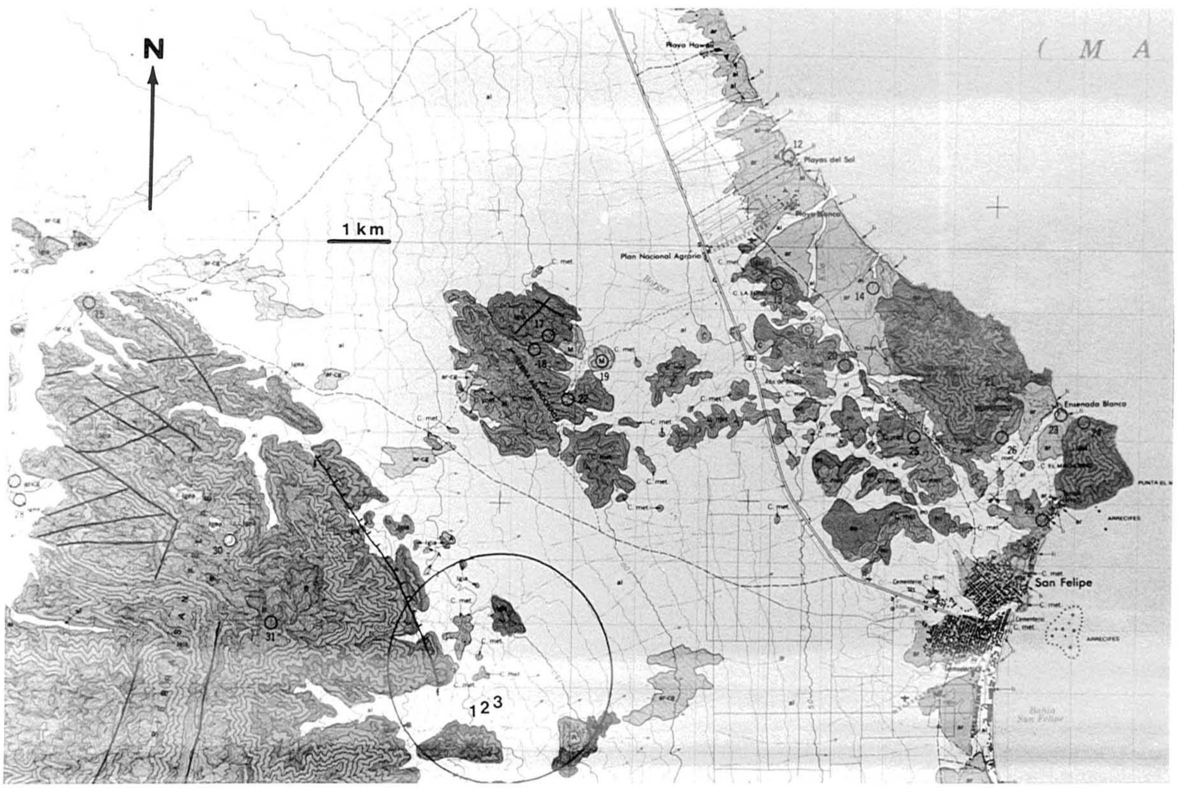


Fig. 5.5 San Felipe fan. Location of described sections.

The slope of the outcrop horizontal plane may not be greater than 2^{o}. The section can be divided in two parts which are texturally different.

The first one occupies the westernmost end and all of the upper part of the section. Maximum thickness is 3 m in the West and 0.8 m in the East. Average clast size is 0.2 m, clasts are relatively well sorted, loosely packed and 60 % clast supported. The matrix consist of poorly sorted pebbles to coarse sand. The clasts are moderately imbricated in the upflow direction.

The second conglomerate occupies the lower central and eastern part of the section. Maximum thickness is 1.5 m and is over 12 m long. The ten largest clasts range between 20 and 5 cm in diameter; the clasts are poorly sorted, loosely packed and 100 % matrix supported. The matrix consists of poorly sorted gravels to coarse sand, there is no imbrication. Inverse grading is apparent due to the presence of coarser conglomerates above.

<u>Section 2</u> is located adjacent to Section 1 in the downslope direction. It is 3 m high and over 14 m long. The ten largest clasts range between 1.0 and 0.4 m; the clasts are poorly sorted, loosely packed and 90 to 50 % clast supported. The matrix consists of poorly sorted pebbles to coarse sand. There is no imbrication.

Section 3 is located near the intersection point. It is 1.8 m high and over 8 m long. The section can be divided into three different textures roughly parallel to each other.

The lower part has a maximum thickness of 1 m. The ten largest clasts rang between 0.7 and 0.5 m in diameter; the clasts are well sorted, well packed and 100 % clast supported. Imbrication is very well developed in the upflow direction.

The middle part of the section is "draping" the underlying deposit and it ends up in a nearly flat surface. The average clast size is 4 cm, the clasts are moderately sorted, moderately packed and 100 to 50 % clast supported. The matrix consists of poorly sorted pebbles to coarse sand. Imbrication is not present. Normal grading is well developed at the bottom of the deposit.

The upper part of the section is resting on a slope not greater than 3^{o}. The average clast size is 0.1 m, the clasts are moderately packed and 80 % clast supported. The matrix consists of gravels to coarse sand. The clasts are roughly parallel to the bed. Close inspection in the field revealed that the matrix is infiltrated because of its well sorted nature and a faintly developed lamination.

5.5.2 Facies C:

The main characteristic of this facies is the 100 % clast-supported texture. The coarseness of the clasts is similar to facies A. Facies C is generally forming a single rough "bed". This is interpreted as being the result of stream flood reworking of original facies A.

Facies C occurred mainly capped most of the incised channels, therefore it is assumed that the upper fan-surface is covered by facies C. There is a clast size reduction downfan and a gradual reduction of the 100 % clast supported characteristic of facies C; this generally occurs past the intersection point.

5.5.3 Facies B:

The salient characteristic of this facies is the "fresh concrete" appearance. It is less coarse than facies A and C and it is 50 to 100 % matrix supported. The matrix may range from fine pebbles and gravels to nearly pure coarse sand. This facies is interpreted as being deposited by coarse dispersed debris flow, where the clast support mechanism is relative to grain-size fractions. The pebble and gravel mixture generates dispersive pressure by interparticle collisions, whereas the dispersed cobbles and boulders are supported by matrix strength (Las Palmas fan; section 3, and La Poderosa fan; section 5). In the other case, when the matrix is composed of nearly pure coarse sand (Las Palmas; section 4) inverse grading is also associated with a gradual upwards decrease in the amount of sand. Matrix strength is thought to be the main mechanism of maintaining the clasts in dispersion.

5.5.4 Facies D:

This facies is similar to facies C but in a smaller clast size range of cobbles and pebbles. Although originally 100% clast supported, facies D usually contains allochthonous matrix capping the deposit. Facies C and D grade laterally on the fan surface particularly past the intersection point (La Poderosa; section 6, Las Palmas; section 5). It is interpreted as being a channel-lag material reworked by subsequent stream floods, which provide the secondary matrix.

5.5.5 Facies F:

This facies is perhaps the most abundant, volumetrically, in the alluvial fan environment. It occurs in the fan toe covering a wider area than any other facies. The predominance of flat beds of coarse sand suggests upper flow regime deposition. Facies F contains a few percent of fines (silts and clays) indicative that most of the suspended load continues to flow towards the playa.

