Compaction of Sediments Underlying Areas of Land Subsidence in Central California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 497-D

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By ROBERT H. MEADE

MECHANICS OF AQUIFER SYSTEMS

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A study, partly statistical, of the factors that influence the pore volume and fabric of water-bearing sediments compacted by effective overburden loads ranging from 3 to 70 kilograms per square centimeter

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By Robert H. Meade

ABSTRACT

An increase in effective overburden load from 3 to 70 kilograms per square centimeter, partly natural and partly manmade, has caused an average reduction of 10 to 15 percent in the volume of alluvial sediments in the San Joaquin and Santa Clara Valleys of California. The effects of load, however, are complicated by the effects of other factors on the pore volume. The most easily discerned of these factors in the alluvial sediments are particle size and particle sorting. The variation in pore volume that is related to differences in average particle size is of the same order as the variation related to differences in load. The effects of particle sorting are probably subsidiary to the effects of load and average particle size.

A multiple-regression analysis of the pore volume, overburden load, and selected petrologic characteristics of a group of 20 fine alluvial and shallow-marine sediments from the east side of the San Joaquin Valley shows the pore volume to be most closely related to particle size, diatom content, and the proportion of sodium (relative to other exchangeable cations) adsorbed by the clay minerals. Other factors that may have direct or indirect influence on the pore volume are the large proportions of montmorillonite in the sediments, and the variable pH and concentration of the interstitial electrolytes. The effects of overburden load on the pore volume of this group of sediments is completely obscured by the influence of the petrologic factors.

The degree of preferred orientation of the montmorillonite particles in the fine sediments in the San Joaquin Valley shows no regular relation to the depth of burial. The degree of orientation is related most consistently to the types of deposits represented by the sediments and decreases in the order: lacustrine, shallow marine, flood plain, and alluvial fan. The identity of the specific sediment properties or environmental characteristics that control the orientation, however, is uncertain.

The only effects of compaction observed in the sands are distorted and broken fragments of mica, shale, and metamorphic rock.

INTRODUCTION

The compaction of clastic sediments is influenced by several factors in addition to the load exerted by overlying sediments. During the early stages of compaction, these factors include such textural properties as particle size and sorting, such compositional characteristics as the proportions of mica or the different clay minerals, and such chemical properties as the composition and concentration of the material dissolved in the interstitial waters. Our understanding of the process of compaction, therefore, involves understanding how these factors interact with each other and with increasing overburden loads to inhibit or to enhance the removal of fluids and the reduction of pore volume in sediments.

The compaction of the water-bearing sediments in three areas of land-surface subsidence in the San Joaquin and Santa Clara Valleys of California is the subject of this report. The historic compaction and land subsidence in these areas are clearly related to the depletion of artesian pressure (increase of grain-to-grain load) in the sediments, which is a result of confined ground water being pumped from the sediments faster than it is being replenished. Because the rates of compaction and subsidence are rapid and can be measured, these areas were selected as field laboratories for a program of study of the mechanics of aquifer systems. Because the compaction represents an acceleration of the natural processes that would have taken place with the further accumulation of overlying sediments, these are also opportune areas for general studies of the compaction of sediments.

Two factors complicate these studies of compaction which are based on void ratios (pore volumes) determined in the laboratory from core samples obtained between 1957 and 1960. First, the void ratios reflect the combined effect of (1) the natural compaction due to the slow long-term increase in effective stress (effective overburden load) accompanying gradual burial and (2) the manmade compaction due to the rapid short-term increase in effective stress resulting from decline in artesian head. At the time the cores were taken, the increment of void ratio resulting from the natural compaction was in equilibrium with the effective overburden load because time, an essential ingredient, had been adequate. The deeper cores, 1,000 to 2,000 feet beneath the land surface, have been compacting under increasing sediment burial for one to possibly 5 million years. On the other hand, the application of the additional manmade stress began only 30 to 50 years ago and this stress had increased irregularly but rapidly to the coring date. The thicker fine-grained beds of low permeability were still experiencing pore-pressure decay and had not had time to attain hydraulic equilibrium with the head decline in the beds of coarser texture and higher permeability—the aquifers. Hence, in the fine-grained beds, the void ratio increment had not reached equilibrium because of man's change of the hydrologic regimen.

Second, data are not available for differentiating the increments of void ratio due to the natural and manmade increases in effective stress partly because, at the time of coring, the manmade increment was transient. The reader should keep this in mind, especially in the chapter on analysis of factors influencing compaction of the sediments.

At the time the samples were cored, the ratio of manmade to natural stresses varied with depth and hydrologic regimen and ranged from 0 to about 22 percent. For example, in the Santa Clara Valley at San Jose, the natural effective overburden load in 1960 (time of coring) at a depth of 500 feet was about 16 kg per cm^2 (kilograms per square centimeter) or 230 psi (pounds per square inch), and the manmade increase was about 3.5 kg per cm^2 based on 120 feet of artesian-head decline. Thus, the manmade increase in effective stress at the 500-foot depth in San Jose as of 1960 was 22 percent. On the other hand, in the San Joaquin Valley at Cantua Creek, the natural effective stress in 1958 at a depth of 300 feet was 13 kg per cm^2 (185 psi) and the manmade increase was zero (based on a constant water table); at a depth of 2,000 feet, however, the natural effective stress was about 65 kg per cm^2 (930 psi), and the manmade increase was about 13 kg per cm^2 based on 400 feet of artesian-head decline. Thus the manmade increase in effective stress at the 2,000-foot depth at Cantua Creek as of 1958 was 20 percent.

A discussion of the problems of land subsidence and aquifer compaction and the ways in which the problems have been approached are given by J. F. Poland in his foreword to the first chapter of this series (Johnson and others, 1967).

PURPOSE OF REPORT

This report is one of a series of chapters of Geological Survey Professional Paper 497, on the mechanics of aquifer systems in California and elsewhere. It is also the last of three chapters by the same author that concern the petrologic aspects of compaction. The first of these three chapters (Meade, 1964) is a comprehensive review of previous work on the factors that influence pore volume and fabric of clayey sediments under increasing overburden loads. The second of the chapters (Meade, 1967) is a description of the variation and distribution, in the sediments of central California, of some of the petrologic factors that the review of previous work showed to be significant influences on compaction. The third chapter—this report— relates, partly by statistical analysis, the variations in overburden load and petrologic factors to variations in the pore volume and fabric of the sediments. Although these reports are part of a comprehensive series, their organization and content are such that they can be read separately.

The first section of this report is a review of previous work that identifies and evaluates factors that influence the responses of clastic sediments to loads between 0 and 100 kg per cm^2 or 1,422 psi (15 psi$\approx$1 atmosphere$\approx$ 1 ton per sq ft$\approx$1 kg per cm^2). This section consists of (1) a brief summary of the first chapter (Meade, 1964) plus a discussion of new evidence, mostly on the development of preferred orientation in clays, that has become available since the earlier chapter was completed, and (2) a review of the factors that influence the compaction of sands. Then follows a brief summary of the second chapter (Meade, 1967), describing the distributions of relevant petrologic factors in the sediments of the San Joaquin and Santa Clara Valleys in enough detail to set the stage for what follows.

The final sections are detailed studies, largely statistical, that explore the following questions: (1) What factors influence the water content and fabric of these sediments under effective overburden loads between 3 and 70 kg per cm^2? (2) What is the relative importance of these factors? Some preliminary results of these studies have been published in three earlier papers (Meade, 1961b, 1963a, 1963b), which are now superseded by the present report.

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REVIEW OF FACTORS INFLUENCING COMPACTION OF CLAYS AND SANDS

Because the pore volume of clastic sediments decreases with increasing overburden loads, it is a useful and convenient measure of compaction. In water-saturated sediments, it is also a measure of water content. Factors other than overburden load, however, influence the pore volume and water content of sediments and must be considered in any comprehensive study of compaction. This section of the report summarizes the pertinent previous studies that identify these factors and indicate the nature and degree of their influence on compaction processes.

This review is restricted largely to compaction in the range of pressures between 0 and 100 kg per cm^2, which includes the range that applies to the water-bearing sediments whose compaction accounts for the observed land subsidence in central California. It is further restricted mainly to consolidation processes that involve direct responses to load and mostly ignores the reduction of pore volume by the formation of interstitial cement.

The measure of pore volume used most extensively in this report is the void ratio, which is defined as the ratio of the volume of pore space to the volume of solids. Percent porosity is also included in most of the figures and in some of the text discussions.

REMOVAL OF WATER FROM CLAYS

Because of the intimacy of the relations between water and clay, the reduction of pore volume in clays under increasing overburden loads is best considered in terms of the removal of water. The factors that are known to influence the water content of clayey sediments under applied loads are particle size, clay minerals, adsorbed cations, interstitial electrolyte solutions, acidity, and temperature. The effects of all but the last two of these factors are shown in figure 1. With the exception of particle size, the influence of these factors is inferred mainly from laboratory studies of monomineralic clays mixed with simple electrolytes. Very little of the present knowledge is based on the study of sediments in nature or on laboratory mixtures of clays and electrolytes that approach the complexity found in nature.

This section of the review is mainly a summary of material that was treated earlier in much greater detail (Meade, 1964, p. B2–B13). Some newer evidence on the influence of acidity and temperature, taken from the work of Warner (1964), is included here to bring the earlier paper up to date (1965). Void ratio is used as a volumetric measure of water content.

The influence of particle size on the pore volume and water content of fine sediments is represented in figures 1*A* and 1*B*. The five lines in figure 1*A* represent groups of sediments from different areas—river reservoirs, an estuary, and the deep sea. None of these sediments were buried more than 20 feet below the water-sediment interface. Figure 1*B* is a summary of the effects of particle size on the water content of sediments under pressure that was prepared by Skempton (1953, p. 55) from studies of sediments in the United States and Great Britain. The two graphs show the inverse relations between particle size and pore volume and how these relations persist during compaction under pressures approaching 100 kg per cm^2.

The influence of different clay minerals on water content is discernible over a wide range of pressures, as shown in figure 1*C*. The observed differences are related to differences in the surface areas per unit weight (specific surfaces) of the clay minerals. The larger the specific surface, the larger the amount of water retained by the clay under pressure. Montmorillonites have larger specific surfaces than illites, which in turn have larger specific surfaces than kaolinites.

The influence of different exchangeable cations on the water content of montmorillonite is shown in figure 1*D*. Sodium-saturated montmorillonites retain more water than montmorillonites whose exchange positions are saturated with other common cations. These effects, however, have only been observed at pressures less than 50 kg per cm^2; at greater pressures, differences in the exchangeable cations do not seem to be related to differences in water content. Because of the larger specific surface of montmorillonite and its associated larger capacity for adsorbing cations, the effects of different exchangeable cations on water content are much more pronounced in montmorillonite than in the other clay minerals. But in addition to showing effects of a lesser degree, other clay minerals may be affected in different ways by the exchangeable cations. An experiment by Samuels (1950; see Meade, 1964, fig. 12) on kaolinite saturated with different cations showed the largest water content in kaolinite saturated with aluminum and the smallest in kaolinite saturated with sodium—an effect opposite to the one shown in figure 1*D*. The relative differences in water content, however, were substantially less than those shown in figure 1*D*.

The graphs in figures 1*E* and 1*F* show two opposite effects of electrolyte concentration on the water content of clays under pressure. The relation shown in figure

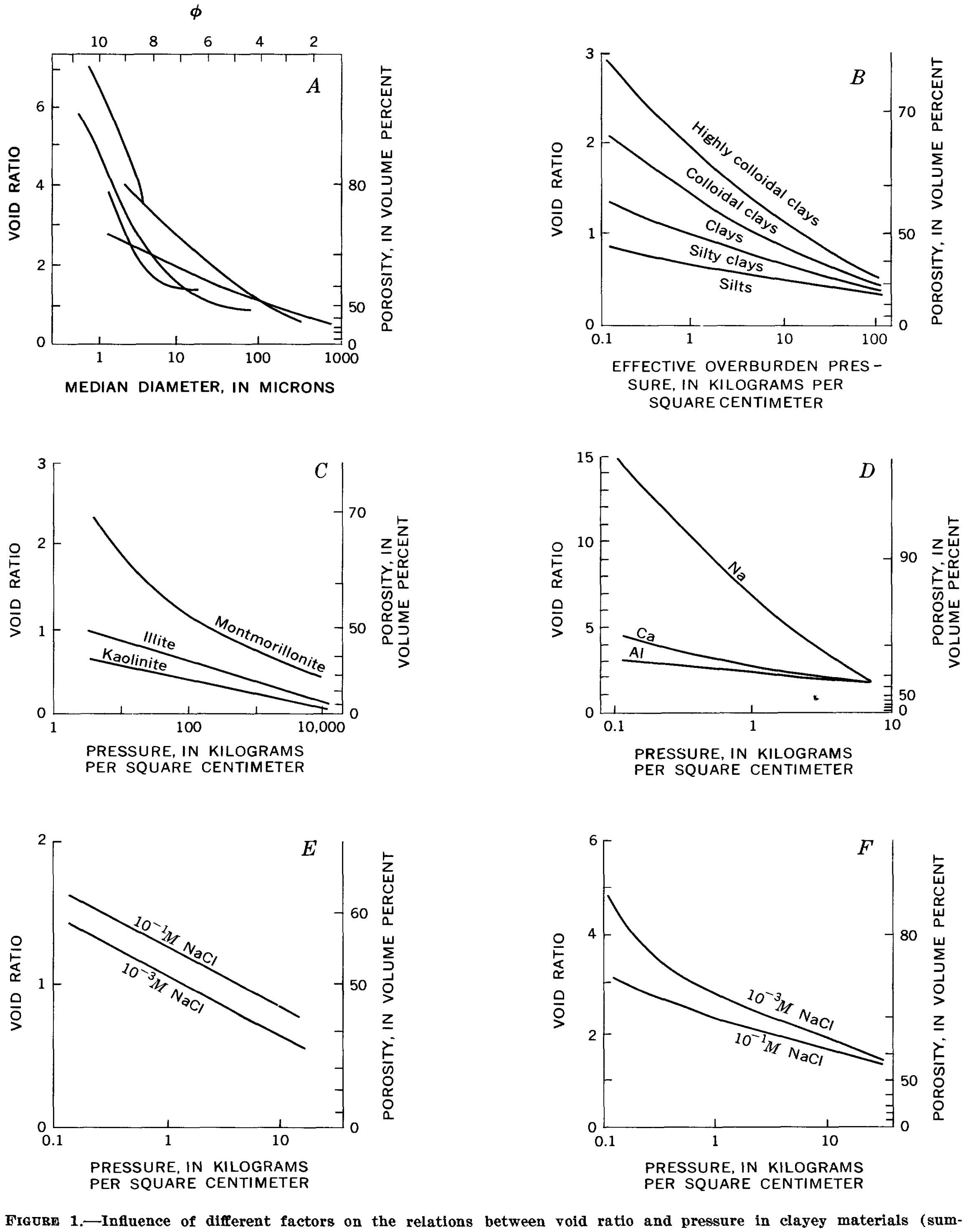

FIGURE 1.—Influence of different factors on the relations between void ratio and pressure in clayey materials (summarized from Meade, 1964, p. B5–B12). Note different void-ratio and pressure scales. *A*, Relation of void ratio to median particle diameter at overburden pressures less than 1 kg per cm² (Meade, 1964, p. B6). *B*, Generalized influence of particle size (modified from Skempton, 1953, p. 55). *C*, Influence of clay-mineral species (modified from Chilingar and Knight, 1960, p. 104). *D*, Influence of cations adsorbed by montmorillonite (modified from Samuels, 1950), *E*, Influence of sodium chloride concentrations in unfractionated illite—about 60 percent coarser than 2 microns (modified from Mitchell, 1960, fig. M–3). *F*, Influence of sodium chloride concentration in illite finer than 0.2 micron (modified from Bolt, 1956, p. 92).

1*E*—greater water contents associated with more concentrated electrolyte—seems to be characteristic of most clay-water-electrolyte systems. The effect is related to the tendency of the clays to flocculate more readily in more concentrated electrolyte and to form openwork aggregate structures that resist compaction. The opposite relation shown in figure 1*F* is characteristic of a restricted clay-water-electrolyte system, namely fine clays (montmorillonite or fine illite) associated with sodium electrolytes in concentrations less than about 0.3 *M* (molar solution). In this system, the effect of the electrolyte concentration may be its control (as predicted by double-layer theory) of the tendency of the adsorbed sodium to diffuse and its consequent control of the thickness of the layer of adsorbed water that surrounds each particle. The different electrolyte concentrations do not seem to affect the water content of clays at pressures greater than 50 kg per cm^2. They do, however, seem to affect the fabric of clays at greater pressures, as discussed in the next section.

Recent experiments by Warner (1964, p. 51–62) describe some of the effects of acidity on the water content of clays. In figure 2, showing some results of Warner's pressure experiments on kaolinite (<4 microns) mixed with 10^{-3} *M* sodium chloride at different pH values, the greater void ratios are associated with the lower pH. This effect is related to the tendency of kaolinite and illite flakes to form more open flocculated structures in acid than in alkaline solutions—as shown by the studies reviewed earlier (Meade, 1964, p. B15), and supported by Warner's (1964, p. 38–46) own sedimentation experiments. Warner found, however, that kaolinite mixed with a more concentrated electrolyte (0.55 *M* sodium chloride) showed void ratio-pressure relations that did not vary with changes in pH (in the range 2.0 to 8.5). Furthermore, he found no variations in the void ratio-pressure relations in illite or montmorillonite (mixed with different concentrations of sodium chloride solution) that could be related to variations in pH. The sum of his results seems to indicate that (1) the degree of acidity influences the water content of kaolinite under pressure and in contact with dilute electrolyte solutions and (2) that it has no influence on the pressure response of kaolinite mixed with more concentrated electrolyte, of illite, or of montmorillonite.

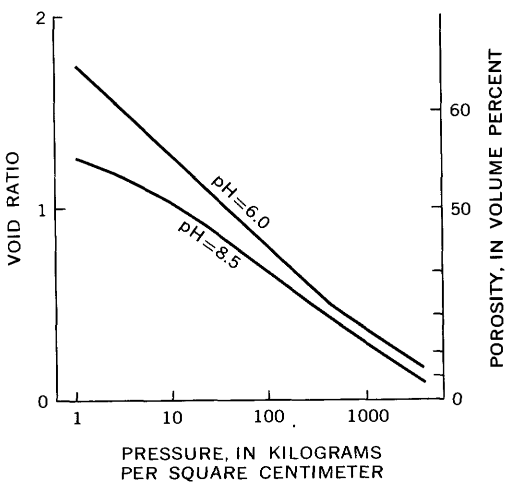

FIGURE 2.—Influence of pH on relations between void ratio and pressure in <4-micron fractions of kaolinite mixed with 10^{-3} *M* sodium chloride solution. Modified from Warner, 1964, p. 52.