CHAPTER 6

SIERRA CUCAPAS ALLUVIAL FANS

6.1 INTRODUCTION:

Sierra Cucapas is covered in the east side by an impressive apron of bajada deposits (Fig. 5.1). Towards the southwest, individual alluvial fans debouch from fault-controlled canyons and spread over the Colorado River delta plain. Although these fans are rather small, they were included in this study because of their accessibility and the existence of good outcrops in gravel pits.

6.1.1 Location and Accessibility:

La Puerta and El Pantano fans are located 45 and 60 km southeast of Mexicali, respectively. Access to these fans are by Mexican highway 5 South. La Puerta Fan is located at La Puerta village, the highway dissects the fan toe area. El Pantano Fan is located at El Mayor village, the outcrop may be reached by following the gravel pit signs 300 m past the "El Mayor" gas station.

6.1.2 Lithology:

Sierra Cucapas has a very similar lithology to Sierra Juarez; Mesozoic intrusive rocks, largely granodiorite and adamellite plutons. However, large blocks of metasedimentary rocks of Cretaceous age are more abundant than in Sierra Juarez. At least 25% of the clasts in La Puerta fan and 10% in El Pantano fan are of metamorphic origin. These source rocks strongly influence the composition of the fines in the fans, by increasing the mica flake content.

6.1.3 Topography:

Sierra Cucapas and its southward extension Sierra del Mayor where La Puerta and El Pantano fans are respectively located, have a maximum elevation of 1110 and 963 m. The Colorado River delta plain has a maximum elevation of 43 m at its head in Yuma, to a minimum of 11 m, where it encroaches with Sierra Cucapas.

Drainage in Sierra Cucapas is largely controlled by fault-generated drainways (Fig. 5.1). Slope angles on bare rock drainage basins average 18° but sections steeper than 30° are found at El Pantano and a maximum of 21° at La Puerta drainage basins.

6.2 EL PANTANO FAN:

6.2.1 Morphology:

El Pantano fan has a wide conical shape (Fig. 6.1). The thickness at the apex is 120 m. The maximum radial distance from the apex to the toe is 2.4 km. The average slope in the drainage basin is 20.7°, the fan surface averages only 1.4° (Fig. 6.2B). The fan area is 1.8 km^2. The surface of the fan is very smooth, the main channel diverges past the apex into two shallow channels not deeper than 1 m. Older channels are not distinctive from the ground. There are two older deposits in the mid fan area, clearly distinguished by their heavy coating of desert varnish. The canyon linking the drainage basin with the fan is a wide smooth alluviated stream course in which the apex is arbitrarily chosen at the narrowest point of the canyon. El Pantano fan toe passes directly into the mudflat with no sandflat transition. An open pit cut by bulldozers on the

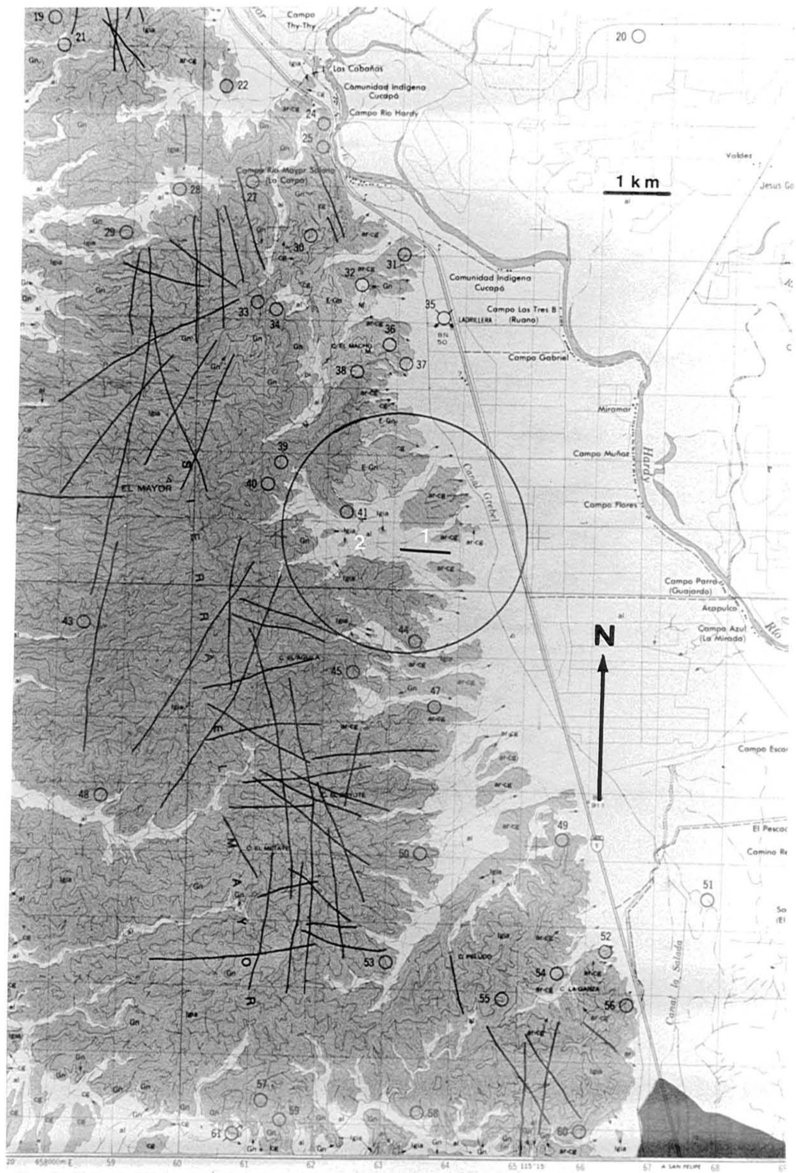
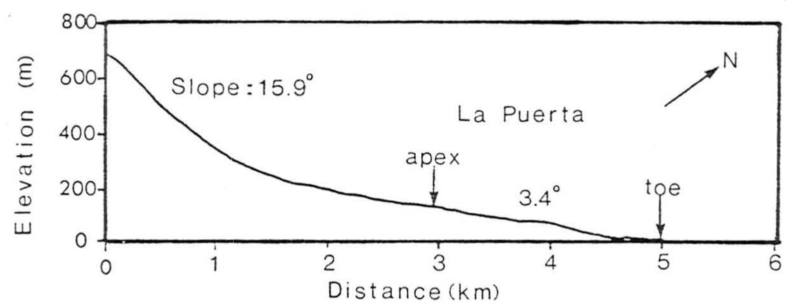


Fig. 6.1 El Pantano fan. Location of described sections.

DRAINAGE LINE & FAN ACTIVE CHANNEL CROSS SECTIONS



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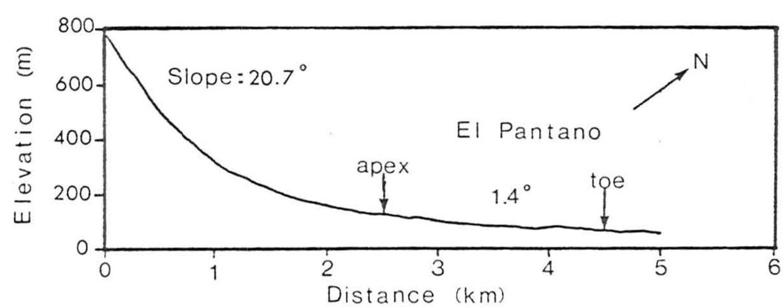


B

Fig. 6.2

medial part of the fan is the only longitudinal outcrop available since the upper fan channels are very shallow.

6.2.2 Description:

The longitudinal section is located past the intersection point (Appendix I; Photolog 6.1). It is 2.8 m high and over 100 m long. The upper surface of the pit is remarkably flat. The entire outcrop is composed of crudely bedded cobbles and gravels, all of the contacts are gradational forming fining and coarsening upwards sequences with no overall trend. A very few channel-fill structures were found oblique to the outcrop.

The thickness of the beds vary from a few centimetres to a maximum of 15 cm. The length of the beds can be traced up to a few metres. Even where a long horizontal plane can be distinguished it does not seem to be formed by a single bed, but rather by a discontinuous layer of beds lying on the same plane.

The channel fill structures (4 in the 100 m outcrop) are not thicker than 20 cm and vary in width from 1 to 2 m. They are filled with pebbles and coarse sand which are crudely stratified. They generally cut through slightly coarser conglomerate.

The upper part of the fan, near the canyon, is covered by a surface of relatively uniform grain-size consisting of 5 to 10 cm pebbles. The few incised channels are not deeper than 1 m and are generally 3 to 5 m wide. Their walls reveal a finer grain size composition of gravels and pebbles; this gives a coarsening upwards appearance (Photolog 6.1). Crude bedding is scarce at this site.

6.2.3 Interpretation

El Pantano fan seems to be entirely formed by sheetflows. The upper part of the fan presents good evidence of wide extensive tongues of coarse sheetflows of relatively well sorted grains and uniform thickness. The width and the slope of the canyon probably facilitates the formation of such sheetflows.

The thickness of the crude beds found on the intersection point area seem to be closely related to their grain size, suggestion that they were deposited by tongues as thick as the maximum clast size. The lack of interclast voids suggests either that the original slurry was not further washed out by stream flow activity or that the matrix has percolated from above.

The scarcity of channel fill structures as well as the barely incised fan surface suggests that stream flows are, in fact, rare.

The well developed orientation of the elongated clasts parallel to bedding suggests that the clasts were transported very close to the bed, probably sliding and rolling.

6.3 LA PUERTA FAN:

6.3.1 Morphology:

La Puerta fan has a perfect conical shape (Fig. 6.3). The thickness at the apex is 120 m. The maximum radial distance from the apex to the toe is 2.0 km. The average slope of the drainage basin is 15.9°, and the surface averages 3.4° (Fig. 6.2A). The fan area is 1.4 km^2. The fan surface is relatively smooth, a main channel runs in the axial plane of the fan. Maximum depth of the channel at the apex is 60 cm. Older channels depart radially from the apex, however their relative age is not contrasted by various hues of desert varnish as in previously described fans; instead, the entire surface seems to be covered by uniformly young sediment, lightly coated with desert varnish. The apex is very wide and gives the appearance that the fan has backfilled the canyon far into the drainage basin. La Puerta fan has no sandflat; it

Fig. 6.3 La Puerta fan. Location of described sections.

passes directly into flat cultivated fields. Mexican highway 5 cuts the toe of the fan transversally exposing a better outcrop than those along the main channel.

6.3.2 Description:

The transversal section along the fan toe is 2 m high and over 70 m long (Appendix I; Photolog 6.2). Some parts of the section are longitudinally cut by gullies or eroded into talus. The outcrop exhibits crude bedding composed of boulders and cobbles, and a few channel-fill structures. Despite being located in the lower part of the fan and adjacent to the Colorado River delta plain, very little interfingering of fines was observed.

The crude beds are composed of a flat layer of cobbles generally lying over fine pebbles and coarse sand beds. The length of the beds rarely exceed 3 m.

The channel-fill structures are difficult to observe due to their coarseness. Only 3 were observed in the 70 m section, although more may be present but masked by texture or eroded talus. The best exposed channel-fill (Photolog 6.2) is the largest one found. It is 3 m long and nearly 1 m thick, and composed of poorly sorted and moderately packed boulders and cobbles ranging 35 to 5 cm in diameter. They are 100% clast supported although a little matrix material, consisting of pebbles and coarse sand, remains in some voids. Orientation of clasts is random, imbrication is poorly developed, although if field measurements were done probably there will be a good imbrication and preferred orientation of clasts since this is a transverse-to-flow section. Grading and stratification are absent. The channel cuts through a finer grained conglomerate of cobbles and coarse sand. The two other channel-fill structures are nearly identical but on a smaller scale, both in clast size and width and length of the channel fill.

In the medial part of the fan surface, near the intersection point, numerous shallow braided channels are found (Photlog 6.2). Levees up to 50 cm high are common; they are composed mainly of boulders 20 to 30 cm in diameter with cobbles but no matrix. Between levees bordering the braided channels, flat sieve deposits are common, consisting of a veneer of mainly cobbles and very few boulders. Typical dimensions of these deposits are a few 10's of metres long and 10 to 15 m wide.

In the upper fan area, just below the canyon, the most recently incised channel varies from 20 to 60 cm deep and over 30 m long, although frequently eroded into talus. Most of the outcrop consists of poorly sorted cobbles and a few boulders embedded in a pebbly gravelly matrix rich in coarse mica flakes. Imbrication up to 30^{o} upflow is common and occasionally, clast supported lenticular bodies are found. Most of the section surface is evenly flat due to the high content of water-laid coarse sand.

6.3.3 Interpretation:

La Puerta fan seems to be largely formed by debris flows and some sheet flows. Most of the debris-flow sieve deposits found near the apex suggest subsequent stream-flow reworking. The unexpected coarseness of the clasts in some parts of the fan toe area is probably indicative of unusually high flood events in the recent past. However, the lack of deeply incised channels in the present-day fan surface and the significant fining upwards texture found at the apex area channels, suggest that the most recent events have been dominated by sheet flows rather than debris flows. This may account for the relative smoothness of the fan surface and the canyon bed.

CHAPTER 7

ANCIENT ANALOGUES

7.1 INTRODUCTION:

The modern megafanglomerates of Laguna Salada are unique to their tectonic/climatic framework. This type of sedimentary environment is certainly restricted to a few deserts of the world today and in the past. Therefore, the probability that similar megafanglomerates will be represented in the geologic record is rather small. Nevertheless, an extensive search was made in the literature for ancient analogues. The easiest approach was to locate those batholiths in the North American cordillera which were under a semiarid climatic regime in the recent past. The best example, a megafanglomerate in Wyoming, proved to be the most directly comparable to the modern analogues in Laguna Salada (see section 7.2).

The less-coarse fanglomerates of Sierra Cucapas are more likely to be represented in the geologic record than the megafanglomerates because they are less dependent on specific tectonic factors. Therefore, some examples among ancient red beds may be comparable to the modern analogues of Sierra Cucapas. The Triassic red beds of southern New Brunswick were visited, a small outcrop was documented, and is briefly described in the section 7.3.

7.2 ANCIENT MEGAFANGLOMERATES:

The Laramida Orogeny uplifted many of the granite mountains on the middle Rockies during earliest Eocene time. A brief spasm of the orogeny during most of the Oligocene, permitted regional deposition of thick units of clastic debris, many of them consisting of giant granite boulders. After deposition subsidence, burial, uplift, deformation and erosion took place (Love, 1970).