The influence of temperature on the water content of clayey sediments under pressure is not well defined. It is well known, however, that temperatures between 100° and 150° Celsius (centigrade) will remove the interstitial water from most clays under otherwise atmospheric conditions. One would expect the natural increase in temperature that accompanies increasing depth of burial to enhance the tendency of the increasing overburden load to remove water from clays. Little evidence is available, however, to support this expectation. At low pressures, furthermore, the temperature may have little effect. Warner's experiments (1964, p. 51–55, 59–62, 70–75) showed that variations in temperature in the range between 25° and 80°C caused no differences in the equilibrium water content of kaolinite or montmorillonite at pressures between 1 and 8 kg per cm^2. The rates of compaction under these pressures, however, did increase with increasing temperature. The experimental studies of van Olphen (1963, p. 183–186; reviewed by Meade, 1964, p. B13), suggest that increasing temperatures may assist in the removal of water at pressures greater than several hundred kilograms per square centimeter. The influence of temperature on the compaction of clays is a promising subject for future study—especially enlightening would be experiments in which pressure and temperature were increased simultaneously by appropriate increments that corresponded to geostatic and geothermal gradients.

REARRANGEMENT OF CLAY-MINERAL PARTICLES

As a corollary to the reduction of pore volume under increasing loads, clay particles must move closer together in space and into more efficient packing arrangements. Many different arrangements are possible. The most widely considered arrangement, taking the characteristically platy shape of clay-mineral particles into account, is a preferred orientation such as is represented in figure 3*A*. This arrangement has been assumed to be the most likely result of the compression of clays—often to the exclusion of other possibilities. Another arrangement which some evidence suggests might be formed during compaction is shown in figure 3*B*, and consists of packets or domains of clay particles within which the planar orientation is perfect and between which the orientation is random. This fabric has been called turbostratic by Aylmore and Quirk (1960, p. 1046). Other regular fabrics as yet undescribed may be formed during compaction. Some clays may be compacted without developing any regular arrangement of particles.

DEVELOPMENT OF PREFERRED ORIENTATION

Because preferred orientation has received most of the attention in studies of the changes in clay fabric under increasing loads, many of the factors that influence its development have been identified. In the studies published through 1962, as reviewed earlier (Meade, 1964), much of the evidence on which the identification was based was indirect and included few actual measurements of the degree of orientation. In the years 1963 through 1965, several new studies have been completed that provide more direct evidence in the form of X-ray-diffraction measurements of clay fabric. Mainly on the basis of the newer studies, we may make a systematic assessment of the nature and degree of the influence of the following factors on the relations between pressure and preferred orientation in clayey sediments: initial water content, particle size, clay minerals, exchangeable cations, electrolyte concentration, acidity, and organic matter.

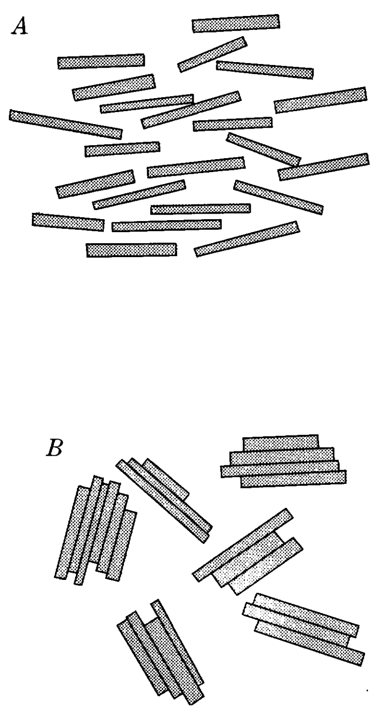

FIGURE 3.—Idealized arrangements of clay-mineral particles that may be formed during compaction. *A*, Preferred orientation. *B*, Turbostratic orientation.

Experiments by Martin (1965) on kaolinite slurries and by O'Brien (1963, p. 20–40) on illite and kaolinite pastes indicate that, given sufficient initial water content, most of the reorientation of clay particles that occurs at pressures less than about 100 kg per cm^2 takes place during the very early stages of compaction. Martin stated that a pressure of 1 kg per cm^2 produced "a very marked preferred orientation which does not change upon further consolidation up to 32 kg/cm^2." O'Brien's experimental results tabulated in the next paragraph also show well-developed preferred orientation at low pressures—0.02 to 0.2 kg per cm^2.

The influence of the initial water content on the development of preferred orientation is shown in the following results obtained by O'Brien (1963, p. 36–37; 1964, p. 827–828) during pressure experiments on pastes of kaolinite and illite mixed with a prepared "marine" water (27 grams sodium chloride plus 1 gram calcium chloride per liter).

Initial water content (percent of wet weight)	Pressure (kg per cm^2)	Orientation value
Kaolinite (unfractionated)		
Not specified	Uncompressed	1.2
23	48	2.4
32	48	7.6
Illite (<2 microns)		
Not specified	Uncompressed	1.5
44	0.08	1.5
Illite-kaolinite (<2 microns)		
Not specified	Uncompressed	3.0
50	0.17	20.0
55	.08	38.0
67	.02	28.0

The orientation value here is similar to the orientation ratio described on page D29: values near 1.0 denote random orientation, higher values denote greater degrees of preferred orientation. These data show fairly clearly that the initial water content is a critical factor in determining the degree of preferred orientation that develops during the early stages of compaction. A certain amount of interstitial water is required to allow the particles to move easily past one another into positions of preferred orientation. The studies cited in this and the previous paragraphs substantiate Hedberg's (1936, p. 272, 281) inference that most of the mechanical rearrangement of particles during compaction takes place while porosities of the sediment are on the order of 75 to 90 percent and perhaps within 5 to 10 centimeters of the surface of deposition.

The relation of particle size to the preferred orientation of clays is not clear. Grim, Bradley, and White (1957) in studying Paleozoic shales in Illinois suggested that preferred orientation was better formed in fine-grained shales (in which most of the particles were finer than 2 microns) than in coarser grained shales that contained appreciable amounts of nonclay mineral grains. A similar observation was reported by Folk (1962, p. 541) in Silurian black shales in West Virginia: the most extreme examples of preferred orientation of clay-mineral particles were seen in shales having the least calcite and the least silt. On the other hand, Beall (1964, p. 79) said that he could find no relation between the degree of orientation and the grain size of the Cretaceous mudstones that he studied in Texas. No experimental evidence is available to shed light on these studies of natural claystones. They may only indicate that some fine-grained sedimentary rocks have well-developed preferred orientation and some have not.

Studies reviewed earlier (Meade, 1964, p. B17–B19), supported by the experiments of Martin and O'Brien cited above, give the impression that low pressures on the order of a few kilograms per square centimeter can produce marked preferred orientation in kaolinite and illite but do not seem to produce much orientation in montmorillonite. Greater pressures on the order of 100 kg per cm^2 or more, as applied in laboratory studies, can produce preferred orientation in any clay minerals of platy habit—including montmorillonite. At lower pressures, however, the larger clay particles of illite and kaolinite seem to be more susceptible to preferred orientation than the smaller particles typical of montmorillonite. This impression is substantiated by Beall's (1964, p. 42) studies of the fabric of Cretaceous mudstones of Texas in which kaolinite and illite always showed a greater degree of preferred orientation than montmorillonite, within the same rocks. Odom (1963, 1964), on the other hand, noted a lack of correlation between the variable clay-mineral composition and the preferred orientation of different Paleozoic argillaceous rocks in Illinois.

The only previous direct evidence of the influences of the different exchangeable cations on fabric was presented by Beall (1964, p. 82–84). He noted that the degree of preferred orientation of the clay minerals was inversely related to the amount of exchangeable sodium, relative to exchangeable calcium and magnesium, in seven samples of the Cretaceous mudstones that he studied. However, the opposite relation—a direct relation between the degree of montmorillonite orientation and the proportion of adsorbed sodium—was found in 11 samples of shallow-marine sediment in the San Joaquin Valley (described later in this report).

The influence of electrolyte concentration on the fabric of clays under pressure is indicated by the results of experiments made by Engelhardt and Gaida (1963, p. 926–927), and by Warner (1964, p. 84–91). In montmorillonite compacted under a pressure of 800 kg per cm^2, Engelhardt and Gaida found an increase in the degree of preferred orientation with decreasing concentrations of sodium chloride solutions in the range 1.1 to 0.16 *M*. A similar increase in orientation with decreasing sodium chloride concentration (range 2.4 to 0 *M*) was shown in experiments with kaolinite compacted under a pressure of 160 kg per cm^2, although these results were not as clearly expressed as the results of the experiments with montmorillonite. From experiments with kaolinite sedimented at a pH of 8.5 in sodium chloride solutions of two concentrations (0.55 and 0.001 *M*) and compacted under a pressure of 4,200 kg per cm^2, Warner reported that the better developed preferred orientation was associated with the lower electrolyte concentration. These results, however, pertain to pressures greater than 100 kg per cm^2.

No clearly expressed relations between electrolyte concentration and preferred orientation resulted from the experiments conducted at low overburden pressures by O'Brien (1963, p. 21–28). He suspended two different concentrations of kaolinite in three different electrolyte solutions and allowed the clay to settle out. Then, over a period of 3 weeks, he sedimented 3 feet of silt and sand on top of the clay. The volume of the clay was reduced by about half during the 3-week period. The degrees of orientation produced are illustrated in the following table. The number in the last column is the final orientation value after the overburden load was applied.

Solution	Electrolytes (grams per liter)		Kaolinite in original suspension (grams per liter)	Final orientation value
	NaCl	$CaCl_2$		
"Salt lake" water	85	0. 55	5	48
Do	85	. 55	50	11. 2
"Marine" water	27	1	5	64
Do	27	1	50	10
"Fresh" water	0. 05	0. 1	5	4. 5
Do	. 05	. 1	50	34

Whereas the data do not show a simple relation between electrolyte concentration and fabric, they may indicate a complex, and as yet undefined, interrelation between fabric, concentration of clay suspensions, and concentration of electrolytes.

The effects of variations in acidity on the orientation of clay particles under pressure can only be inferred indirectly from Warner's (1964, p. 51–62) experiments that were discussed earlier (fig. 2). In kaolinite mixed with electrolyte solutions of low concentration, the degree of preferred orientation may be better developed in alkaline than in acid solutions. On the other hand, acidity may have little or no effect on the orientation of kaolinite associated with more concentrated electrolyte solutions, of illite, or of montmorillonite.

The presence of organic matter seems to enhance the degree of preferred orientation in argillaceous rocks. Odom (1963, 1964) found, in claystones overlying coal beds in Illinois, that the degree of preferred orientation correlated directly with the content of organic carbon (as C). This is substantiated by O'Brien's (1963, p. 13) summary of his measurements of the preferred orientation of illite and kaolinite in black and gray shales of Pennsylvanian age in Illinois—the black shales, having an approximate range of orientation values from 10 to 20, contain more organic matter than the gray shales, having a range of orientation values from 6 to 10. Beall (1964, p. 86–87) also reported a greater degree of preferred orientation in the darker colored of some of the Cretaceous mudstones that he studied in Texas. These newer studies confirm the earlier work of Ingram (1953, p. 873–875) on the orientation of clay-mineral particles in clayey rocks, Ordovician to Eocene in age, from Colorado, Iowa, and Wisconsin. Ingram noted, in thin sections of the rocks, that organic stain was associated with clays that showed preferred orientation and was absent from clays in which the orientation was random. In one rock sample, this relation was expressed in alternate organic and nonorganic clay layers. Folk (1962, p. 541) has suggested that a large proportion of organic matter in a sediment may aid the development of preferred orientation by its initial deposition as a stagnant clay-organic "soup" which is compacted markedly and allows the clay flakes to become well oriented.

Spatial variations of the preferred orientation of clay minerals with respect to depth of burial and the inferred environments of deposition of Cretaceous mudstones in Texas have been described by Beall (1964, p. 46–54, 104–107). He noted no variation in preferred orientation that could be related to overburden load or degree of compaction—that is, no relation between fabric and bulk density. He did note, however, lateral changes in preferred orientation that were related to changes in the inferred depositional environment: in one horizon that graded laterally from shallow-marine to near-shore sediments, the better preferred orientation was associated with deposits of a tidal mud flat or shallow lagoon. In an overlying horizon, the whole pattern of depositional types and associated preferred orientation was shifted laterally, indicating a westward transgression of the Cretaceous sea. Beall concluded that preferred orientation was best developed in a low-energy brackish-water environment. The specific characteristics of the environment that are most responsible for the development of preferred orientation are not clearly shown, but he did note (as cited in the preceding paragraphs) relations with clay minerals, exchangeable cations, and the dark color of the rocks.

These laboratory and field observations of preferred orientation can be summarized as follows. During the compaction of clayey sediments under pressures between 0 and 100 kg per cm^2, most of the rearrangement of clay particles takes place and most of the preferred orientation is developed very early—at pressures of only a few kilograms per square centimeter. During this very early stage, the amount of water held in the clayey sediment may be the most critical factor. If enough water is present, the particles may slip past one another easily into efficient packing arrangements; if not, the preferred orientation may be poorly developed or absent. A large concentration of carbonaceous organic matter seems to assist the development of preferred orientation by its ability to retain large amounts of water during the early stages. The influence of other factors is less certain, but one might expect the development of preferred orientation to be favored by larger proportions of kaolinite and illite relative to montmorillonite, by lower concentrations of interstitial electrolytes, and perhaps by greater alkalinity of interstitial solutions.

DEVELOPMENT OF TURBOSTRATIC ORIENTATION

Whether a turbostratic fabric of the kind shown in figure 3*B* can be formed during the compaction of clayey sediments is not certain. This fabric consists of domains of clay particles within which the planar orientation is nearly perfect and between which the orientation is random. If the domains were also oriented with respect to each other, this fabric would be nearly indistinguishable from the preferred orientation of individual particles shown in figure 3*A*. Note that the permeability of a clay that has a turbostratic fabric is greater than the permeability of a clay of the same water content that has preferred orientation—the two sketches in figure 3 are drawn with approximately equal void ratios. Several indirect lines of evidence, summarized from an earlier chapter (Meade, 1964, B9–B10, B18), suggest that a turbostratic fabric may develop under pressure in some montmorillonites.

Montmorillonite that is mixed with electrolyte solutions containing calcium or magnesium and that has exchange positions saturated with these cations will not swell to interparticle distances greater than 9 A (angstrom), regardless of the concentration of the interstitial electrolyte (Norrish, 1954). This is in contrast to mixtures of montmorillonite and sodium electrolytes in which the interparticle distance is a direct function of water content (greater than about 50 percent) and an inverse function of electrolyte concentration (less than about 0.3 *M*). Nitrogen-sorption measurements of calcium montmorillonite by Aylmore and Quirk (1962, p. 109–112) showed the existence of two different sizes of interparticle spaces, the smaller of which was on the order of 10 A, which suggested a particle arrangement such as the one shown in figure 3*B*.

Other experiments suggest that pressure may assist in the development of domains in calcium montmorillonite or in sodium montmorillonite associated with a concentrated electrolyte. From measurements of the sharpness of X-ray reflections from compressed calcium montmorillonite, Blackmore and Miller (1961, p. 171) inferred that the number of unit 10–A sheets per domain increased progressively with pressure and ranged from about five unit sheets at 0.5 kg per cm^2 to nearly eight unit sheets at 90 kg per cm^2. The process seemed to be irreversible; that is, the sheets in the domains did not seem to dissociate when the pressure was released. In sodium montmorillonite compressed under 800 kg per cm^2, Engelhardt and Gaida (1963, p. 926) found that increasing concentrations of interstitial sodium chloride solution (from 0.16 to 1.1 *M*) were related to decreasing degrees of preferred orientation and increasing permeabilities. The equilibrium water content, however, was the same at all sodium chloride concentrations. These results may be explained by a lessening development of preferred orientation and a greater degree of turbostratic orientation at the higher concentrations. Because of the small size of the domains and their random orientation, however, the existence of a turbostratic fabric is difficult to prove, either optically or by X-ray diffraction.

REDUCTION OF PORE VOLUME IN SANDS AT PRESSURES LESS THAN 100 KILOGRAMS PER SQUARE CENTIMETER

The compaction of sands and the factors that influence the pore volume of sands and sandstones under pressure have received less attention than the corresponding processes and factors in clays and shales. One reason is that the decrease in pore volume with increasing depth of burial is not as easily observed in sands and sandstones as it is in clays and shales because cementation and other effects obscure the relation. Another reason is that unconsolidated sands are difficult to core and nearly impossible to bring to the laboratory without disturbing their natural pore volume. Furthermore, sands have not received the same attention from soil engineers that clays have because sands cause fewer difficulties in foundation engineering.

Information on the response of sands to increasing pressures between 0 and 100 kg per cm^2 consists of laboratory compression tests summarized in table 1. One cannot extrapolate indiscriminately from these results to most natural sands because the comprehensive testing to date has all been done on pure quartz sands in a restricted range of sizes. Although the experiments were made under different conditions (sample dimensions, rate of pressure application), they seem to show that the void ratio of a well-sorted and rounded quartz sand will decrease by about 0.03 in pressures from 0 to 70 kg per cm^2. If the sand consists of angular grains, its void ratio will decrease by 0.15 to 0.30 in the same pressure range.

Under pressures between 0 and 100 kg per cm^2, the experimental quartz sands compacted principally by the shifting of particles into more dense packing arrangements and, to a lesser degree, by elastic compression of the grains themselves. At pressures in excess of about 100 kg per cm^2 (especially in the experiments of Roberts and de Souza), the rate of compaction increased as the grains cracked and shattered under pressure. I doubt, however, that quartz grains would shatter extensively at these pressures in naturally compacting sands. The slow rate of pressure application in nature allows the grains to accommodate themselves in other ways, perhaps mainly by solution and reprecipitation at points of contact. Furthermore, polymineralic sands should respond differently to pressures, the softer grains deforming more readily and bearing much of the load.

The factors that influence the pore volume of sands at pressures between 0 and 100 kg per cm^2 are mainly the textural characteristics of the constituent particles: size, sorting, roundness, shape, and flexibility. The influence of these factors on the pore volume of uncompacted sands has been reviewed and discussed extensively by Engelhardt (1960, p. 3–16), Fraser (1935), Gaither (1953), and Hamilton and Menard (1956). They will be reviewed here rather briefly, with some emphasis on their effects under pressure.

INFLUENCE OF PARTICLE SIZE

Although ideally the pore volume of well-sorted sands is independent of particle size, most natural sands show a slight inverse relation between pore volume and average size (fig. 4). Notice, however, that the relation is much more pronounced in silts than in sands.