A few well preserved megaconglomerates were reported in the Rockies as early as 1930. The best documented outcrop is the Monocrief gravel in the Big Horn Mountains, Wyoming (Sharp, 1948).

7.2.1 The Monocrief Gravel:

This unit outcrops in the east side of the Big Horn

Mountains.

It consists of "beds" composed of subangular to rounded boulders 0.3 to 1.6 m in diameter. Numerous boulders up to 5 m in diameter are also present. They are composed of Precambrian granite and gneissic granite. The nearest exposure of Precambrian bed rock lies 2 miles from the coarsest boulders. Matrix is predominantly arkosic and sparse particularly between the coarsest boulders. The boulders become finer downward and eastward (towards the basin) while the sandstone increases in thickness (Fig. 7.1). Cementation is poor, colour is white to light gray and tan, bedding is nearly indistinguishable in the coarsest parts of the deposit. Maximum thickness of the Monocrief Gravel is up to 400 m (Sharp, 1948).

7.3 NEW BRUNSWICK RED BEDS:

Triassic red beds of the Lepreau Formation in southwestern New Brunswick were examined. The alluvial conglomerates outcrop in a small area along the coast of Maces Bay, 70 km west of St. John (Fig. 7.2). The Maces Bay member is 1,175 m thick and it has been previously described within the Lapreau Formation by Nadon (1972) and Rust (1981). The following description is restricted to the

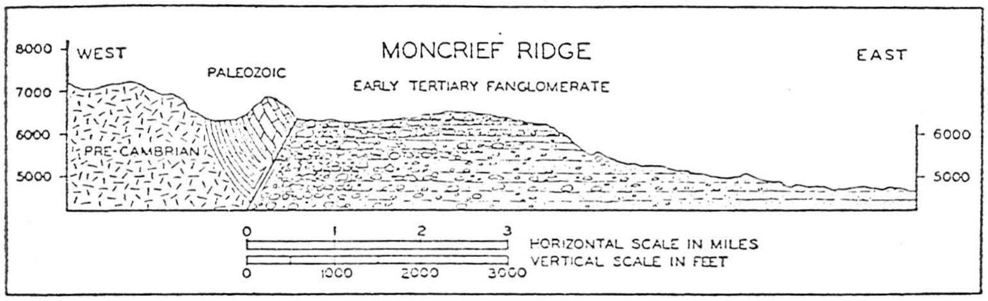


Fig. 7.1 The Monocrief Fanglomerate, located in the Big Horn Mountains of Wyoming. Note the fining outwards and the coarsening upwards trend. The coarsest boulders are up to 5 m in diameter. (After Sharp, 1948).

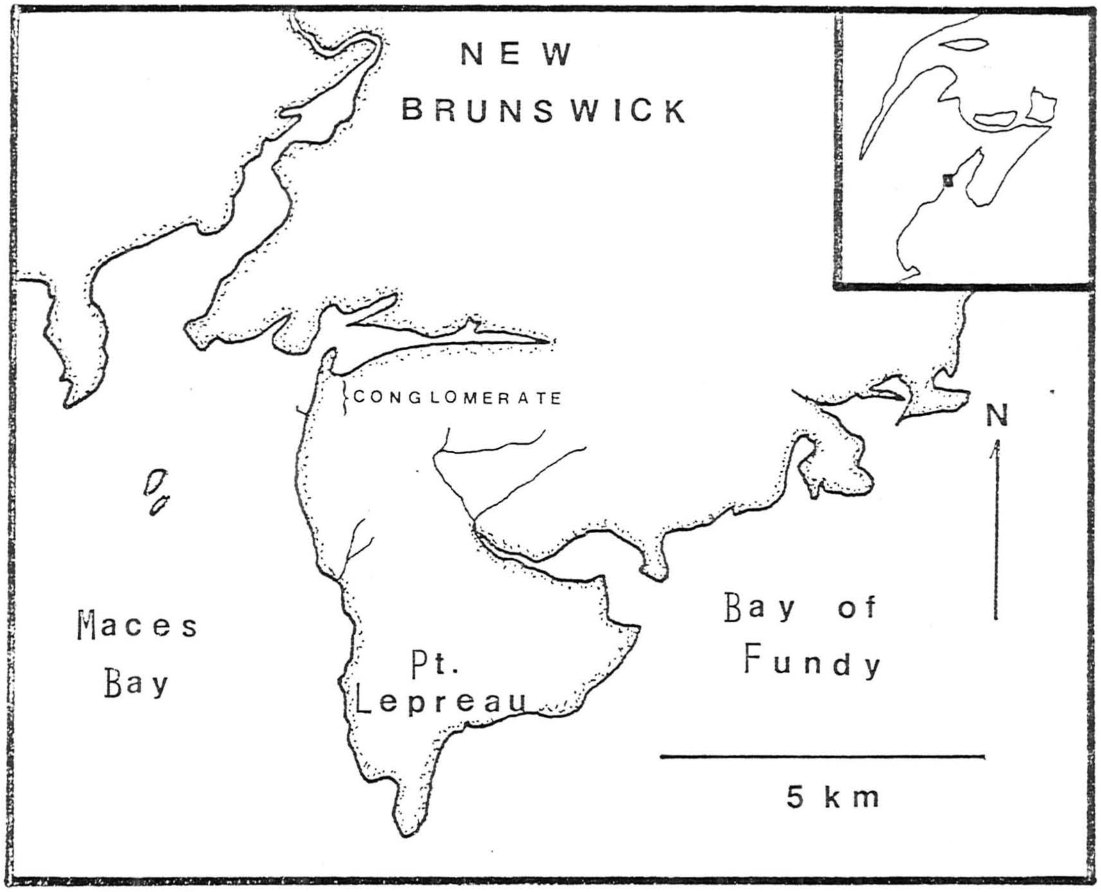


Fig. 7.2 Maces Bay Triassic conglomerate. Location and physiography.

section with the coarsest conglomerates.

The lower boundary of the section was arbitrarily chosen where the conglomerates ceased to interfinger with sandstone beds. This boundary is located exactly at the Maces Bay wharf and the section continues above this point for a thickness of 90 m (Fig. 7.2).