In sandstones or in sands that are buried under several hundred feet or more of overburden, the relation between pore volume and particle size is both similar to

TABLE 1.—*Summary of experimental data on compaction of unconsolidated sands*

[Void ratio and porosity at 70 kg per cm² are interpolated from data as presented; 70 kg per cm² represents approximate maximum pressure to which sands from cores in San Joaquin and Santa Clara Valleys have been subjected by natural overburden loads]

Reference	Properties of sand				Interstitial fluid	Pore volume					
	Size (mm)	Mineral composition	Initial packing	Roundness		Void ratio at indicated pressure			Porosity in percent volume at indicated pressure		
						Initial	70 kg per cm²	Maximum	Initial	70 kg per cm²	Maximum
Terzaghi (1925, p. 987–988).	0.25–1.0	Quartz	Loose	Angular	Dry	0.97	0.66	0.56	49.2	39.8	35.9
Do	.25–1.0	do	Compacted.	do	do	.67	.53	.45	40.1	34.7	31.0
Botset and Reed (1935).	.42– .6	--------	Compacted by tamping.	--------	Kerosene	.70	.67	.60	41.2	40.1	37.5
Do	.42– .6	--------	Compacted six times at 210 kg per cm².	--------	do	.58	.56	.56	36.8	36.0	35.9
Urul (1945—data reported by Weller, 1959, p. 295).	--------	--------	--------	--------	Dry	.79	.74	.33	44.0	42.5	25.0
Roberts and de Souza (1958).	.42– .84	Quartz (Ottawa).	Loose	Rounded	Dry	.65	.62	.49	39.4	38.3	32.9
Do	.42– .84	do	do	do	do	.60	.58	.31	37.5	36.7	23.7
Do	.42– .84	do	do	do	Water	.55	.53	.44	35.5	34.7	30.6
Do	.42– .84	Quartz	do	Angular	Dry	.97	.71	.30	49.2	41.5	23.1
Do	.1 – .84	Quartz (Ottawa).	do	Rounded	do	.49	.47	.32	32.9	32.0	24.2

TABLE 1.—*Summary of experimental data on compaction of unconsolidated sands*—Continued

Reference	Applied pressure (kg per cm²)		Elastic recovery (percent difference in porosity at initial and maximum pressures)	Grains crushed at maximum pressure (weight percent)	Pressure application		Dimensions of sample (cm)	
	Initial	Maximum			Increment (kg per cm²)	Minimum interval between applications (hours)	Initial height	Diameter
Terzaghi (1925, p. 987–988).	0	110	--------	None, presumably	1	1/60	4.0	15
Do	0	115	--------	do	1	1/60	4.0	15
Botset and Reed (1935).	0	240	27	--------	5–12	2	6.7	7
Do	0	210	80	8 (after 7 load-unload cycles).	5–12	2	----	7
Urul (1945—data reported by Weller, 1959, p. 295).	----	1,970	--------	Extensive	--------	--------	----	----
Roberts and de Souza (1958).	1.3	410	--------	About 15	Two times previous increment.	24	1–2	3–7
Do	1.3	985	--------	About 50	do	24	1–2	3–7
Do	1.3	575	--------	--------	do	24	1–2	3–7
Do	1.3	705	--------	--------	do	24	1–2	3–7
Do	1.4	915	--------	About 10	do	24	1–2	3–7

and different from the relation in unconsolidated sands. It is similar in that the pore space, if it is not filled by cement, increases with decreasing particle size: curve V in figure 4 represents Cretaceous sandstones buried under 3,580 to 3,680 feet of overburden. The relation may be different, however, in that the void ratio may be expressed as a linear, rather than curvilinear, function of the logarithm of the median particle size. Although this is only suggested in the narrow range of particle sizes represented by curve V, it is supported by other evidence that will be presented in the final sections of this paper.

INFLUENCE OF PARTICLE SORTING

Sorting of constituent particles also affects the pore volume of a sand. "Generally the porosity decreases as grains vary from a uniform size because (a) the finer grains tend to occupy voids between larger grains and (b) the coarsest grains reduce porosity by occupying a volume that would otherwise be occupied by finer grains and voids" (Gaither, 1953, p. 184). This statement is supported by the experiments of Rogers and Head (1961) on lognormally distributed artificial mixtures of different sand sizes (fig. 5*A*). The void ratio is related inversely to quartile deviation (QD_ϕ)—a measure of sorting which was introduced and explained by Krumbein (1936, p. 102–103), and which is the logarithm to the base 2 of the Trask sorting coefficient, *So* (Trask, 1930, p. 594). Although the relations in figure 5*A* seem to plot as straight lines, they probably apply only to the short range of QD_ϕ values indicated. If they were extrapolated, they would imply that sands whose quartile deviations amounted to 2.5 or more would have no porosity at all.

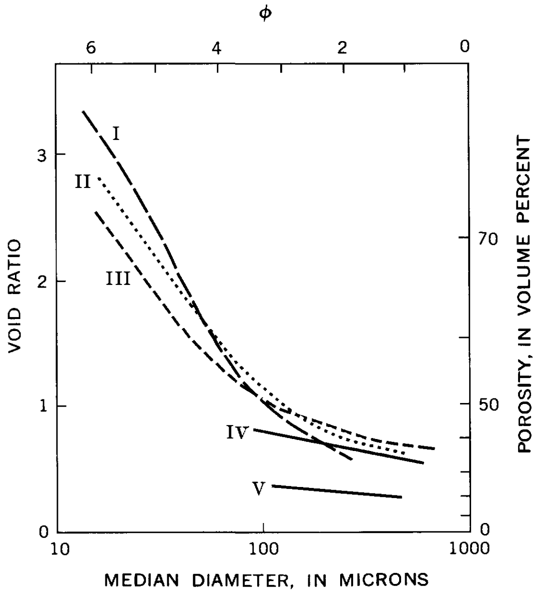

FIGURE 4.—Influence of particle size on void ratio of silts, sands, and sandstones. Curves I through IV represent unconsolidated sediments. I, North Sea bottom off Wilhelmshaven (modified from Füchtbauer and Reineck, as reported by Engelhardt, 1960, p. 15); II and III, shallow sea bottom off San Diego (II, data from Shumway, 1960, p. 454–457; III, data from Hamilton and others, 1956, table 1); IV, Colorado River delta in Lake Mead (modified from Sherman, 1953, p. 399). Curve V represents Cretaceous sandstone (Germany) buried under 3,580 to 3,680 feet of overburden (modified from Engelhardt, 1960, p. 21).

The results plotted in figure 5*A* also show how particle sorting influences the relation between the pore volume and particle size of sands. In the well-sorted sands, the void ratio is virtually independent of the average particle size. As the sorting becomes poorer (QD_ϕ increases), the void ratios of the different-sized sands diverge—the finer sands having the greater pore volumes.

The influence of particle sorting on the relation between void ratio and pressure is indicated in figure 5*B*, which is adapted from the experimental data of Roberts and de Souza (1958) on well-rounded quartz grains. The void ratio of the less well sorted sand (greater QD_ϕ) remained below that of the two better sorted sands at pressures up to a few hundred kilograms per square centimeter. At the greater experimental pressures, the well sorted sand was fractured more extensively (see details in table 1), and its void ratio-pressure curve converged with the curve for the less well

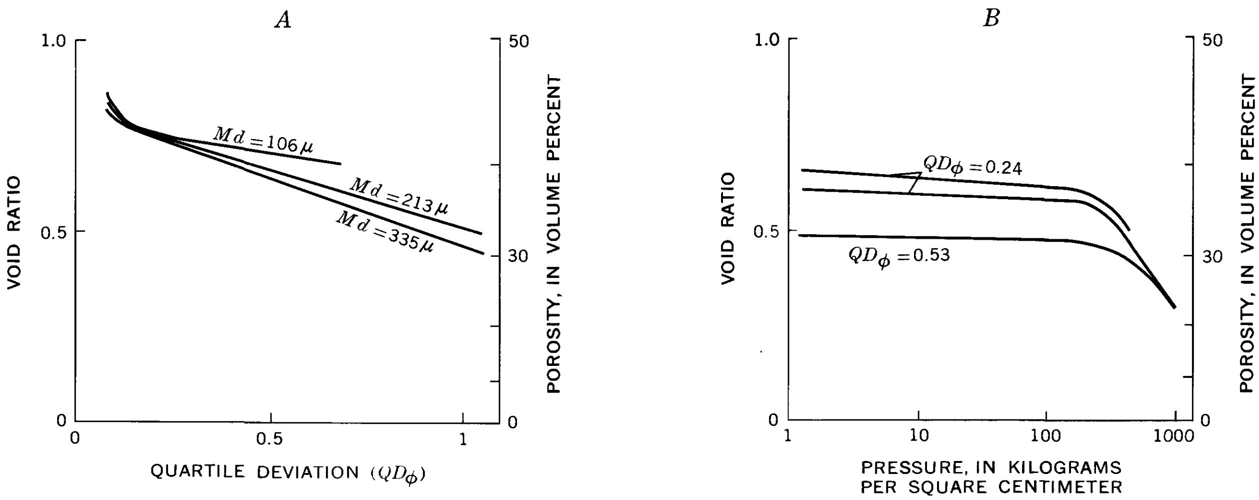

FIGURE 5.—Influence of particle sorting on void ratio of sands. *A*, In artificial mixtures of fractions of two natural sands from Texas (modified from Rogers and Head, 1961, p. 469). *B*, In well-rounded pure-quartz sand under pressure (modified from Roberts and de Souza, 1958); median diameter (*Md*) of the two better sorted sands, 600 microns; median diameter of the poorer sorted sand, 480 microns; details of pressure experiments listed in table 1.

sorted sand. As pointed out, however, this type and degree of fracturing is probably not common at these pressures in nature.

INFLUENCE OF PARTICLE ROUNDNESS

The angularity of sand particles also affects the pore volume, as shown in figure 6 by the experiments of Roberts and de Souza (1958). Whereas the initial void ratio of angular, ground quartz was nearly 1.0, the initial void ratio of rounded quartz (Ottawa sand) was considerably lower—on the order of 0.6. The initial void ratio of the loose angular quartz used by Terzaghi (1925) in his experiments was also large (0.97), as shown in table 1. These void ratios reflect the instability of the initial packing of angular grains. Furthermore, angular sands are more compressible than rounded ones. This relation also has been observed in consolidated sandstone by Fatt (1958, p. 1940–1941) who noted that sandstones consisting of poorly sorted, angular grains are more compressible than sandstones whose grains are well sorted and rounded.

INFLUENCE OF MICA PARTICLES

If a sand contains a few percent of mica flakes, the flexibility and elasticity of the micas contribute to the compressibility of the whole. The pronounced effect of increasing mica content on the compressibility of prepared sand-mica mixtures has been demonstrated by Gilboy (1928). Figure 7*A* shows the results of some of his experiments on mixtures of rounded quartz grains and "white mica" (presumably muscovite) flakes. The larger initial pore volume of the more micaceous sands is apparently caused by bridging of open spaces by the mica flakes. Because the flakes respond to pressure by bending around spherical grains, the more micaceous sands are more compressible and their greatest compaction takes place at lower pressures than in less micaceous sands. Note also the greater elastic rebound upon release of pressure on the more micaceous sands.

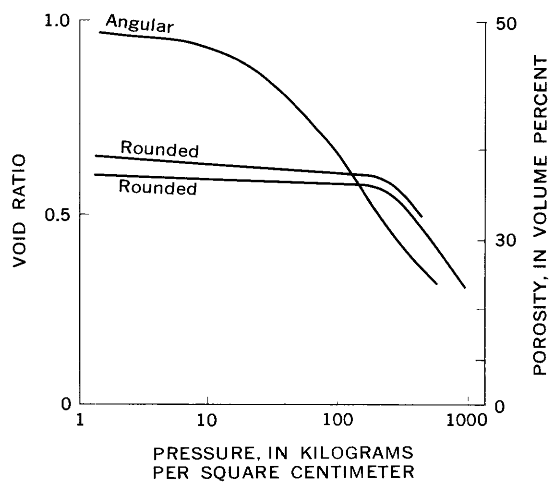

FIGURE 6.—Influence of degree of roundness of pure quartz, 420 to 840 microns in size, on relation between void ratio and pressure. Modified from Roberts and de Souza (1958). Details of experiments listed in table 1.

Results of experiments made by McCarthy and Leonard (1963) on the compressibility of mixtures of different proportions of two different sizes of fine muscovite and a natural sandy silt from Pennsylvania are shown in figures 7*B* and 7*C*. Because the samples were compacted dynamically by tamping rather than being compressed under a static load, the results are not strictly comparable to those in figure 7*A*, nor are they directly applicable to equivalent sediments under natural loads. The results do show, however, that the addition of mica increases the void ratio of the silt and that, the finer the mica, the greater the increase in void ratio per unit increase in mica content.

INFLUENCE OF INTERSTITIAL WATER

The degree to which the presence or absence of interstitial water influences the compressibility of a sand is related to the amount of finer material that the sand contains. In clean sands, the compressibility is apparently independent of the water content. Terzaghi (1925, p. 987) noted this in his early experiments, and the results obtained by Roberts and de Souza (1958) substantiate his observations. In figure 8, the difference in void ratio between wet and dry sands is the same as the difference between duplicate tests on the dry sand.

When clay is present in sufficient quantity to act as a binder or as a coating on sand grains, however, the difference between the behavior of the wet and dry aggregates is substantial. Bull (1964, p. A58–A59), for example, made compression tests on a sand that contained 5 percent clay, most of which was montmorillonite. The sand was markedly more compressible when wet than when dry. In the compression tests made by McCarthy and Leonard (1963) on sands and silts mixed with different proportions of mica, the water content had a small but markedly consistent effect on the compaction. In the range of water contents roughly between 39 and 84 percent of saturation and in the range of mica contents between 0 and 100 percent, the void ratio at a given pressure was nearly always smaller (by 0.01 to 0.04) in the more saturated sediments. This indicated a small but consistent influence of water content on the efficiency of the compaction.

PORE VOLUME OF SANDSTONES AT PRESSURES GREATER THAN 100 KILOGRAMS PER SQUARE CENTIMETER

Although studies of the porosity of sandstones and the factors that influence it at pressures greater than 100 kg per cm^2 (depth of burial about 3,000 feet) are not directly applicable to the studies that follow this review, they indicate effects that may be incipient at lower pressures and they provide useful insights. Although the work reviewed below relates to sandstones rather than sands, its chief asset is that most of it is based on natural sedimentary rocks rather than on sands prepared in the laboratory.

The porosity of sandstones seems to decrease regularly with increasing depth of burial. In well-sorted quartzose sandstones, the relation between depth of burial and percent porosity (rather than void ratio) may be linear (Maxwell, 1964; Philipp and others, 1963a, p. 461; 1963b, p. 465; or Füchtbauer and Reineck, 1963, p. 304). On the basis of the available studies, however, one cannot be certain of the depth range in which such a linear relation might apply (Walker and Maxwell, 1964), or what form the relation might have in poorly sorted mixtures of sand, silt, and clay.

One of the most informative studies of the processes by which sandstones respond to pressure was made by Taylor (1950). In thin sections of Mesozoic sandstones from Wyoming, she studied the number and types of contacts between sand grains. The number of contacts increased with increasing depth of burial, and the type

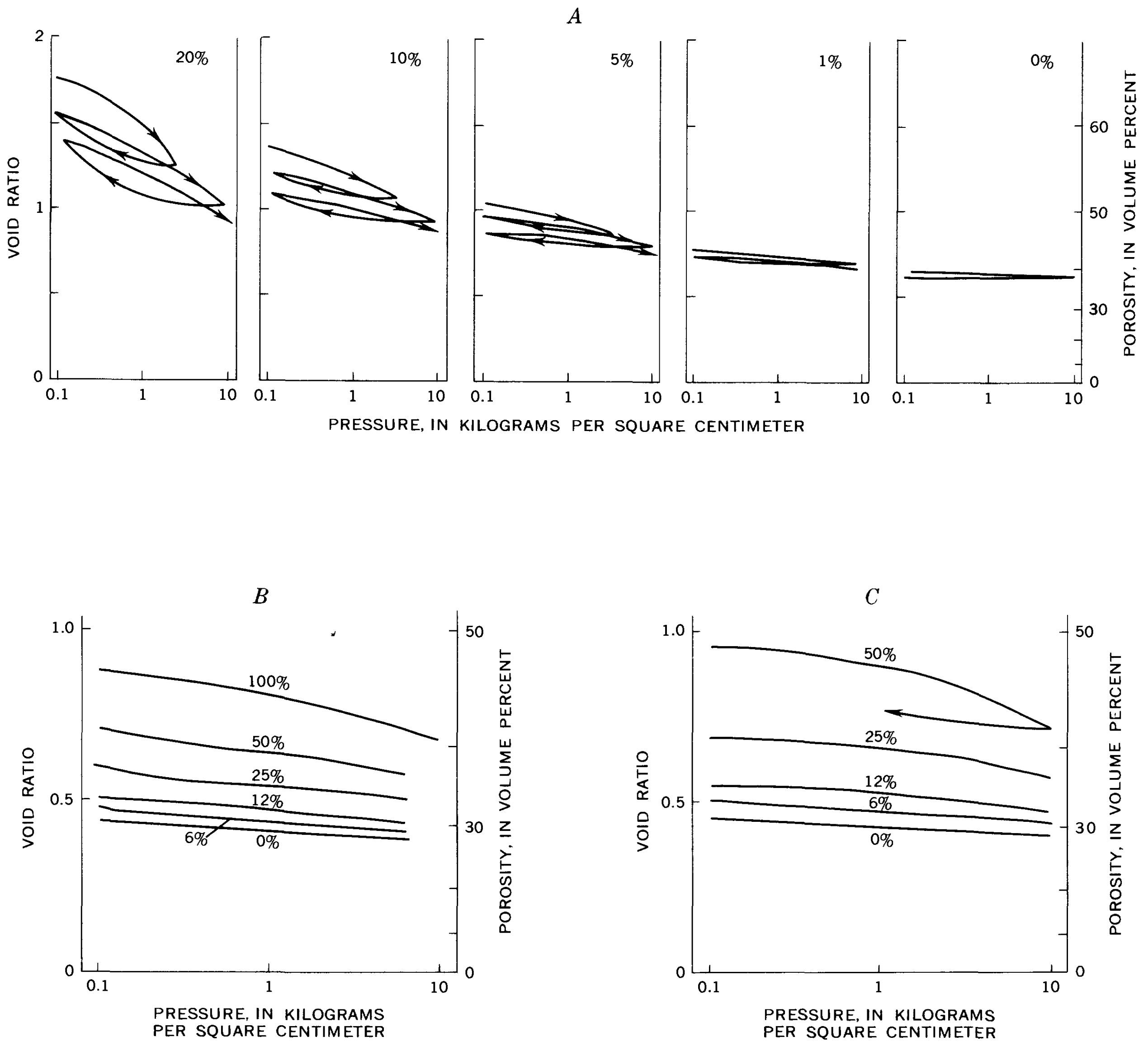

FIGURE 7.—Influence of proportion and size of mica particles on relations between void ratio and pressure in sands and silts. Percentage of mica by weight indicated on each diagram. A, Artificial mixtures of mica and quartz; particles of both constituents 420 to 590 microns in size (modified from Gilboy, 1928, p. 560). *B*, Sandy silt (Md=60 microns, $QD\phi$ =1.7, material finer than 4 microns in size=12 percent) mixed with silt-sized mica (Md=24 microns, $QD\phi$ =2.5); water saturation 80 to 82 percent (modified from McCarthy and Leonard, 1963, p. 33). *C*, Sandy silt as in *B*, mixed with finer grained mica (Md=7 microns, $QD\phi$ = 0.7); water saturation 78 to 80 percent (modified after McCarthy and Leonard, 1963, p. 34).

changed progressively from tangential through long and concavo-convex to sutured. She believed that the progressive change of contact type was due to (1) solid flow of material under pressure and (2) solution and redeposition of dissolved material, both of which were caused by the pressure that accompanied deep burial. Other pressure effects that she observed were "the crushing and yielding of micas, feldspar and rock fragments, and the development of tension and pressure cracks in the grains" (p. 715). Unfortunately, she did not report the depths at which these phenomena became important.

Factors other than pressure that have been clearly shown to affect the porosity of sandstones are the interstitial cement (carbonate or silica), the size of the sand particles, and temperature.

The effect of interparticle cement on porosity is intuitively obvious, and it is documented by recent detailed studies. Clear inverse relations between porosity and calcite content, for example, are described by Füchtbauer (1964, p. 243–244) in Tertiary sandstones buried at depths between 3,600 and 11,500 feet in Switzerland, Austria, and Bavaria. Similar inverse relations between porosity and silica overgrowths on quartz grains are shown by Füchtbauer (1961, p. 172–173) in Mesozoic sandstones buried at depths between 4,700 and 5,300 feet in northwest Germany. Inverse relations between porosity and the amount of cementing material (both carbonate and silica) are also revealed by the statistical studies of Paleozoic sandstones in the Appalachian region by Griffiths (1964, p. 653–664) and his students. (See also Griffiths, 1958, p. 27–29.)

In sandstones that do not contain large proportions of cement, the relations of porosity to particle size and, to a lesser extent, particle sorting are often clearly visible (curve V in fig. 4; Griffiths, 1958, p. 27–29; 1964, p. 652–664). Whereas the relation between porosity and particle size in sandstones is often inverse, it occasionally is found to be direct—that is, in some sandstones the porosity increases with increasing particle size (Füchtbauer, 1964, p. 243–244; McCulloh, 1964; Modaressi and Griffiths, 1963, p. 258). This reversal in the relation between porosity and particle size is at least partly a function of the depth of burial. Although finer sediments have greater initial porosities than coarser sediments, they are compressed more rapidly during the early stages of compaction. As compaction continues with progressive depth of burial, a critical depth or depth range must be reached at which the porosity of the finer sediments equals that of the coarser and below which the porosity of the finer sediments is less than that of the coarser. This extrapolation is supported by the well-known fact that, among older or deeply buried sediments, sandstones are usually more porous than closely associated claystones—see, for example, the data of Proshlyakov cited by Maxwell (1964, p. 698).

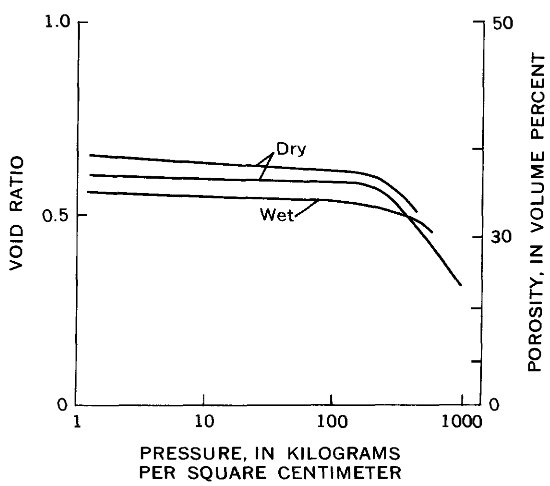

Figure 8.—Influence of interstitial water on relation between void ratio and pressure in well-sorted clean quartz sands. Modified from Roberts and de Souza 1958). Details of experiments in table 1.

The effects of temperature on the porosity of quartzose sandstones are best shown in the laboratory experiments and, to a lesser extent, in the analysis of field data by Maxwell (1960, 1964). Two main effects were observed in the laboratory experiments. Increasing temperatures from 20° to 235° C and from 270° to 345° C increased the compaction of quartz sands under a fixed pressure of about 2,000 kg per cm^2—roughly equivalent to a depth of burial of 26,500 feet. The greater temperatures apparently decreased the strength of the quartz grains so that they failed mechanically under pressure. Furthermore, temperatures greater than 270° C seem to enhance the solution of silica and its reprecipitation as interparticle cement.

The reduction of porosity in sandstones seems to be a time-dependent process. In Maxwell's laboratory studies (1960), the longer the experimental conditions of temperature and pressure were maintained (up to 100 days), the greater the observed decrease in porosity. Observations of progressively smaller porosities in successively older natural sediments by Maxwell (1964) and McCulloh (1964) supported the laboratory results and led Maxwell to suggest (1964, p. 708) "that compaction will continue so long as porosity exists; that is, there is no suggestion of an equilibrium porosity at a given depth which would persist throughout geologic time."

SUMMARY OF PETROLOGY OF SEDIMENTS IN AREAS OF LAND SUBSIDENCE

The petrologic features of the sediments whose compaction accounts for the observed land subsidence in central California were described in some detail in the preceding chapter in this series (Meade, 1967). Special emphasis was given to the features that influence the compaction behavior of the sediments. A short summary is given here as general background for the studies that follow. Selected petrologic features are plotted against depth in figure 10.

The sediments included in the studies that follow were collected from eight cored sections whose locations are shown in figure 9. Four of the cores—Oro Loma, Mendota, Cantua Creek, and Huron—were taken in the Los Banos-Kettleman City area on the west side of the San Joaquin Valley. Two cores—Pixley and Richgrove—were taken in the Tulare-Wasco area on the east side of the San Joaquin Valley. Two cores—Sunnyvale and San Jose—were taken in the Santa Clara Valley. Details of the coring procedure, core recovery, and sampling are given in an earlier chapter (Meade, 1967, p. 2–3, 48).

The source terranes of the sediments, identified by the distinctive assemblages of minerals and rock fragments that comprise the sand and gravel fractions, are represented by letter symbols in the composite logs in figure 10. The sediments in the Sunnyvale and San Jose cores in the Santa Clara Valley were derived entirely from the Coast Ranges—specifically, the Diablo and Santa Cruz ranges that flank the valley on the northeast and southwest. The sediments in the Pixley and Richgrove cores in the Tulare-Wasco area were derived entirely from the Sierra Nevada. The sediments in the

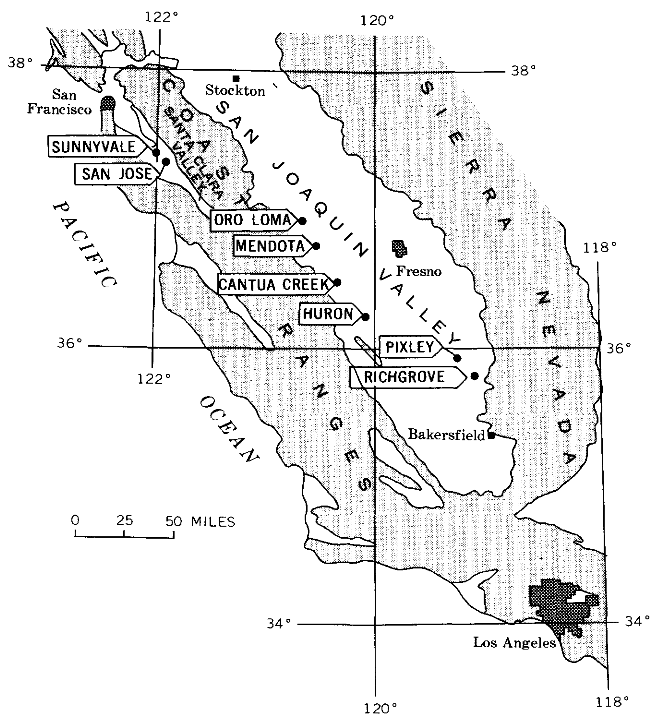

Figure 9.—Locations of core holes in central California.

Oro Loma, Mendota, Cantua Creek, and Huron cores in the Los Banos-Kettleman City area were derived from both the Sierra Nevada and the Coast Ranges.

The sediments are mainly alluvial, having been deposited either on alluvial fans or on the flood plains of perennial streams. This is shown in the second column of each composite log in figure 10. Other types of deposits, subsidiary in their abundance, are the lacustrine sediments cored in five of the six holes shown in the San Joaquin Valley, the shallow-marine sediments below about 760 feet in the Richgrove core, and the deltaic sediments below 1,800 feet in the Huron core.

Particle sizes are represented indirectly by the electrical resistivity of the sediments and numerically by the median diameter. Resistivity, in the third column of each composite in figure 10, increases to the right; the greater resistivities are characteristic of the coarser sediments. Median diameter, in microns on a logarithmic scale, is plotted in the fourth column. The particle sizes are diverse, ranging from fine clay to gravel. The geometric mean size is probably in the coarse-silt range, or between 30 and 60 microns. The general degree of sorting is fair to poor; the average quartile deviation (QD_ϕ) is about 2.0. The general degree of skewness of the particle-size distributions indicates (1) that the sizes are not distributed lognormally and (2) that the sediments contain disproportionately large admixtures of finer particles.

Variations in the degree of rounding of the sand-sized particles are not extreme, ranging from subangular in quartz grains to subrounded in the softer rock fragments.

The proportions of mica flakes in the sediments reflect the source terranes.

Source of sediments	Percent of mica	Relative size of mica flakes to associated nonmica particles
Los Banos-Kettleman City area [Cores: Oro Loma, Mendota, Cantua Creek, Huron]		
Sierra Nevada	2 to 5, max 10	Same or larger.
Coast Range	Trace to 2, max 8	Same or smaller.
Tulare-Wasco area [Cores: Pixley, Richgrove]		
Sierra Nevada	2 to 5, max 10	Same.
Santa Clara Valley [Cores: Sunnyvale, San Jose]		
Coast Range	0 to trace, max 1	

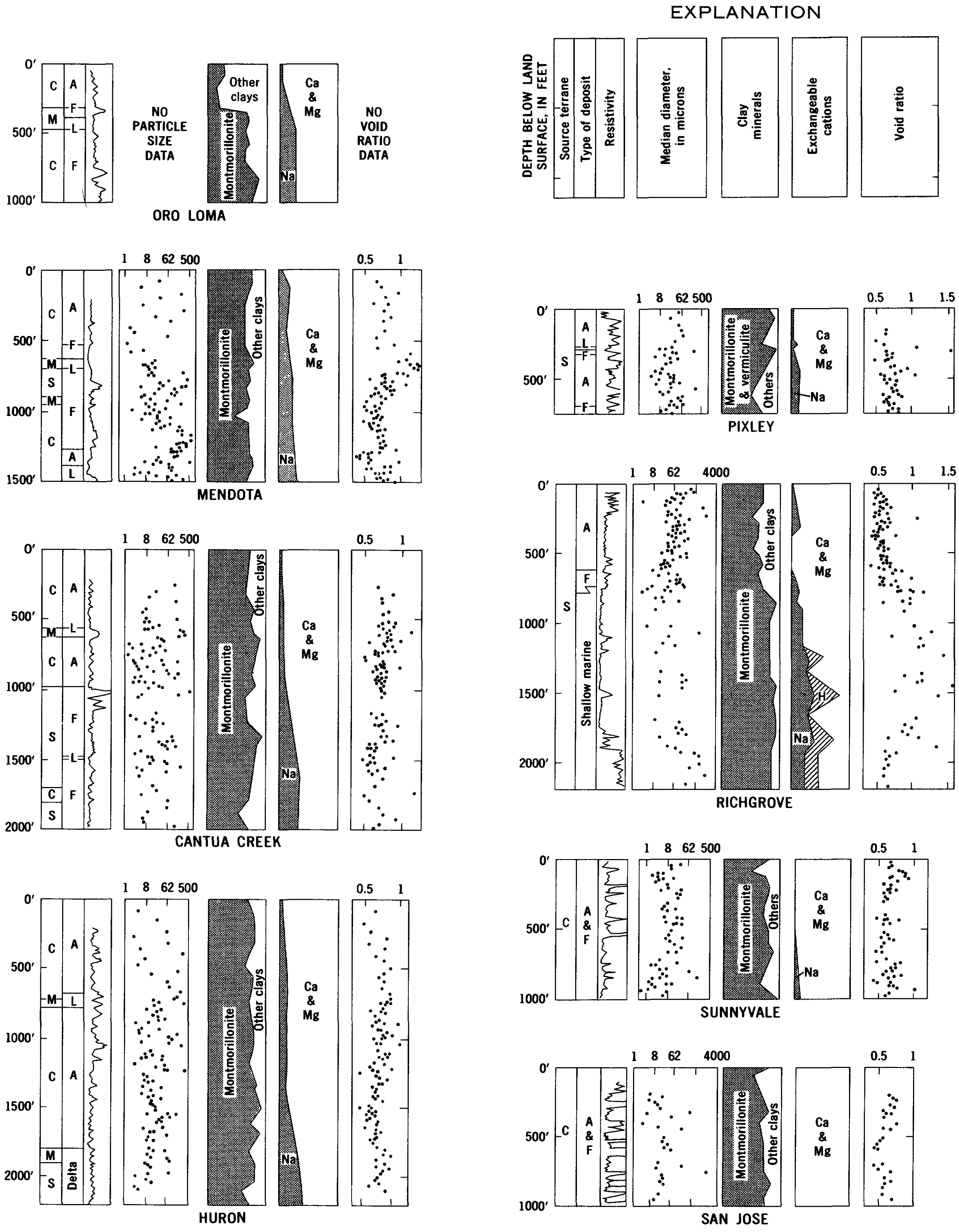

FIGURE 10.—Composite logs of petrologic characteristics of sediments cored in areas of land subsidence in central California. Key to composites in upper right corner. Source terranes indicated by C (Coast Ranges), S (Sierra Nevada) and M (mixed Coast Range and Sierra Nevada). Types of deposits indicated by A (alluvial fan), F (flood plain), and L (lacustrine). Locations of core holes shown in figure 9.

More mica in larger flakes is present in the sediments derived from the Sierra Nevada.

Montmorillonite is consistently the dominant clay mineral, as shown by the shaded area of the central column of each composite in figure 10. It comprises 60 to 80 percent of the clay-mineral assemblages and 5 to 25 percent of the different sections of sediments represented in the several cores. Vermiculite is included with montmorillonite in the log for the Pixley core. Other common but subsidiary clay minerals in the sediments, included in "other clays" in figure 10, are illite, chlorite, a kaolinite-type mineral, and mixed-layer illite-montmorillonite.

Exchangeable cations, adsorbed largely by the montmorillonite, are represented in figure 10 in terms of the proportion of sodium (and hydrogen, in the Richgrove core) relative to calcium and magnesium. Calcium is the most abundant of the exchangeable cations. The proportion of adsorbed sodium increases downward in most of the cores, probably reflecting the corresponding downward increase in the proportion of sodium dissolved in the associated interstitial waters.

Although pore volume was not treated in detail in the preceding chapter in this series (Meade, 1967), it is included in figure 10 to show its spatial variations relative to variations in the petrologic characteristics. Expressed as void ratio, it is plotted in the right column of each composite. The largest void ratios are found in some of the lacustrine sediments of the Mendota and Pixley cores and in the shallow-marine sediments of the Richgrove core. No decrease in void ratio with increasing depth of burial is obvious. The most apparent relation is with particle size: the graphs of void ratio for several cores—especially Mendota, Richgrove, and Sunnyvale—are distorted mirror images of the graphs of median diameter.

ANALYSIS OF FACTORS INFLUENCING COMPACTION OF THE SEDIMENTS

This section of the report is an assessment of the influences of selected factors on the pore volume of the sediments whose compaction accounts for the land subsidence observed in central California. It consists mainly of two progressive multiple-regression analyses of successive factors or groups of factors. The first analysis explores the influence of overburden load, particle size, and particle sorting in a large number of samples in the following general steps: (1) evaluation of effects of overburden load, (2) relation of particle size to the variation in void ratio that is "unexplained" by load, (3) evaluation of combined effects of load and size, and (4) relation of particle sorting to the variation in void ratio that is "unexplained" by the combination of load and size. The other multiple-regression analysis is an attempt to sort out the relative influences of overburden load, particle size, clay minerals, exchangeable cations, electrolyte concentration, pH, fabric, and diatom content in a small group of fine-grained samples by successive eliminations of the less significant factors.

In addition, the influence of montmorillonite is assessed qualitatively without resort to statistical techniques. Judging from experimental results such as the ones shown in figure 1*C* (others are shown in Meade, 1964, fig. 4) the large proportions of montmorillonite must exert a strong influence on the compaction behavior of these sediments. This influence cannot be demonstrated by statistical analysis because the montmorillonite content within the sediments does not vary sufficiently to cause any discernible variations in void ratio. The abundance of montmorillonite, however, probably contributes to the compaction behavior in several ways. The void ratios are probably larger and the sediments are probably more sensitive to changes in load than they would be if less montmorillonite were present. And the large exchange capacity and surface area of montmorillonite certainly contribute to the discernible effects of the different exchangeable cations on the void ratio shown in this report.

Three progress reports of this work have been published (Meade, 1961b, 1963a, 1963b). The approach used in the earliest of these—involving computations of the amounts of adsorbed water and free pore water in clayey sediments in the Cantua Creek core—may not be valid. Two of the assumptions that were made, concerning the thickness of the layers of adsorbed water and the uniformity of interparticle distances, are questionable enough to throw serious doubts on that approach to the removal of water. In any event, all three earlier papers are superseded by this report.

USE OF MULTIPLE-REGRESSION STATISTICS FOR ANALYSIS

The statistical techniques of multiple-regression analysis are the principal tools used in this section of the study. These techniques have been used previously and successfully by Griffiths (1964) and his students to sort out the relative influences of different petrologic factors on the porosity of Paleozoic sandstones. Although this is a promising approach, especially because the necessary arduous computations can be done quickly on a digital computer, it involves some difficulties. In the first place, one must be able to give numerical values to each factor. For some factors, such as effective overburden load, one can use numerical measures that describe the factor fairly completely. For others, one must use generalized index measures that do not describe the factor completely: the average size and sorting, for instance, do not characterize entirely the nonnormal distribution of particle sizes in many natural sediments.

Another difficulty in using the techniques of multiple regression is that one must either find out or assume the nature of the numerical relations between the measure of pore volume and the measures of the influencing factors. That is, one needs to know whether the relations are linear or nonlinear. As these relations are virtually unknown, much of this chapter is concerned with attempts to discern their nature. This is a first step in applying numerical statistical techniques to the study of pore volume.

For selected groups of samples, the following statistics were computed on the U.S. Geological Survey's Burroughs 220 computer:

1. Correlation coefficients—simple, multiple, and partial—using void ratio as the dependent variable.
2. Probability of significance (Student's t test) of correlation coefficients.
3. Regression equation of the straight line that best represents the observed relation between void ratio and the other variables.
4. Residuals (arithmetic differences) between the measured values of the void ratio and the values predicted from the regression equation.
5. Standard error of estimate of the void ratio.

The simple correlation coefficient is a measure of the degree of linear correlation between any two variables; the multiple correlation coefficient measures the linear correlation between the dependent variable (void ratio in this study) and a combination of independent variables. When correlation is perfect, the coefficient (r) equals ± 1 (the sign is a convention to indicate whether correlation is direct or inverse); when correlation is poor or absent, r values fall near zero.

The significance test yields a probability (P) that the observed correlation is not due to chance alone. For example, when P equals 0.95, chances are 19 to 1 that the observed correlation is real rather than merely fortuitous.