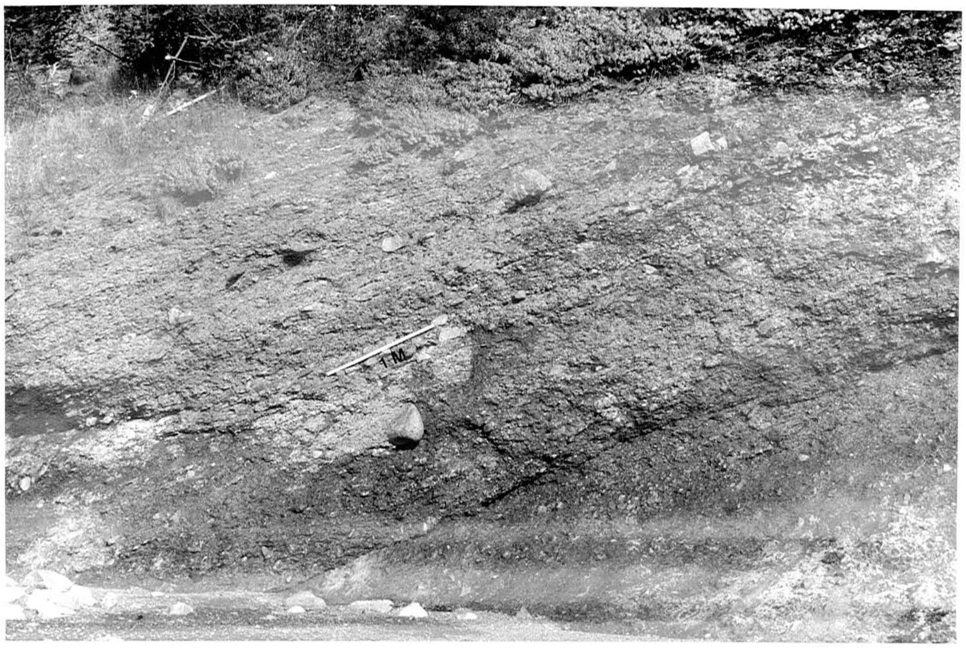
7.3.1 Description:

The first 20 m are dominated by a conglomerate breccia composed of clast-supported, subangular, moderately well packed, granite clasts averaging 8 cm in diameter but ranging from 1 to 30 cm. A relatively well sorted fine sand of reddish colour cemented with calcite comprised the matrix. Crude bedding was common while cross stratification was rare. The number of "floating" clasts larger than 20 cm increased towards the top of the section. Few and thin lenses of red sandstone were common as well as pure calcite layers (Fig. 7.3A). In the next 50 m of the section the average clast size gradually increased from 8 to 20 cm and ranged from 4 to 60 cm in diameter. The matrix material became coarser, consisting mainly of pebbly sandstone. Bedding planes spaced from 2 to 12 m apart were common.

Finally, the last 20 m of the section are characterized by crude beds 2 to 4 m thick composed of

Fig. 7.3A Pebbly conglomerate at the base of the Maces Bay section. Note the parallel bedding planes and the few dispersed boulders. Looking North.

Fig. 7.3B Bouldery conglomerate at the top of the Maces Bay section. Note the crude beds tilted 30° towards the observer (West).



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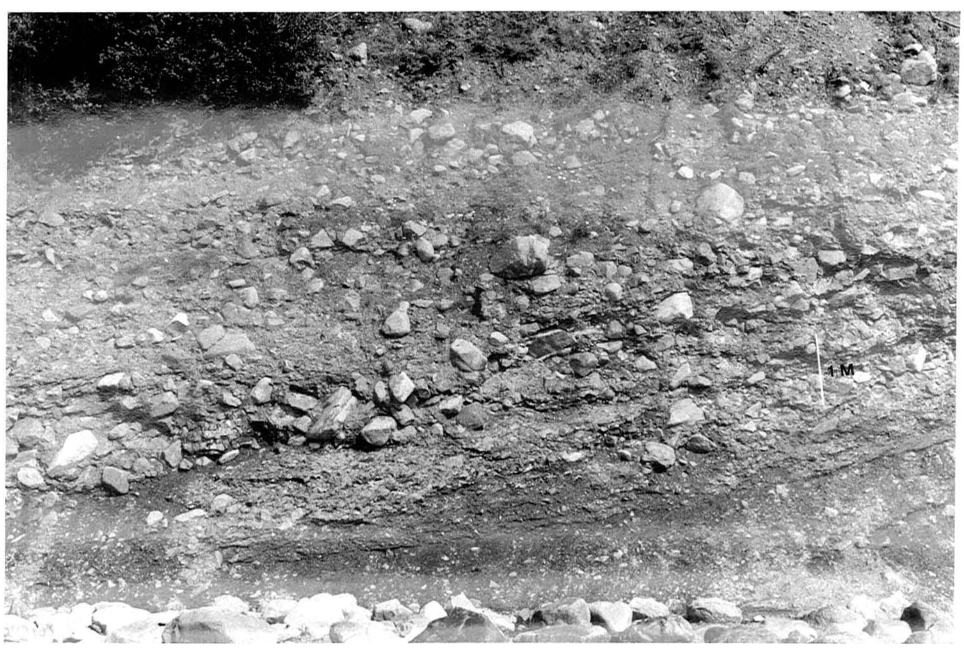

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coarse matrix - supported conglomerate. The subrounded granite boulders range between 60 and 100 cm in diameter. The matrix consists of coarse to medium sandstone and a variable content of pebbles. Crude bedding was observed within the matrix material (Fig. 7.3B)

7.3.2 Interpretation:

The lower part of the Maces Bay member seems to be comparable to the El Pantano fan deposits, that is to say, sheetflow sedimentation. The upper part is comparable to some deposits in the San Felipe fan, where coarse dispersed debris flows were dominant.

CHAPTER 8

SUMMARY AND CONCLUSIONS

Five Holocene alluvial fans in Baja California were examined. The most significant characteristic of these fans is the coarseness of the boulders, which are generally between one and two meters in diameter. The three coarsest-grained fans (located in Sierra Juarez) are formed mainly of debris-flow deposits, whereas the less-coarse fans (located in Sierra Cucapas) are largely composed of sheet-flow and some debris-flow deposits. The following conclusions are drawn.

GRAIN SIZE: The coarseness of the boulders is largely controlled by joint spacing, a characteristic feature of granite plutons located in high-stress tectonic environments. Differential weathering by moisture trapped in the joint spaces seems to have two important consequences; i.e. the rounding of the block apices and the production of grus. Therefore, tectonics controls joint spacing; and joint spacing controls grain size of both the coarse boulders and the finer material. The most significant aspect of this in-situ rock erosion is that it takes place in the upper reaches of the drainage basin, where the probability of catastrophic removal is high.

SEDIMENTARY FACIES: In the Sierra Juarez fans, facies A and C were the most abundant on the upper fan area.

Facies A consists of very coarse boulders, 70 to 90% clast supported and inversely graded. This facies was probably deposited from coarse, concentrated debris flows.

Facies C consists of very coarse boulders 100% clast supported generally forming a single rough "bed". It is probably a channel-lag and/or was reworked from facies A.

In Sierra Cucapas and to a lesser extent in the Sierra Juarez fans, facies B and D were locally dominant.

Facies B consists of 50 to 100% matrix supported boulders, cobbles and pebbles, in some cases inversely graded. This facies was probably deposited from coarse dispersed debris flows.

Facies D is similar to facies C, but the clast-size range of cobbles and pebbles is smaller, and percolated matrix is common. This is interpreted as being reworked material.

At El Pantano fan, facies E was dominant. This facies consists of crudely bedded cobbles and gravels interpreted as being deposited from sheet flows.

Finally, facies F, comprised all the fluvial deposits found in the fan toe and sandflat area. Horizontal discontinuous stratification was the most common structure and is interpreted as being deposited by upper-flow regime streams.

TRANSPORT PROCESSES: Debris flows are by far the most important process transporting the coarse boulders in Sierra Juarez fans. It is thought that debris flows originate by remobilization of boulders accumulated in the canyon by previous rockfalls. The slurry necessary to remobilize the boulders must originate in the drainage basin shortly after a heavy rainfall.

Coarse concentrated debris flows are thought to behave in a similar way to those described by Takahashi (1980), in which dispersive pressure generated by clast collisions is the main mechanism of boulder support.