The standard error of estimate, expressed in units of the void ratio, is a measure of the deviation of the observed void ratios from the regression line. Approximately two-thirds of the observed void ratios should fall within one standard error of the values predicted from the regression equation. Approximately 19 observed values in 20 should fall within 2 standard errors of the predicted values.

Several assumptions, in addition to the assumption that the numerical relations between void ratio and the independent variables are linear, are involved when probability statements, such as those in the preceding paragraphs, are made on the basis of the computed statistics. None of the assumptions are entirely satisfied by the data used in this study. The correlation coefficient is computed with the assumption that the sample errors are random and normally distributed. Significance tests concerning the equation of the regression line are based on the assumption that the distribution of the values of the void ratio that correspond to any single value of the independent variable follows the normal distribution law. The use of the standard error of estimate as in the preceding paragraph adds the additional assumption that the distribution of void ratio with respect to the independent variable is constant for all values of the independent variable. Although their underlying assumptions are not fulfilled entirely, these statistical measures and methods are used with the understanding that their interpretation involves more risk than is indicated by the statistics themselves.

The statistical terms used in this paper are defined in the glossary. For simple and nontheoretical discussions of correlation and regression, see Ezekiel and Fox (1959), Fisher (1950), and Williams (1959).

EFFECT OF OVERBURDEN LOAD

The relations between pore volume and overburden load are examined in selected groups of alluvial sediments, including 135 samples from the Mendota, Cantua Creek, and Huron cores of the Los Banos-Kettleman City area and 23 samples from the Sunnyvale and San Jose cores of the Santa Clara Valley. The alluvial sediments are singled out for study because they are more abundant than the other types. No distinction is made between alluvial-fan and flood-plain deposits. The clays and clayey silts included among the analyzed samples are only those whose textures suggest that they were deposited by moving water (Meade, 1967, p. 7). Lacustrine sediments and other sediments whose finely laminated textures suggest that they were deposited in standing water (that is, some of the fine flood-plain deposits) are not included in the statistical study, nor are samples included that represent heterogeneous or cemented alluvial sediments. Clean, well-sorted sands are also excluded because they are the most likely to have been disrupted during the coring process; only those sands containing 25 percent or more of silt and clay are included. All sediments included in the analysis were collected from below the water table. No sediments from the Tulare-Wasco area are included in the analysis—the range of effective load between the water table and the bottom of the alluvial-fan sediments in the Pixley and Richgrove cores (roughly 16 to 27 kg per cm^2) is too small for the effects of load to be clearly visible.

Void ratio and effective overburden load are the dependent and independent variables in this analysis. Depth of burial is not used as a variable because the presence of artesian pressures in the sediments causes the relation between depth and load to be irregular. I computed the void ratios from the porosity measurements that were made on these sediments by Johnson, Moston, and Morris (1967). Effective overburden loads were computed by subtracting the fluid pressures in the sands and gravels, as measured at the time that the sediments were cored, from the total load (bulk weight) of the overlying sediments. R. E. Miller computed the effective loads in the Los Banos-Kettleman City area; J. H. Green computed those in the Santa Clara Valley. Computed effective overburden loads are listed in "Appendix B." The tabulated data represent loads that were computed at discrete points in the sections, based on the physical properties of the sediments and water-level conditions. The effective overburden loads at intervening depths, which were used in the statistical analysis, were estimated by linear interpolation between the data points listed in the table.

The effective (grain-to-grain) loads computed for the sands and gravels, however, probably do not represent the effective loads in the adjacent silts and clays because of a time lag in the adjustment of the finer sediments to the rapid declines in artesian pressure. The artesian head in the sands and gravels has been falling at rates as great as 15 feet per year because of the excessive pumping of confined ground water. The less permeable silts and clays cannot equilibrate immediately to such a rapid change. Residual excess pore pressures remain in the finer sediments and decay at rates that are controlled by sediment thickness and permeability. These excess pore pressures cause the void ratios of the silts and clays to be larger than the void ratios that represent a state of equilibrium with the effective overburden pressures in the adjacent sands and gravels.

Another effect that may limit the use of the void-ratio measurements is the expansive rebound that probably takes place when the overburden load is removed from the sediments as they are cored (Poland, 1963). The actual amount of rebound involved, however, is not easily determined. For laboratory tests made of compression and rebound of 48 of the fine clayey sediments from the San Joaquin and Santa Clara Valleys, rebound from the simulated field effective load to the unloaded condition was accompanied by an average increase in void ratio of about 0.1 (from 0.56 to 0.67). This rebound, however, took place in the presence of excess water over rather long periods of time. Saturated clays must imbibe water in order to swell, and the silts and clays whose void ratios are used in this study were not exposed to excess water long enough to swell to their full rebound capacity during the coring process. I suspect, therefore, that the increases in void ratio related to rebound experienced by these samples are considerably less than the 0.1 observed in the laboratory compression and rebound tests.

The relation between void ratio and the logarithm of effective overburden load is assumed to be linear. This assumption is based on the data of Hedberg (1936, p. 256, 262) and Storer (1959, p. 520–523), which are summarized together by Engelhardt (1960, p. 39–42). These data suggest that the relation between void ratio and the logarithm of depth is linear in the depth range between 1,500 and 10,000 feet. Using these data to support the assumption of a linear relation between void ratio and the logarithm of effective load in the sediments of the San Joaquin and Santa Clara Valleys involves two further assumptions: (1) that the relation between depth and effective overburden load in the sediments studied by Hedberg and Storer is linear and (2) that the relation between void ratio and the logarithm of depth is also linear at depths shallower than 1,500 feet.

Relations between void ratio and the logarithm of effective overburden load in the selected groups of alluvial sediments are shown in figure 11. The sediments from the Los Banos-Kettleman City area are segregated into four groups (A through D, fig. 11) by particle size in order to minimize the effects of the strong correlation between size and void ratio that is also found in these sediments (fig. 13). The 23 sediments from the Santa Clara Valley were treated in one group (E, fig. 11). Although the correlation between size and void ratio in this group is also strong (fig. 13), there are too few suitable samples from the Santa Clara Valley to permit any further segregation by particle size. Most of the sediments that were sampled in the Santa Clara Valley are either heterogeneously bedded or too full of calcite cement to be included in the analysis of pore volume. The solid lines through the scatter diagrams are the regression lines that best represent the observed change in void ratio with overburden load. The dashed lines represent approximately the 95-percent confidence limits: 19 void ratio observations in 20 should fall within these limits. Details of the regressions illustrated in figure 11 are listed in the upper part of table 2.

The conspicuous gap in the plots for groups A through D, between loads of 25 and 35 kg per cm^2, shows the manmade change in effective load across the principal layer of fine sediment (the lacustrine Corcoran Clay Member of the Tulare Formation) that confines the artesian aquifer system in the San Joaquin Valley. Samples that plot to the left of the gap are from the

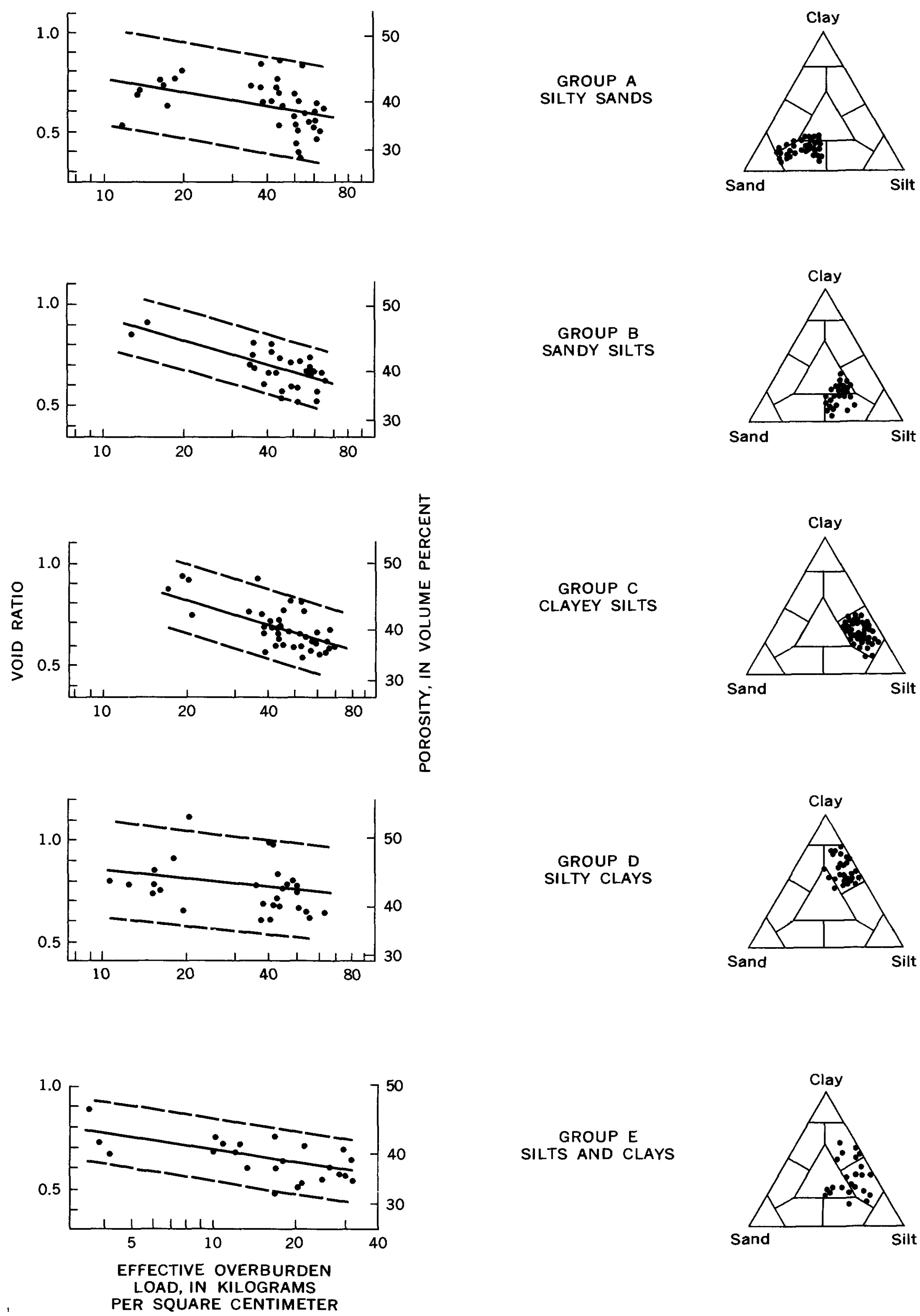

FIGURE 11.—Simple relations between void ratio and effective overburden load in fresh-water-bearing alluvial sediments. Groups A through D from Mendota, Cantua Creek, and Huron cores from Los Banos-Kettleman City area; group E from Sunnyvale and San Jose cores from Santa Clara Valley. Note different range of effective load for group E. Particle sizes in each group are represented by triangular sand-silt-clay diagrams, which are subdivided according to the system proposed by Shepard (1954).

semiconfined aquifer system above the confining layer; those to the right are from the confined artesian system. The gap represents the increase in effective overburden load caused by excessive pumping of the artesian water.

The correlation between void ratio and load in the silty sands (group A) is not entirely as represented in figure 11. The void ratio also correlates significantly with QD_ϕ (see bottom of table 2 and figure 16), and the correlation between load and QD_ϕ may be significant ($r=0.29$, $P=0.92$). That is, the sorting becomes progressively poorer (QD_ϕ increases) at greater depths, and this accounts for part of the apparent decrease in pore volume with increasing load. The line representing the actual change of void ratio under increasing load, therefore, should be less steep than the regression line in figure 11.

The silts and clays of groups B, C, and E show the most unequivocally significant relations between void ratio and load. The slopes of the regression lines in groups B and C should represent the relation between pore volume and load fairly clearly, as no simple correlation was observed between load and the particle-size variables in these groups. Note, in table 2, that the equations for the regression of void ratio on load are virtually identical for groups B and C.

In the silty clays of group D, the decrease in void ratio with increasing load is only fairly significant ($P=0.88$). The wide scatter of samples in this group may be related to variability in several other factors. Some sediments in this group, for example, contain aggregates of fine silt and oriented clay particles surrounded by a poorly sorted and disoriented sand-silt-clay matrix (Meade, 1967, p. 8); whereas other clays in this group contain few of these aggregates or none at all. Considering that the geometry of the pore space within the aggregates may be different from that of the pore space in the rest of the sediments, the variable proportions of aggregates may cause some of the wide scatter of points in group D. Another possible cause of the scatter is the influence of variations in particle size: The correlation between void ratio and median diameter (Md_ϕ) within group D is probably significant ($P=0.96$). Still another cause might be differences in the elastic rebound of the clays between the time that they were cored and the time that their pore volume was measured in the laboratory, although, as stated previously, I doubt that this is a strong enough effect to account for the wide scatter in group D. And finally, considering also that the rate of decrease in the void ratio in group D is anomalously low, the scatter of

TABLE 2.—*Details of significant regressions of void ratio on effective overburden load, median particle diameter, and quartile deviation of particle-size distribution*

[e=void ratio, log L=logarithm (base 10) of effective overburden load (in kg per cm^2), Md_ϕ=median particle diameter (ϕ units, see Inman, 1952, p. 133), QD_ϕ=quartile deviation (particle sorting, ϕ units, see Krumbein, 1936, p. 102–103)]

Group	Designation in figures	Number of samples	Correlation coefficient (r)	Probability of significance of correlation coefficient (P)	Regression equation	Standard error of estimate of void ratio
Simple regressions of void ratio on effective overburden load						
Los Banos-Kettleman City	A–D	135	−0.48	>0.99	$e=1.15-0.28\log L$	0.11
Silty sand	A	39	−.40	>.99	$e=1.00-0.23\log L$	.12
Sandy silt	B	28	−.68	>.99	$e=1.33-0.39\log L$	.07
Clayey silt	C	40	−.62	>.99	$e=1.35-0.40\log L$	.08
Silty clay	D	28	−.30	.88	$e=1.00-0.15\log L$	.12
Santa Clara	E	23	−.63	>.99	$e=0.90-0.21\log L$	.08
Simple regressions of void ratio on median particle diameter						
Los Banos-Kettleman City	A–D	135	0.38	>0.99	$e=0.55+0.024\,Md_\phi$	0.11
Santa Clara	E	23	.60	>.99	$e=0.33+0.048\,Md_\phi$	.08
Tulare-Wasco	F	48	.52	>.99	$e=0.37+0.054\,Md_\phi$	.10
Multiple regressions of void ratio on effective overburden load and average particle diameter						
Los Banos-Kettleman City	A–D	135	0.58	>0.99	$e=0.99-0.26\log L+0.020\,Md_\phi$	0.10
Santa Clara	E	23	.78	>.99	$e=0.61-0.18\log L+0.038\,Md_\phi$	.06
Simple regression of void ratio on quartile deviation						
Silty sand	A	39	−0.44	>0.99	$e=0.81-0.099\,QD_\phi$	.11

points above the regression line may show the effect of residual excess pore pressures in the thicker silty clays of low permeability.

EFFECT OF PARTICLE SIZE

The decrease in pore volume that corresponds to increasing particle size is studied in 3 groups of alluvial sediments: those included in groups A through D (fig. 11) from the Los Banos-Kettleman City area, those in group E from the Santa Clara Valley, and a group of 48 alluvial-fan sediments from the 2 cores of the Tulare-Wasco area. These 48 samples were all taken from below the water table; excluded from the group are sediments that contain calcite cement or conspicuous soil cavities of the types shown in the earlier chapter (Meade, 1967, fig. 18).

Void ratio and median diameter are the dependent and independent variables used in this part of the analysis of pore volume. The median diameters are taken from particle-size analyses that were made in the Hydrologic Laboratory of the Geological Survey. They are expressed logarithmically in ϕ units, wherein ϕ is the negative logarithm to the base two of the diameter in millimeters. (See Inman, 1952, for further explanation of the ϕ notation.) Note that a numerical increase in Md_ϕ corresponds to a decrease in median diameter.

Whether the numercial relation between void ratio and Md_ϕ is linear is uncertain. From most of the studies that are summarized in figures 1*A* and 4, one might expect the relation to be nonlinear. Those studies, however, were done on sediments that were under overburden loads less than 1 kg per cm^2. The large initial void ratios of sediments should be expected to be reduced rapidly under increasing overburden loads to values on the order of 1.5 or less (as shown in fig. 11). The question then becomes: Would such a reduction of void ratio involve a transformation of the numerical relation between void ratio and Md_ϕ from a nonlinear relation to one that is essentially linear within the sand-silt-clay size range?

Considering that the fresh-water-bearing alluvial sediments of the San Joaquin and Santa Clara Valleys are all under significant overburden loads, one might suppose that the relations between void ratio and Md_ϕ could be linear. This supposition is tested, but not conclusively, by plotting the residuals of the void ratio-load equations against Md_ϕ in 2 groups of sediments, namely the 135 samples of groups A through D and the 23 samples of group E (fig. 12). The residual is the difference expressed in void-ratio units between the measured value of the void ratio and the value predicted from the equation for the regression of void ratio on the effective load. (See the first and sixth equations listed

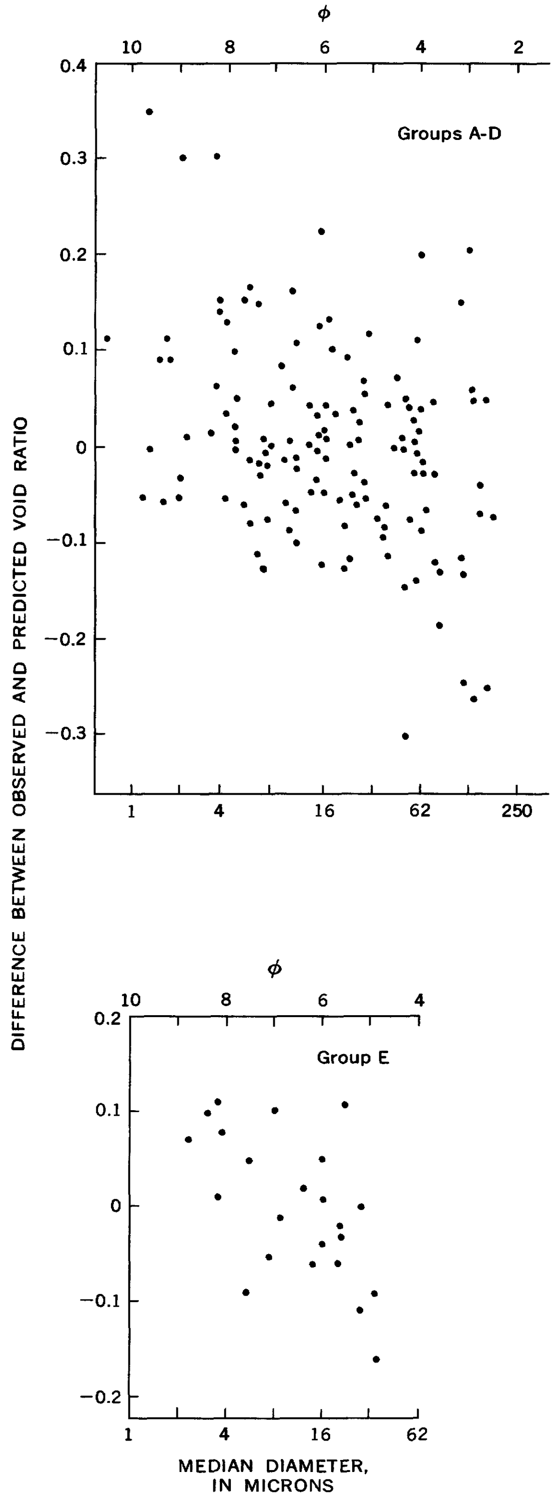

FIGURE 12.—Relations between median diameter and the residuals of the void ratio-load regressions (observed void ratio minus the void ratio predicted by the regression equation) in sediments of groups A through D and group E. See figure 11 and table 2 for identification of groups.

in table 2.) The residual is an indication of the variation in void ratio that is unaccounted for by variation in load. If its relation to Md_ϕ is linear, then presumably the relation between void ratio and Md_ϕ also should be linear. Unfortunately, the scatter in the graphs of figure 12, reflecting the influence on void ratio of sampling error, and of factors other than load and average particle size, is so great that one cannot draw firm conclusions about the nature of the relation. These graphs do show that the pore volume decreases with increasing particle size. This, however, is shown more clearly in the simple correlations between void ratio and Md_ϕ illustrated in figure 13.

Figure 13 shows the simple relations between void ratio and the logarithm of median diameter in 3 groups of sediments: groups A through D taken together, group E, and the 48 samples from the Pixley and Richgrove cores of the Tulare-Wasco area which are designated group F. As in figure 11, the solid and dashed lines represent the regression equation and the 95-percent confidence limits. Pertinent statistical details are listed in table 2. In all three groups, the decrease in void ratio with increasing particle size (decreasing Md_ϕ) is clear. The relation between void ratio and Md_ϕ seems to be approximately linear.

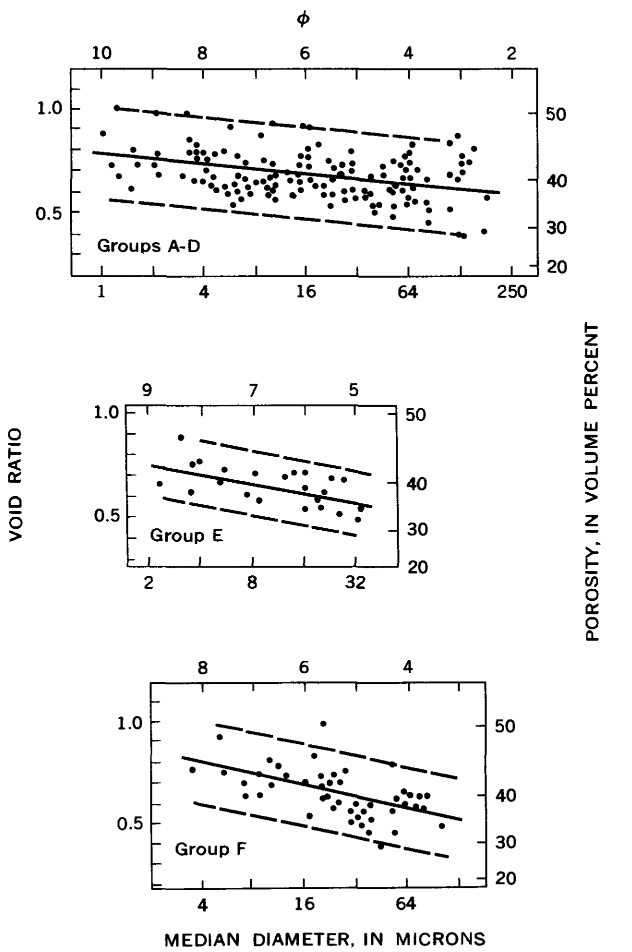

FIGURE 13.—Simple relations between void ratio and median particle diameter in fresh-water-bearing alluvial sediments. Groups A through D and E as in figure 11. Group F from Pixley and Richgrove cores of Tulare-Wasco area.

COMBINED EFFECTS OF OVERBURDEN LOAD AND PARTICLE SIZE

After treating separately the relations between pore volume and the two factors, overburden load and particle size, we may now consider the relations in combination with each other. This is done in two ways: (1) in qualitative terms of the influence of particle size on the relations between void ratio and load, and (2) in the numerical terms of multiple-regression analysis.

The regression lines from figure 11 are grouped together in figure 14 for comparison with each other and with similar curves derived by Skempton (1953, p. 55). The curves in the upper graph in figure 14 are segments of the more complete curves shown in figure 1*B*. They represent the most complete synthesis of information of this sort that has been published so far. They show that, with decreasing particle size in the

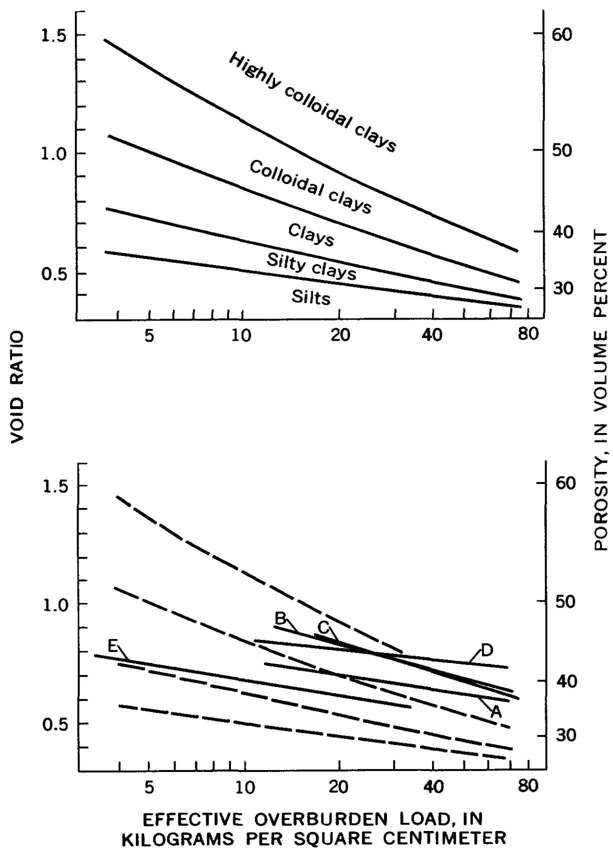

FIGURE 14.—Influence of particle size on relations between void ratio and effective overburden load. Upper: As modified from summary by Skempton (1953, p. 55). Lower: As observed in San Joaquin and Santa Clara Valleys; letters correspond to sample groups in figure 11; dashed lines are from upper graph by Skempton.

silt-clay range, the void ratio becomes greater at any given load, and it decreases more rapidly with increasing load. The sediments from the San Joaquin and Santa Clara Valleys (fig. 14, lower graph), however, do not behave exactly as predicted from Skempton's curves.

Before comparing Skempton's results with those observed in California, one must understand that Skempton's size nomenclature does not coincide with the nomenclature used in this report. His nomenclature is based on Atterberg limits; mine is based on particle-size analyses and the Shepard (1954) system. A basis for comparison of the two terminologies is the Atterberg limits of the California sediments, determined and reported by Johnson, Moston, and Morris (1967). The Atterberg limits show that the silts of groups B and C probably correspond to Skempton's "silty clays," and that the silts and clays of groups D and E probably correspond to Skempton's "clays." The silty sands (group A) presumably correspond to Skempton's "silts."

Of the five groups of sediments, only those of group E have void ratios that might have been predicted from Skempton's synthesis. The void ratios of the sediments in groups A through D are larger than expected. Why this might be so is uncertain. The sediments in all five groups have similar clay-mineral assemblages (fig. 10) and appear to have been in fairly similar chemical surroundings. The greater amount of sodium adsorbed by the clay minerals in the sediments of the Los Banos-Kettleman City area may contribute to their larger void ratios: experimental studies by others (fig. 1*D*) and evidence presented later in this chapter suggest strongly that the pore volume of montmorillonite-rich sediments is a direct function of the amount of sodium (versus cations of larger valence) adsorbed by the montmorillonite. However, this would not account for the large void ratios in the silty sands (group A) which presumably do not contain enough clay to reflect strongly the influence of the adsorbed cations. Another difference between the sediments from the two areas of California is the almost complete lack of mica in the Santa Clara Valley and its relative abundance in many of the sediments of the Los Banos-Kettleman City area. As figure 7 shows, the presence of mica may influence the pore volume of sands and silts under loads as great as 10 kg per cm^2. Perhaps it also influences the pore volume of sediments under larger loads.

Whereas the slopes of the regression lines for groups A, B, and C correspond approximately to the slopes of Skempton's curves for "silts" and "silty clays", the regression line for group D is anomalous. If the analogy with Skempton's curves is valid, the line for group D should be steeper than and entirely above the lines for groups B and C in figure 14. This anomaly could be accounted for by at least two possible factors—the downward increase in the proportion of adsorbed sodium or the residual excess pore pressures—both of which could cause the void ratios to be larger than anticipated in the artesian aquifer system below the principal confining layer.

The second approach to the description of the combined relation of overburden load and particle size to pore volume is by way of multiple-regression analysis. Multiple-regression statistics for 2 groups of sediments, namely the 135 samples from the Los Banos-Kettleman City area and 23 samples from the Santa Clara Valley, are given near the bottom of table 2. Taking the correlation coefficients (the square root of the coefficient of determination—see glossary, p. D36) at face value, the combined influence of effective overburden load and average particle size accounts for 61 percent of the observed variance in void ratio in the sediments of the Santa Clara Valley and only 34 percent of the variance in void ratio observed in the Los Banos-Kettleman City area. This leaves approximately one-third and two-thirds of the variances in void ratio, respectively, to be accounted for by other factors.

EFFECT OF PARTICLE SORTING

Experimental studies of the influence of particle sorting on the pore volume of artificial sand mixtures (fig. 5) confirm the intuitive expectation that well-sorted sediments have larger pore volumes than poorly sorted sediments of the same average particle size. The numerical relations involved, however, are uncertain. Figure 5*A* shows the relation between void ratio and quartile deviation (QD_ϕ) to be linear over a short range of QD_ϕ values. The nature of the relation over a wider range of values in natural sands, silts, and clays is not known.

In most of the central California sediments, simple correlations between void ratio and particle sorting are obscured by the more prominent relations of void ratio to overburden load and particle size. To minimize this difficulty, the sorting is compared to the variation in void ratio that is left over from or "unexplained" by the combined influence of load and particle size. That is, QD_ϕ is graphed against the residuals (expressed in void-ratio units) of three regression equations: the two multiple-regression equations for groups A through D and group E and the equation for the regression of void ratio on median diameter for group F (table 2). Inasmuch as these equations assumed linear conditions, any conclusions that are drawn from the graphed relations between the residuals and QD_ϕ involve the

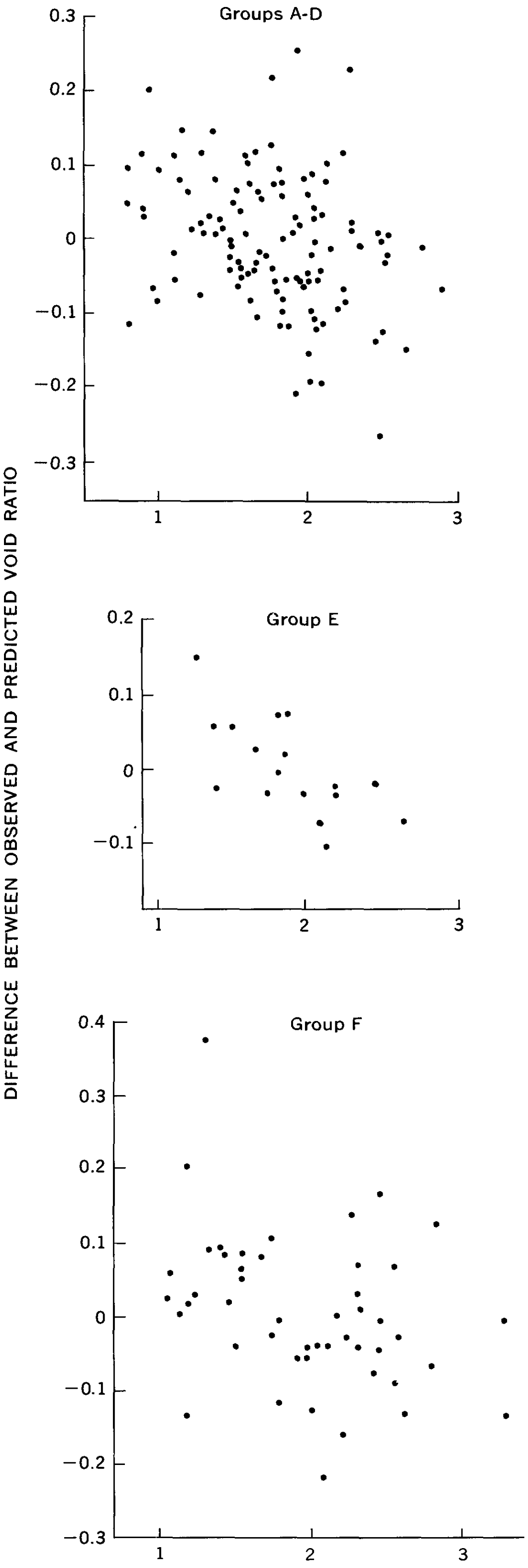

FIGURE 15.—Relations between quartile deviation and the residuals of void ratio-load-Md_ϕ and void ratio-Md_ϕ regressions (observed void ratio minus the void ratio predicted by the regression equation) in sediments of groups A through D, E, and F.

assumptions that the relations of void ratio to Md_ϕ and the logarithm of the effective load are linear. The graphs in figure 15 confirm the expectation that pore volume decreases with decreasing degree of sorting (increasing QD_ϕ). The graphs for groups A through D and group E also suggest that a sediment whose quartile deviation is 1ϕ might have a void ratio that is about 0.2 larger than the void ratio of a sediment whose quartile deviation is 3ϕ.

A significant simple correlation between void ratio and QD_ϕ was found in the silty sands of group A (fig. 16), apparently because the range of QD_ϕ values in this group was especially large. The simple regression equation given at the bottom of table 2 and illustrated in figure 16, however, does not represent the influence of sorting alone. The degree of sorting also decreases systematically with depth, so that the simple regression coefficient of either factor, load or QD_ϕ, reflects some of the effects of the other factor.

The wide scatter in the graphs of figure 15 indicates that even when the relations with load, Md_ϕ, and QD_ϕ are accounted for much of the variance in void ratio remains unexplained. It reflects the influence of other properties of the sediments or characteristics of their surroundings, some of which are evaluated below.

COMBINED EFFECTS OF SELECTED PHYSICAL AND CHEMICAL FACTORS

For several reasons, the sediments of the Richgrove core provide a good opportunity to evaluate some of the factors other than load that might influence the pore volume. In the first place, the apparent relation of the pore volume to depth and load is anomalous: the pore volume increases with increasing depth (fig. 17). The influence of other factors is more strongly expressed than that of load. Secondly, the variations in some of the other factors—the clay-mineral assemblage, adsorbed cations, and other chemical factors—are much greater in the sediments of the Richgrove core than in

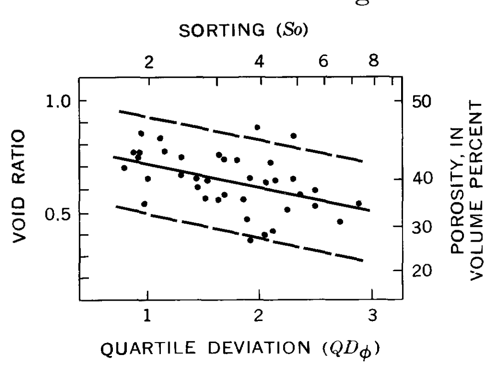

FIGURE 16.—Simple relation between void ratio and quartile deviation in silty sands (group A) from Los Banos-Kettleman City area. See bottom of table 2 for details of regression equation.

any of the other groups of sediments. These variations can be tested statistically to see if they correlate with variations in pore volume.

Although the downward increase in pore volume in the Richgrove core can be related qualitatively and approximately to changes in the type of sediment and the particle size (fig. 17), these changes do not account for all the observed features of the distribution of pore volume with regard to depth. The finest of the nonmarine sediments above 760 feet are generally coarser than the fine-grained marine siltstones below 760 feet (fig. 10), so one might expect the marine siltstones to have generally larger pore volumes than the nonmarine sediments. The gradualness of the increase in pore volume between 600 and 1,300 feet, however, compared with the more abrupt change in the type of sediment between 745 and 785 feet, suggests strongly that other factors are influencing the pore volume.

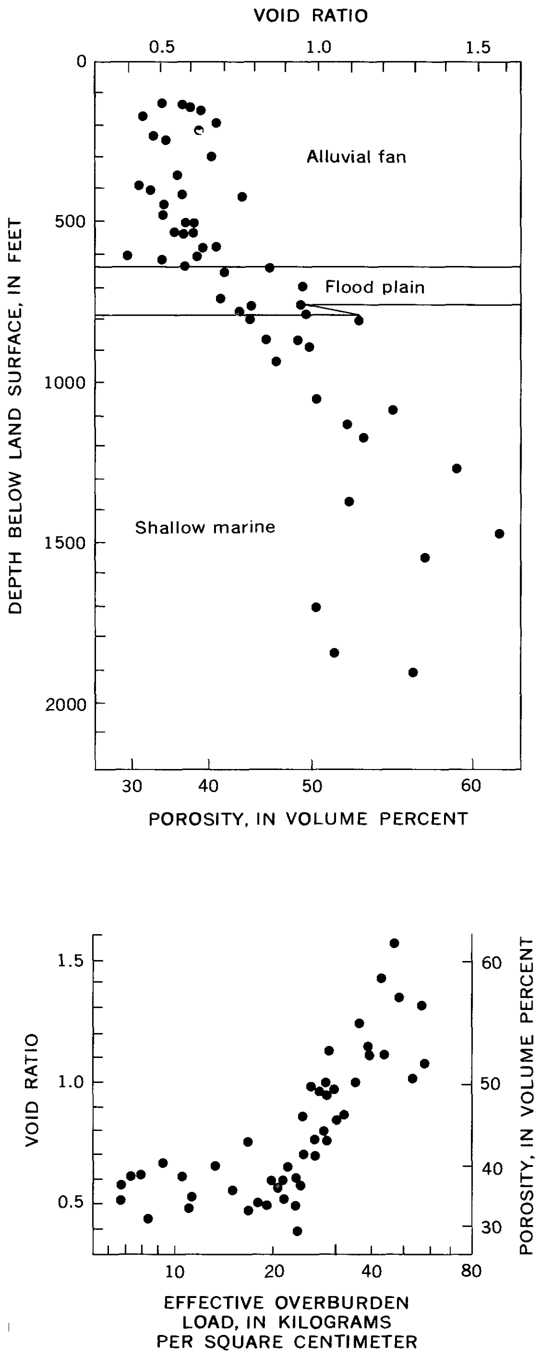

FIGURE 17.—Relations of void ratio of fine sediments in Richgrove core (median diameters finer than 62 microns) to depth of burial, type of sedimentary deposit, and effective overburden load.