Coarse dispersed debris flows are thought to behave in a similar way to those described by Johnson (1970) and Rodine and Johnson (1976), in which the strength of the matrix (the part of the dispersion substantially smaller than the coarsests clasts) is the main mechanism of clast dispersion.

FAN MORPHOLOGY: Alluvial fan morphology seems to be closely related to grain size. The Sierra Juarez fans, for example, are steeper than the Sierra Cucapas fans, which are finer grained. Slopes of the finer grained fans are comparable with the gentle-sloping alluvial fans of Death Valley, which are composed mainly of gravels.

The fan surface area seems to be considerably smaller in steeper and coarse-grained fans than in gently-sloping fine-grained fans. This may be a consequence of the fact that coarse boulders are more difficult to remobilize than gravels.

The lack of erosive bases throughout the fans studied suggests that aggradation of the channel bed by coarse debris flows must occur very rapidly in terms of geologic time. It is thought that subsidence of these coarse fans must be taking place much faster than progradation.

ANCIENT ANALOGUE: The Monocrief fanglomerate of Tertiary age has a thickness and length that closely resembles that of Sierra Juarez fans, whereas the clast dimensions and composition are exactly the same. Since both this ancient fan and the modern Mexican fans are derived from the same Mesozoic granite batholiths, it is concluded that the Laguna Salada alluvial fans represent a unique climatic and tectonic environment of minor volumetric extent but nevertheless of significant importance in the geologic record.

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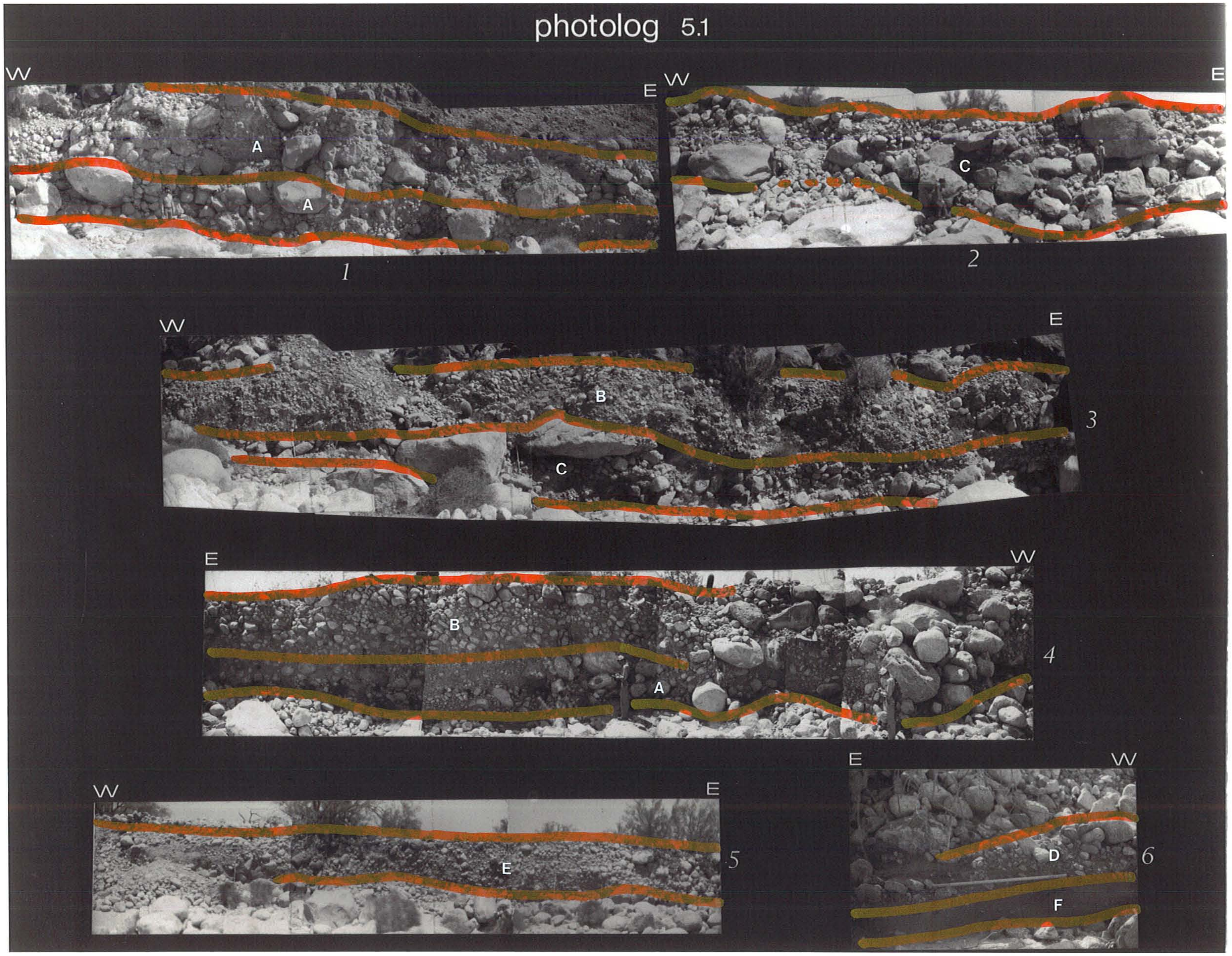
APPENDIX I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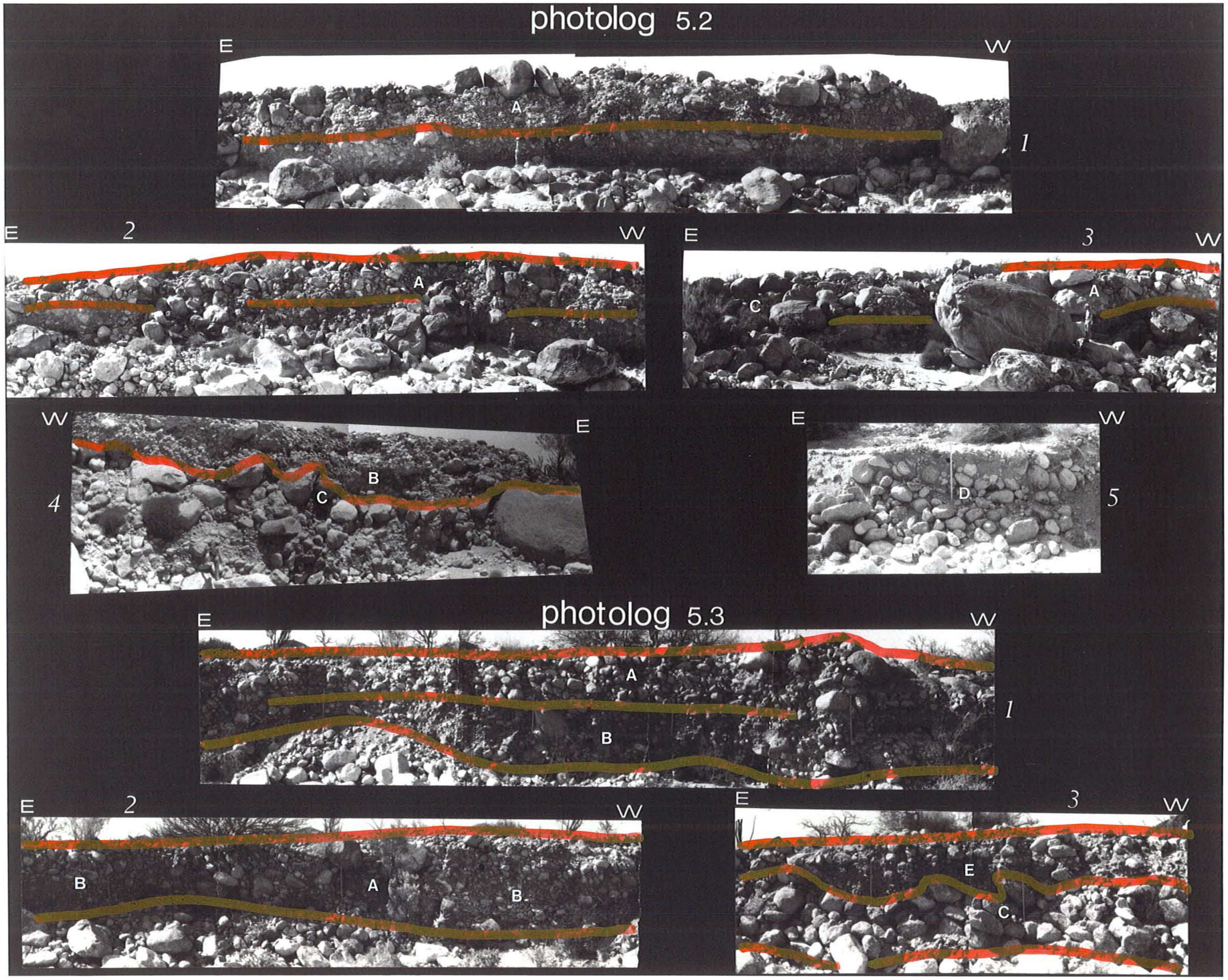
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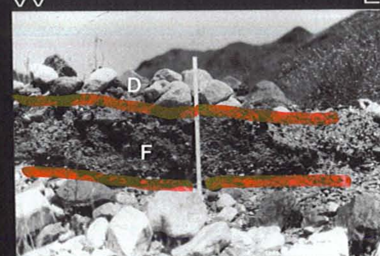