Twenty samples of the fine sediments in the Richgrove core were selected for analysis of a number of factors that might influence the pore volume. These factors are, in addition to overburden load and particle size:

1. Clay minerals, which are represented numerically by the percentage montmorillonite in the clay-mineral assemblage.
2. Exchangeable cations, which are represented numerically by the equivalent percentage of sodium in the exchangeable-cation assemblage.
3. Soluble salts, which are represented by the total dissolved solids leached by 500 ml (milliliters) of hot water from 10 g (grams) of sediment.
4. Acidity, represented by the pH of a mixture of 10 ml distilled water and 1 g of sediment.
5. Orientation of clay-mineral particles, represented by the montmorillonite orientation ratio.

The details of the procedures used in determining the clay minerals, exchangeable cations, soluble salts, and pH are given in the previous chapter (Meade, 1967, p. 65–72). The procedure for determining the orientation ratio is outlined in the next section. Also included in the analysis is the amount of diatom skeletal remains in the sediment; this amount was determined by point counts (300 points each) of thin sections of the sediments. Results of these analyses are listed in table 3.

Multiple-regression techniques are used to sort out the important factors. All the measures that are listed for the 20 samples in table 3, with the exception of Md_ϕ, register simple correlations with void ratio that are significant at the 99-percent level. Furthermore, many of them register significant simple correlations with load—a fact indicating that they change systematically with depth—or with each other. Analyses of simple correlations and regressions would be fruitless, therefore, because of the complex and perhaps fortuitous interrelation of the factors. Multiple-regression techniques must be used with the hope that the variables that seem to be the most significant numerically do in fact represent the most important influences on pore volume. I assume for convenience that the relations between void ratio and the numerical indicators of each

TABLE 3.—*Selected properties of fine sediments in Richgrove core*

Sample [1]	Depth below land surface (feet)	Effective overburden load [2] (kg per cm²)	Void ratio [3]	Median diameter [3] (Md_ϕ)	Montmorillonite (percent of clay-mineral fraction)	Adsorbed cations [4] (adjusted percent of equivalents)			Total dissolved solids in leachate [5] (ppm)	pH [4]	Montmorillonite orientation ratio [6]	Diatom remains (percent of sediment)
						Na	Ca+Mg	H				
59CAL319	148	7.9	0.62	8.7	71	3	97	0	13	8.3	1.1	0
327	232	11.2	.52	4.6	55	3	97	0	11	8.7	1.3	0
333	290	13.2	.67	5.2	57	8	92	0	24	8.7	1.0	0
341	371	16.0	.50	4.0	59	0	100	0	9	8.9	1.1	0
349	444	18.5	.51	5.0	52	0	100	0	6	8.7	.8	0
356	517	20.9	.55	5.8	56	0	100	0	24	9.1	.8	0
363	583	23.1	.63	5.7	68	0	100	0	12	8.6	1.1	0
369	649	25.0	.71	7.2	62	0	100	0	21	8.7	1.5	0
381	764	28.7	.98	7.6	70	9	91	0	74	8.4	1.1	0
385	844	30.9	.96	6.5	89	10	90	0	43	8.7	1.5	0
389	917	33.1	.88	6.6	83	16	84	0	62	8.5	1.8	0
390	1,037	36.4	1.01	7.8	68	20	80	0	94	8.5	2.0	0
394	1,156	39.4	1.16	6.1	80	19	81	0	41	8.6	1.8	3
396	1,240	41.3	1.45	6.6	76	25	46	29	173	4.5	1.7	12
397	1,364	44.0	1.11	5.8	84	23	77	0	47	8.7	1.3	3
401	1,447	46.1	1.58	6.1	86	30	42	28	286	4.0	1.4	6
403	1,527	48.3	1.35	6.2	83	33	20	47	300	4.0	1.6	12
404	1,689	52.0	1.01	6.7	89	26	74	0	69	7.5	1.6	0
410	1,827	55.7	1.08	7.0	89	32	31	37	226	4.1	1.8	0
412	1,912	57.9	.60	3.6	83	18	55	27	98	5.3	1.0	0

[1] Numbers assigned by Hydrologic Laboratory.
[2] Estimated from hydrologic data by B. E. Lofgren.
[3] From analyses made in Hydrologic Laboratory.
[4] Determined by H. C. Starkey.
[5] Determined by Claude Huffman and A. J. Bartell.
[6] Determined with assistance of J. B. Corliss.

of the factors are linear, even though no evidence is available to support this assumption for any of the factors other than load and average particle size. It must be understood that multiple regression is used here only to sort out the factors and not to derive any descriptive equations that can be applied generally to all sediments.

The factors are sorted out by deriving regression equations for several combinations of variables, noting the level of significance of the partial correlation coefficients in each equation, and eliminating the variables that seem to be the least significant. The statistics on which this process is based are given in table 4. All the "significant" partial correlations ($P>0.75$) represented in the table are positive. At first inspection of the significance levels of the partial correlation coefficients, one may eliminate the following variables from further consideration: load, percentage of montmorillonite, and (although only evaluated once) orientation ratio. Although the evidence is not as clear, I suspect that pH may also be eliminated.

If the diatoms are ignored for the moment, particle size, absorbed sodium, and soluble salts are the remaining factors. Of these, particle size and adsorbed sodium seem to be the most important. Soluble salts seem to be of subsidiary importance: note that the large significance levels for soluble salts are registered only when adsorbed sodium is left out of the analysis. Judging from the multiple correlation coefficient of 0.89 (third line from the bottom in table 4), these three factors together may account for about 80 percent of the observed variance in void ratio ($R^2=0.79$).

TABLE 4.—*Selected details of multiple regressions of void ratio on different combinations of variables, representing properties of selected fine sediments in Richgrove core.*

Number of samples	Number of independent variables	Coefficient of multiple correlation (R)	Standard error of estimate of void ratio	Probability of significance (P)[1] of coefficient of partial correlation between void ratio and—							
				$\log_{10}$ load	Md_ϕ	Percentage of montmorillonite	Percentage of adsorbed Na	$\log_{10}$ total dissolved solids	pH	Montmorillonite orientation ratio	Percentage of diatoms
20	8	0.94	0.14	(2)	0.85	<0.75	0.81	<0.75	<0.75	<0.75	>0.99
20	6	.94	.14	(2)	.96	<.75	.83	<.75	------	------	.99
20	5	.89	.18	(2)	.88	(3)	.93	<.75	------	------	------
20	4	.89	.17	------	.90	(3)	.94	<.75	------	------	------
20	4	.89	.17	------	.87	------	.95	<.75	<.75	------	------
20	3	.86	.18	------	.82	<.75	------	>.99	------	------	------
20	3	.88	.17	------	.94	------	>.99	------	<.75	------	------
20	3	.86	.18	------	.82	------	------	>.99	<.75	------	------
20	3	.89	.16	------	.90	------	.95	<.75	------	------	------
15	4	.94	.08	------	.98	------	.96	.85	.91	------	------
15	2	.91	.10	------	.99	------	------	>.99	------	------	------

[1] One-sided significance test used for $\log_{10}$ load, Md_ϕ, percentage of montmorillonite, and percentage of adsorbed sodium; two-sided test used for other variables. (See Dixon and Massey, 1957, p. 97–99.)
[2] Positive (and therefore insignificant) partial correlation with void ratio.
[3] Negative (and therefore insignificant) partial correlation with void ratio.

The influence of the diatoms cannot be evaluated properly by these methods because only five samples contain diatoms. The fact, however, that these five samples have the five largest void ratios suggests strongly that the diatom skeletons contribute significantly to the pore volume. This suggestion is supported by multiple-regression analyses of the 15 diatom-free samples (bottom two lines, table 4), in which the removal of the diatomaceous samples seems to improve the degree of multiple correlation with the other variables and lessen significantly the standard error of estimate of the void ratio.

The specific effect of the diatom remains in the preservation of pore volume under load is uncertain. Perhaps the large open spaces in the skeletons themselves account for the larger void ratios. Or perhaps, as suggested by Hamilton (1964, p. 4263), the diatom skeletons contributed material to an incipient lithification process that kept the pore space open under load. That is, perhaps a little of the silica in the skeletons was dissolved and later reprecipitated at the contacts between sediment particles. Perhaps this slight reprecipitation of silica cemented the particles together but preserved the greater pore volume that was characteristic of a shallower depth of burial. No petrographic evidence of this process could be seen in thin sections of the siltstones; but one should not expect to be able to see such evidence because of the difficulty of resolving minute amounts of cementing material at contacts between fine particles. Hamilton's suggestion does seem paradoxical, however, in that it calls upon cementation, a process that eventually fills pore space, to account for anomalously large pore volumes.

The conclusion in any event is that particle size, the proportion of sodium adsorbed by the clays, and the amount of diatom skeletal material are the main factors influencing the pore volume of this group of sediments. This conclusion is supported by the studies of the sediments in the other cores. The influence of particle size is confirmed by the statistical studies summarized in figures 12 and 13. The influence of the downward increase in adsorbed sodium was suggested as a possible cause of the anomalously low slope of the void ratio-load curve for group D (p. D24). And the influence of diatom skeletons is suggested by the large void ratios of the upper lacustrine layer in the Mendota core (the Corcoran Clay Member, at depths between 600 and 700 feet—see fig. 10), which also contains large proportions of diatom skeletons. But one must keep in mind that the variables are interdependent: the montmorillonite content, pH, and soluble-salt concentration, although they seem to be insignificant or only marginally significant, probably have an indirect influence on the void ratio through their influence on the amount of adsorbed sodium. Although variations in the amount of montmorillonite do not seem to correspond to variations in void ratio, the very presence of montmorillonite with its large cation-exchange capacity probably makes the influence of the exchangeable sodium large enough to be discernible. Furthermore, the proportion of sodium adsorbed by the montmorillonite (see Meade, 1967, fig. 26) is closely related to the concentration of soluble salts and to pH.

FABRIC OF THE SEDIMENTS AND ITS RELATION TO OVERBURDEN LOAD AND OTHER FACTORS

ORIENTATION OF CLAY-MINERAL PARTICLES

The fabric of the fine sediments was studied with the aim of discovering any systematic changes that might be related to an increase in overburden load or to variations in other factors. The results showed no variation in fabric that could be related unequivocally to variation in load. The fabric does seem to vary significantly, however, between the different types of deposits. The best developed preferred orientation was found in lacustrine deposits; whereas little or no preferred orientation was found in alluvial-fan deposits, regardless of the depth of burial below the land surface.

OBSERVATION AND MEASUREMENT

The orientation of clay-mineral particles was observed in thin sections and was measured by a method involving the use of X-ray diffraction. The thin sections were prepared from samples of clayey sediments (whose natural moisture had been sealed in at the coring site) that had been impregnated in the laboratory with a waxlike polyethylene glycol compound according to the method described by Tourtelot (1961).

The X-ray diffraction method for measuring preferred orientation, described in detail in an earlier paper (Meade, 1961a), involves a numerical comparison between the intensities of the basal (001) reflection and the nonbasal (020) reflection from montmorillonite. In the diffraction patterns from each of several sections of air-dry clay, the intensities of these reflections are measured and recorded. From these intensities a peak-height ratio, which is the height of the (001) trace on the diffractometer chart divided by the height of the (020) trace, is computed. Peak-height ratios are measured in at least three mutually perpendicular sections—one parallel, and the other two perpendicular to the bedding direction. (In some samples, six sections were scanned—the three mutually perpendicular sections plus sections at angles of 22°, 45°, and 67° to the bedding direction.) The peak-height ratios are combined into another ratio which is the quotient of the peak-height ratio of the bedding-direction section divided by an average peak-height ratio for the two sections perpendicular to the bedding. This quotient is called the orientation ratio. Values of the orientation ratio near 1.0 signify random orientation of montmorillonite particles with regard to the bedding direction. Progressively larger values signify progressively greater degrees of orientation parallel to the bedding.

The general range of orientation ratios or their equivalents measured by X-ray diffraction in sediments and sedimentary rocks is shown in the following listing.

	Approximate range of orientation ratio
Devonian shales, Alberta [1]	6–13
Pennsylvanian clays and claystones, Illinois: [2]	
Black shales	10–20
Gray shales	6–10
Underclays	1– 3
Cretaceous mudstones, Texas [3]	2–30
Cretaceous shales, Alberta and Saskatchewan [1]	2– 5
Pliocene to Recent sediments, California:	
Lacustrine clays	1.5– 3
Marine silts and siltstones	1.5– 2
Flood-plain clays	1– 2
Alluvial-fan clays	≈1

[1] Computed from data of Kaarsberg, 1959, p. 469–470.
[2] Data from O'Brien, 1963, p. 12–15.
[3] Data from Beall, 1964, p. 154–158.

The main advantage of the X-ray diffraction method is that it provides a numerical expression of orientation that can be used to compare the different amounts of orientation in different samples. The main disadvantages are (1) that it measures the orientation only with regard to a single arbitrarily selected direction and (2) that it measures only the bulk orientation over an area of 3 to 4 square centimeters and does not resolve small-scale orientations.

Montmorillonite, the most abundant of the clay minerals in these sediments, is the mineral whose reflections were used in the study of orientation. The detailed study of orientation was confined to the sediments of the San Joaquin Valley. The sediments of the Santa Clara Valley were not included because they contain a chlorite mineral whose (001) reflection interferes with the (001) reflection of montmorillonite and obscures the relation between the intensity of the reflection and the orientation of montmorillonite. The degree of orientation observed in thin sections (in the samples for which sections were available) generally confirmed the amount of orientation that was measured by the X-ray method.

RELATION TO DEPTH OF BURIAL AND TYPE OF SEDIMENTARY DEPOSIT

The orientation ratios of fine sediments in the four cores from the Los Banos-Kettleman City area are plotted against depth in figure 18. Thirty-five of these measurements were presented and discussed in an earlier paper (Meade, 1961b). Figure 18 contains another 17 measurements, in sediments from the Cantua Creek and Huron cores, that were made since the earlier results were published. All samples were taken from sediments that had been below the water table and had presumably been saturated with water in their natural states. In most of the samples, sand and silt appeared to be "suspended" in clay. That is, the coarser particles did not touch one another, and the clay fraction must have borne any load that was placed on the sediment.

Ignoring the types of deposits for the moment, the results plotted in figure 18 give little indication of progressive development of preferred orientation with increasing depth of burial. The range between 0.9 and 1.2 of most of the orientation ratios indicates that very little orientation of montmorillonite developed parallel to the bedding—either before or during compaction.

Comparison of the orientation ratios to the type of deposit in which they were measured sheds more light on the observed variations in orientation. The best developed preferred orientation is found in the lacustrine deposits in the upper parts of the Oro Loma and Mendota cores—the Corcoran Clay Member of the Tulare Formation—although the orientation in the lacustrine(?) beds at the bottom of the Mendota core seems to be random. The alluvial-fan deposits consistently show the most random orientation. The orientation in the flood-plain deposits ranges from random to fairly well preferred (orientation ratios between 1.0 and 2.0).

The differences in the orientation of montmorillonite particles in the different types of deposits perhaps reflect different means of deposition. In the still waters of a lake, the particles may have an opportunity to settle out individually into a well-oriented arrangement. On an alluvial fan, on the other hand, clayey materials are deposited rapidly, often in a heterogeneous mixture that includes an assortment of coarser particles. The clay particles have little opportunity, therefore, to develop a preferred fabric. On flood plains, the physical conditions of deposition probably range between those visualized in lakes and those on alluvial fans.

Differences in the water content of the sediments, immediately following their deposition and during their burial beneath the first few tens of feet of overburden, may account for the differences in the orientation of montmorillonite. This supposition is based on results of the experimental work of Martin and O'Brien (reviewed on p. D7) which suggested (1) that the preferred orientation, if it develops at pressures lower than about 100 kg per cm^2, forms at pressures near 1 kg per cm^2

and (2) that the amount of water in the clay at this early stage may determine the degree of development of the orientation. The lacustrine sediments must have remained saturated with water as long as the lake in which they were deposited remained in existence, and preferred orientation presumably could develop during the deposition of successive layers of sediment on the lake bottom. The alluvial-fan sediments, on the other hand, were dried out soon after they were deposited, and they did not become saturated with water again until they were buried below the water table. Judging from modern conditions in the Los Banos-Kettleman City area, the alluvial-fan sediments must have been covered with several hundred feet of overburden before they reached the water table. By the time that the sediments met the water table, the volume and geometry of their pore space were such that preferred orientation could not develop. As with the conditions of deposition discussed in the previous paragraph, one might expect the degree of water saturation in flood-plain sediments to have been intermediate between that in lacustrine sediments and that in alluvial fans.

The orientation of montmorillonite particles in sediments from the Richgrove core of the Tulare-Wasco area is shown in figure 19. The 4 samples nearest the land surface may not have been saturated with water at the time that they were cored; the other 16 samples, taken from depths below 400 feet, were below the water table. The alluvial-fan sediments represented in figure 19 are coarser than those represented in figure 18. The sand and silt grains in the alluvial-fan sediments of the Richgrove core are not "suspended" in a clay matrix, and the sand-and-silt skeleton probably supports most of the overburden load. This textural arrangement was found also in many of the samples of marine siltstone.

The orientation seems to be random in the alluvial-fan sediments that make up the uppermost 600 feet of the Richgrove core. Orientation ratios in the samples from this interval range between 0.8 and 1.3. In the marine siltstone layers, on the other hand, most of the orientation ratios fall into the range between 1.3 and 2.0, indicating a degree of orientation greater than in the alluvial-fan sediments but less than in the lacustrine Corcoran Clay Member in the Los Banos-Kettleman City area. Within each type of deposit at Richgrove, there is little indication of a progressive increase in preferred orientation with depth. Such an increase should not be expected, however, in view of (1) the textural arrangement of sand and silt grains that prevents the load from being borne directly by the clay and (2) the observation (fig. 17) that the pore volume does not decrease systematically with increasing depth.