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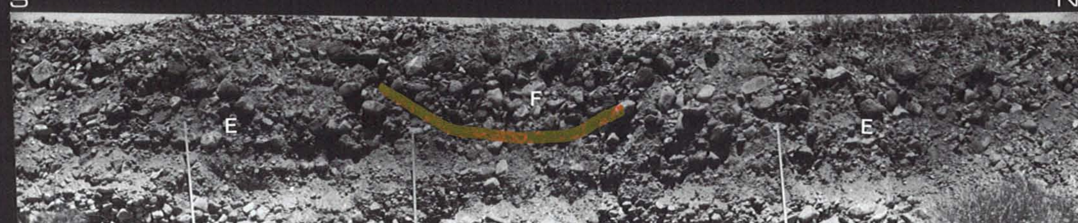

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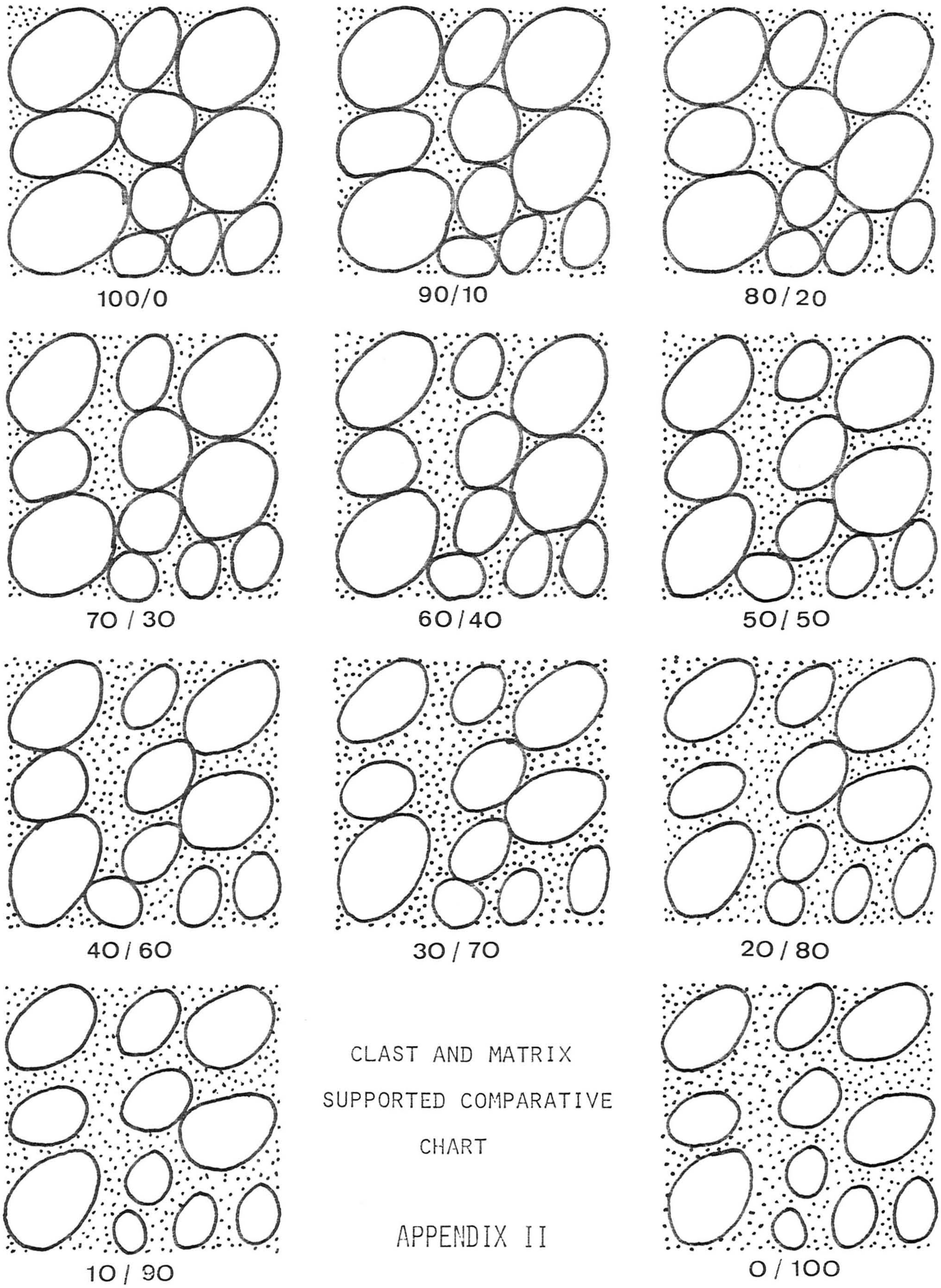
APPENDIX II

APPENDIX II

1. - CLAST AND MATRIX SUPPORTED TEXTURE COMPARATIVE CHART. 100/0 MEANS 100 % OF THE SURFACE AREA IN OUTCROP IS CLAST SUPPORTED AND 0 % IS MATRIX SUPPORTED.

2. - CLAST SORTING COMPARATIVE CHART.



CLAST AND MATRIX SUPPORTED COMPARATIVE CHART

APPENDIX II

FC

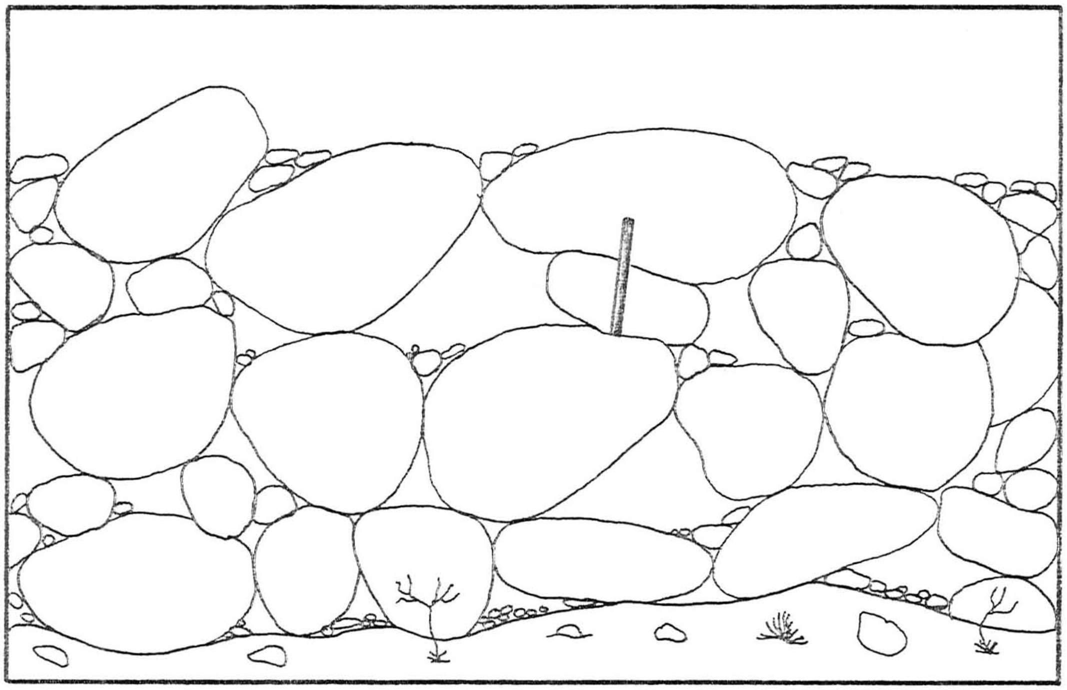


Fig. 3

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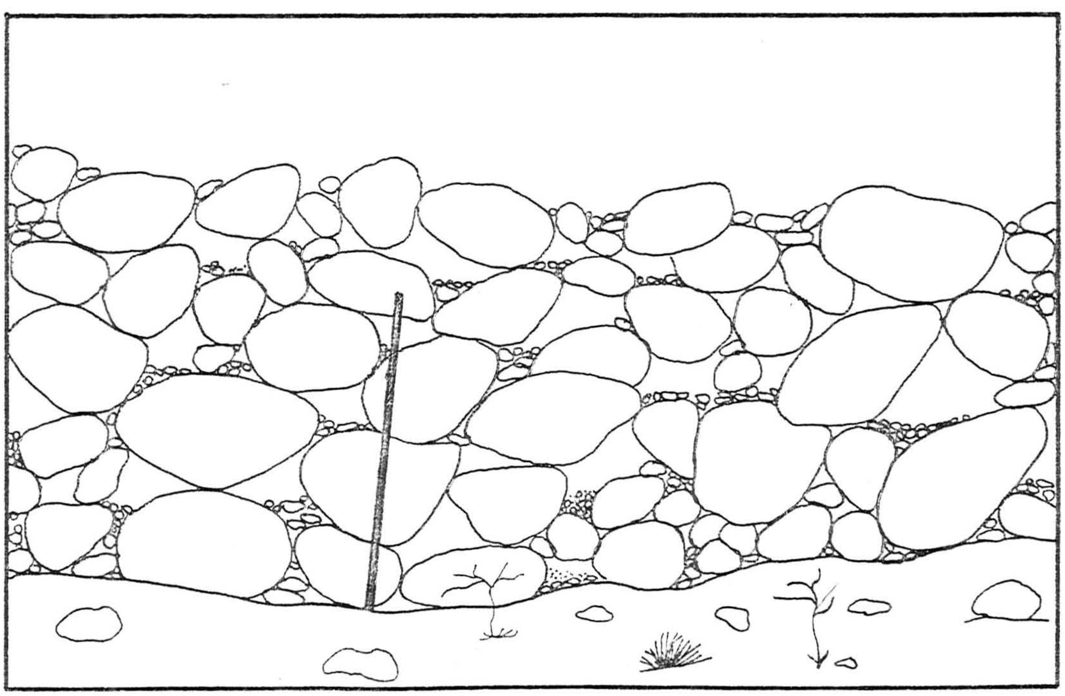

Fig. 4

Scale = 1 m

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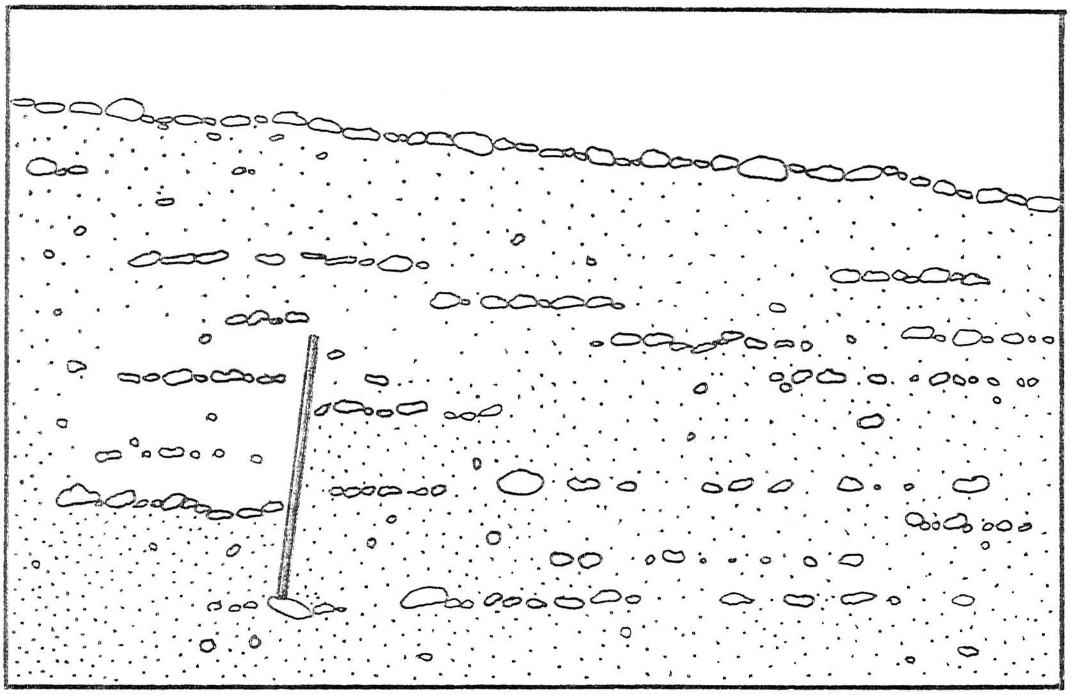

Fig. 5

Scale = 1 m