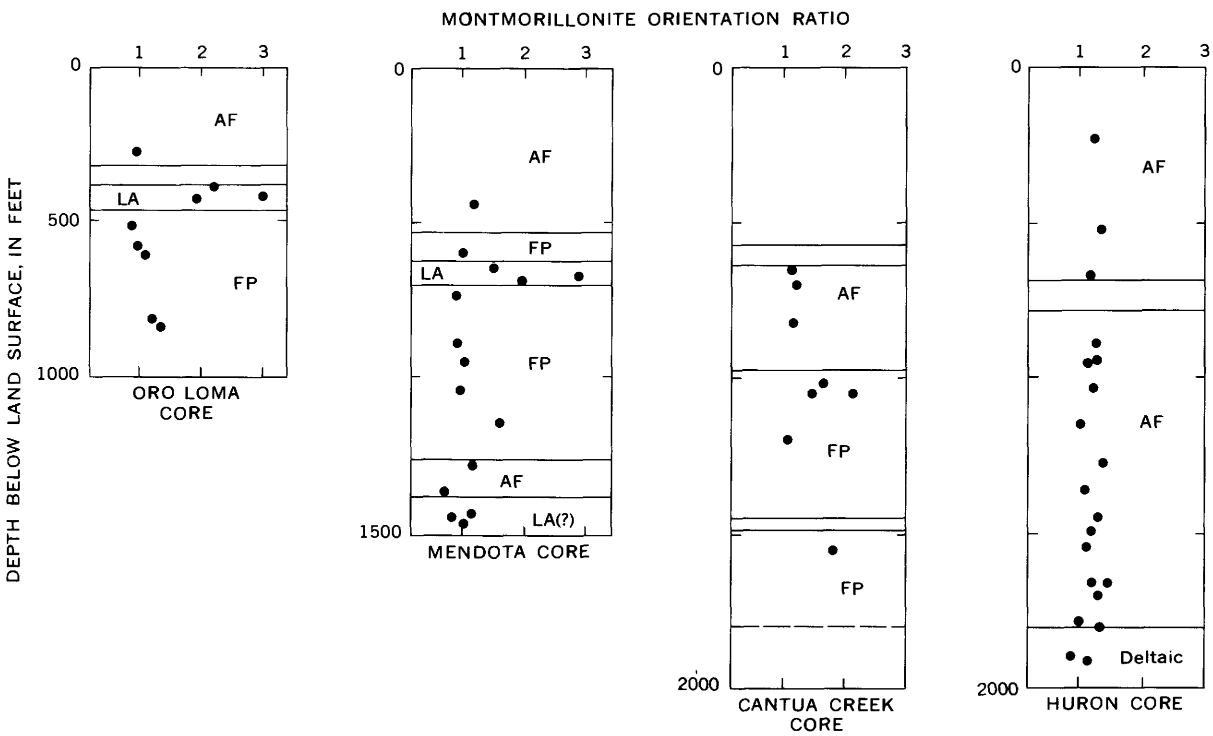

FIGURE 18.—Relations of montmorillonite-particle orientation to depth of burial and type of deposit represented by fine sediments cored in Los Banos-Kettleman City area. Orientation ratios determined with assistance of J. B. Corliss. AF, alluvial-fan deposit; FP, flood-plain deposit; LA, lacustrine deposit.

RELATION TO PARTICLE SIZE AND CHEMICAL FACTORS

The previous work reviewed earlier in this paper showed that certain physical and chemical factors might be expected to help or hinder the tendency of a clay to develop preferred orientation under load. The relation of some of these factors—particle size, electrolyte concentration, exchangeable cations, and pH—to the orientation ratio is examined in the 11 samples of marine siltstone from the Richgrove core (depths between 764 and 1,827 feet below land surface). These samples were selected because (1) their relatively uniform lithology suggests approximately uniform conditions of deposition, (2) the orientation ratio and the other factors are variable enough to show differences that might be correlative, and (3) the data are already available from the analysis of pore volume (table 3).

Multiple-regression techniques are used, in the same way that they were used in a preceding section (table 4), in an attempt to sort out the important factors. The montmorillonite orientation ratio is used as the dependent variable, and its numerical relation to each of the measures of the independent variables is assumed to be linear. The pertinent correlation and regression statistics are listed in table 5. The significant partial correlations between the orientation ratio and each of the first three listed independent variables—effective load, Md_ϕ, and percentage of absorbed sodium—are positive. Partial correlations between the orientation ratio and the concentration of soluble salts are negative. The statistics listed in table 5 suggest that particle size, adsorbed sodium, and soluble salts may have some influence on the degree of preferred orientation in the marine siltstones. The multiple-correlation coefficient of 0.48 for the regression relation in which these three are used as the independent variables (bottom line, table 5) suggests that they only account for about one-fourth of the observed variance in orientation ratio (R^2=0.23). These conclusions are rather tentative, however, mainly because too few samples were available.

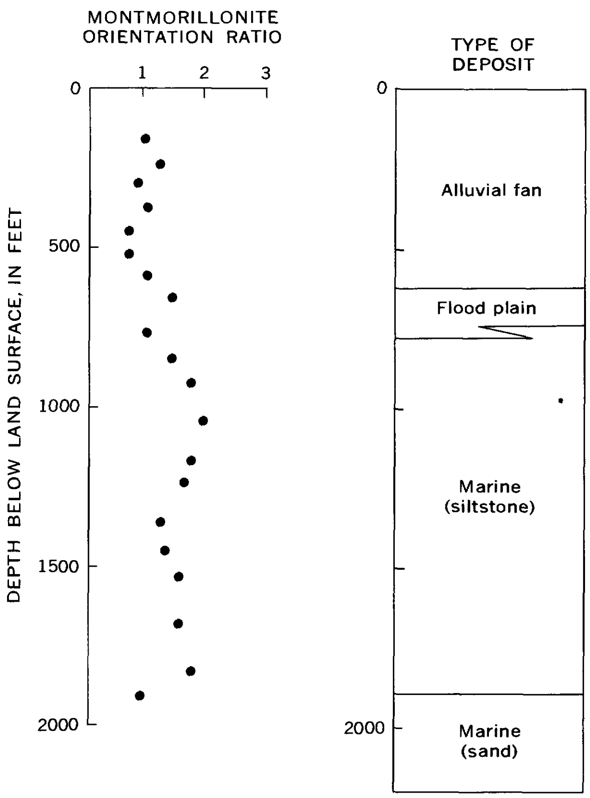

FIGURE 19.—Relations of montmorillonite-particle orientation to depth of burial and type of deposit represented by fine sediments in Richgrove core. Orientation ratios determined with assistance of J. B. Corliss.

DOMAINLIKE AGGREGATES

Many of the fine alluvial-fan sediments of the Los Banos-Kettleman City area have a fabric that consists of sand-sized aggregates of clay-mineral particles in a matrix of poorly sorted and randomly oriented sand, silt, and clay. (See Meade, 1967, fig. 4.) The orientation of clay minerals within these domainlike aggregates is highly preferred, but the orientation of the aggregates with regard to each other or to any plane through the sediment is random. As the orientation is preferred in small areas only (a millimeter or so across) it was not detected by the X-ray diffraction method which integrates the bulk orientation over an area of 3 to 4 square centimeters. The oriented aggregates were apparently deposited as such, either as shale fragments or as fragments of previously deposited clay layers on the alluvial fan. These aggregates were observed in the alluvial-fan sediments of the Los Banos-Kettleman City area only; none were seen in the alluvial sediments of the Tulare-Wasco area or Santa Clara Valley.

Whether or not this kind of orientation is enhanced by increasing overburden loads is not clear from the evidence visible in thin sections. Even though these

TABLE 5.—*Selected details of multiple regressions of orientation ratio on different combinations of variables representing properties of marine siltstones in Richgrove core*

Number of independent variables	Coefficient of multiple correlation (R)	Standard error of estimate of orientation ratio	Probability of significance (P) [1] of coefficient of partial correlation between montmorillonite orientation ratio and—				
			Log_{10} load	Md_ϕ	Percentage of adsorbed sodium	Log_{10} total dissolved solids	pH
4	0.61	0.27	(2)	0.88	0.87	0.87	-----
4	.48	.30	------	.77	.81	<.75	(2)
3	.36	.30	0.76	<.75	---------	<.75	-----
3	.48	.28	------	.81	.85	.77	-----

[1] One-sided significance test. (See Dixon and Massey, 1957, p. 97–99.)
[2] Negative (and therefore insignificant) partial correlation with orientation ratio.

aggregates are much larger than the submicroscopic domains that supposedly characterize turbostatic orientation, perhaps their role during compaction is the enhancement of a fabric that is at least analogous to the one represented in figure 3*B*. The development or enhancement of turbostatic orientation in these sediments is possible on several counts. The main clay-mineral constituent is calcium-montmorillonite, which according to experimental evidence reviewed earlier may be susceptible to this kind of arrangement under pressure. Furthermore, perhaps the deposited aggregates provide nuclei for further orientation of clay-mineral particles under pressure. No evidence, however, was found in the sediments themselves to support or reject this possibility. A fruitful approach might be to measure the internal and external surface areas of the sediments (Diamond and Kinter, 1958) or their pore-size distributions (Aylmore and Quirk, 1962, p. 109–115; Barrett and others, 1951) and look for changes under increasing overburden loads.

DISTRIBUTION OF MONTMORILLONITE ORIENTATION WITHIN THE SEDIMENTS

The distribution of the orientation of montmorillonite particles within some of the sediments from the Huron and Richgrove cores is shown in figure 20. In this figure, the orientation is indicated by the ratio of the heights of the diffractometer peaks that represent the reflections from montmorillonite at 15 A and 4.4 A. Larger values of the peak-height ratio, within any one sediment, correspond to greater degrees of preferred orientation. Determinations for each sample were made for five planes of reference from 0° to 90° from the bedding direction. The peak-height ratio should not be confused within the orientation ratio used in figures 18 and 19, which is computed from the peak-height ratios of different sections.

Within the alluvial-fan and the deltaic sediments (left and center columns, fig. 20), the distribution of the orientation from section to section varies in a random way from sample to sample. In the marine sediments from the Richgrove core (right column, fig. 20), the peak-height ratios seem to decrease at fairly regular rates with increasing angular distance from the direction of bedding. This indicates that the preferred orientation is not strictly confined to the plane of the bedding, but only reaches a maximum there.

FABRIC OF SANDS

This section of the report contains observations of the fabric of the sands and some inferences about how the observed fabric may be related to compaction. No quantitative measurements of sand fabric were made because the sands probably were disrupted somewhat during the coring process. Thin sections were made, however, and some features were observed in them. Indirect inferences were made by relating some of the observable features to the experimental studies whose results were reviewed earlier.

Although its effects do not show in the thin sections, the simple movement of grains into more efficiently packed arrangements was probably the principal response of the sands to increasing overburden loads. This supposition is based mainly on the experimental work, reviewed earlier, on pure-quartz sands. Its chief modifications in polymineralic sands such as those in the San Joaquin and Santa Clara Valleys are the supplementary processes of distortion and bending of the softer and more flexible grains.

PREPARATION OF THIN SECTIONS

A group of well-sorted sands from the Mendota, Cantua Creek, and Huron cores of the Los Banos-Kettleman City area was selected for thin-section study. Their good sorting, atypical of the recovered sands as a whole, was a necessary requisite for the impregnating and sectioning procedures. The sands were sealed in wax at the coring sites to preserve their textures as well as possible. One must assume, however, that their original textures were disturbed during the coring operations. In the laboratory, they were impregnated under partial vacuum with a polyester resin which, when hardened, has a refractive index of 1.54. Thin sections were made from the impregnated sands along planes normal (and, in some samples, parallel) to the bedding. The sections were taken from near the center of the core to minimize the disruptive effects of the coring. Sieve analyses of contiguous samples of the sands were also made and results have been published (Meade, 1967, table 7).

DISTORTION OF COMPRESSIBLE GRAINS

The distortion of compressible grains—elastic micas and nonelastic soft rock fragments—was observed in some of the sections. In the San Joaquin Valley this process is significant in the sands, derived from the Sierra Nevada, which usually contain 3 to 5 percent mica. And many sands, especially those in the Los Banos-Kettleman City area that are derived from the Diablo Range, contain fragments of soft materials such as partly weathered shales or metamorphic rocks.

A few of the distorted grains are sketched in figure 21. The distortion of the mica in figure 21*A* is the most extreme example observed. A more typical degree of mica distortion is sketched in figure 21*B*. This represents a minimum distortion of this grain because one cannot tell how much elastic recovery may have taken place between the time the sand was cored and the time it

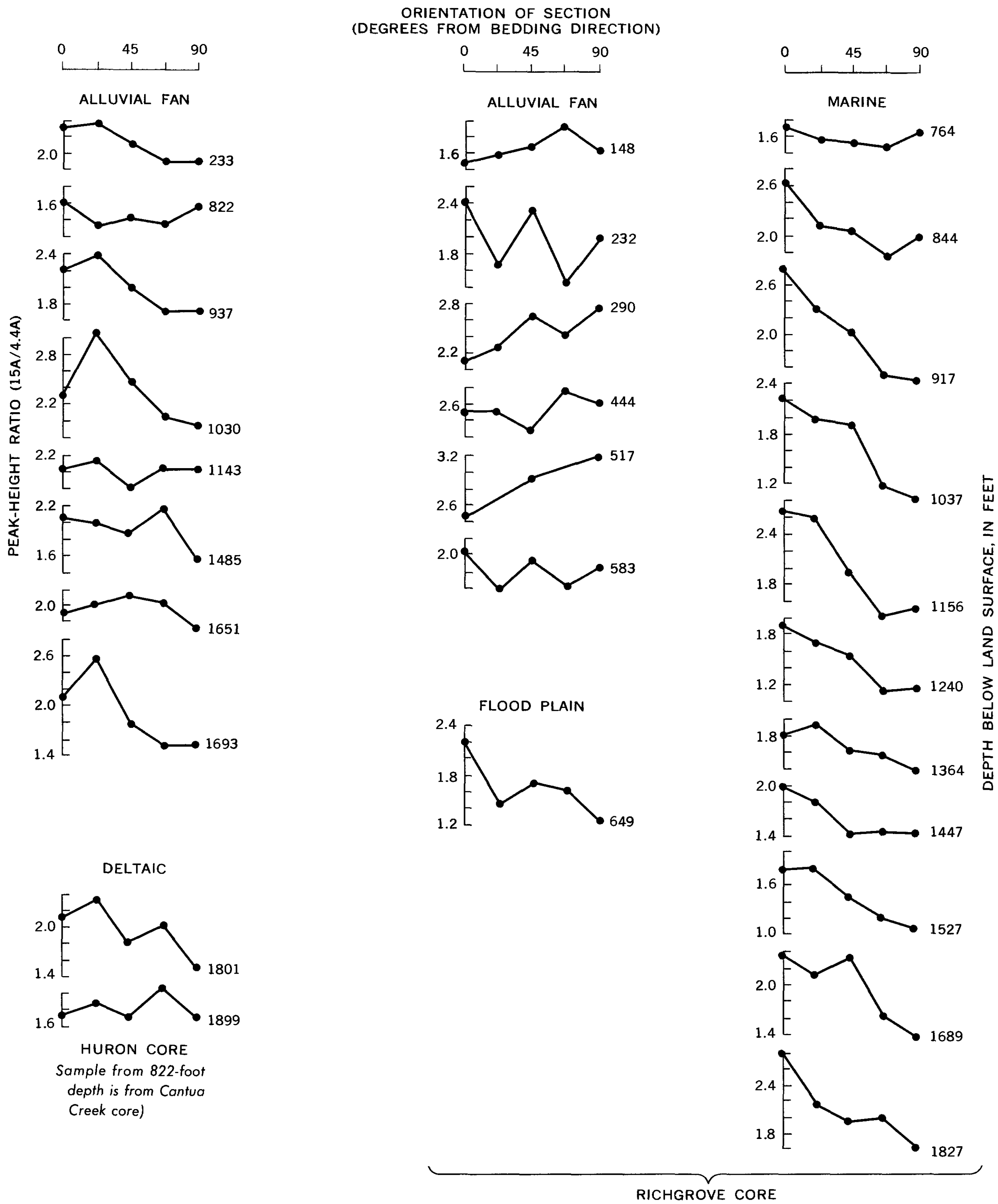

FIGURE 20.—Orientation of montmorillonite in sections cut at different angles to the bedding of sediments from Huron and Richgrove cores. Determined with the assistance of J. B. Corliss.

was impregnated and sectioned. Neither, incidentally, can one be certain of how much of the distortion is due to natural loading and how much is due to the coring procedure. In general, the wide thin flakes of mica were more distorted than the thick books. Other factors influencing the degree of distortion were the orientation of the flakes with regard to the compacting pressure, the size of the mica flakes relative to the sizes of adjoining grains, and the nature of the contacts between flakes and grains. Because of the direction of orientation and poor contacts with adjacent grains, for instance, some mica flakes in the section from which figure 21*A* was sketched showed no evidence of distortion. Shale fragments were broken and squeezed by pressure exerted through more resistant adjoining grains. The distortion in figure 21*C* is as severe as any observed in the sand sections. The distortion of soft rock fragments was controlled by the same factors that controlled the distortion of micas.

ORIENTATION OF MICA PARTICLES

Two mica fabrics—differing in the orientation of mica flakes and the size of the flakes relative to the nonmica grains—are illustrated in thin-section views of sands from the Mendota core. Figure 22*A* shows a micaceous sand derived from the Sierra Nevada; figure 22*B*, one derived from the Diablo Range. In the sand derived from the Sierra, the larger mica flakes tend to be oriented parallel to the bedding. The long dimensions of the mica flakes are generally larger than the diameters of the nonmicaceous grains. In the sand derived from the Diablo Range (fig. 22*B*), the long dimensions of the micas are approximately the same as the diameters of the nonmicaceous grains. Furthermore, the micas are oriented roughly at angles of 45° to the bedding. One cannot be certain whether the orientation is a depositional feature or a result of changes during compaction, but W. B. Bull (written commun., 1964) says that such an orientation is common in the modern alluvial sands in the western San Joaquin Valley.

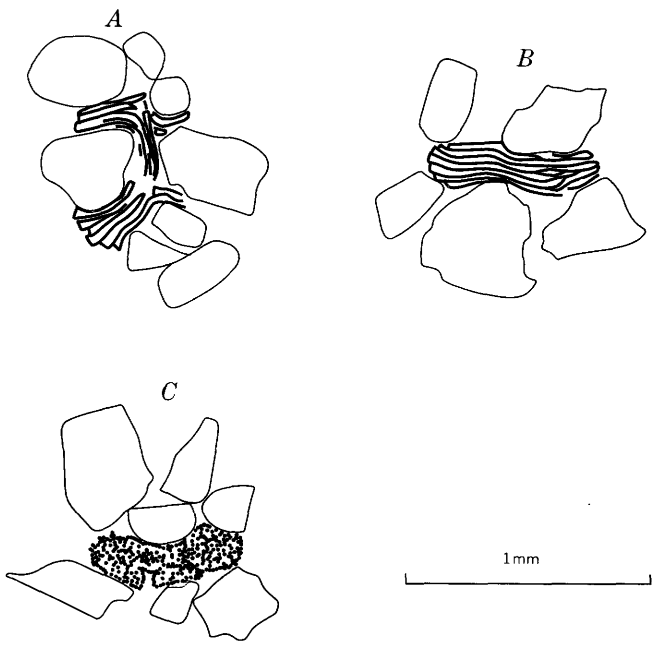

FIGURE 21.—Distortion of compressible sand grains. *A*, Bent and broken biotite; Mendota core, depth 1,347 feet. *B*, Bent biotite; Cantua Creek core, depth 1,551 feet. *C*, Crushed and broken shale fragment (stippled); Mendota core, depth 1,347 feet.

Because of their different mica fabrics, these two sands should be expected to respond differently to compacting pressures. The mica flakes shown in figure 22*A* should respond to loads by bending around adjacent grains, a process that enhances the compressibility of the aggregate. In the event that the pressure is released, the large mica flakes should regain some of their original shape, giving the aggregate a certain amount of elasticity. In the sand shown in figure 22*B*, on the other hand, one should expect a greater degree of compressibility but a lesser degree of elasticity. Their size, shape, and orientation should allow the mica particles to slip more easily past the nonmica particles (or vice versa) into more compact arrangements; but this kind of movement is largely irreversible. The compressibility of both these sands, however, is probably greater than that of otherwise equivalent sands that contain no mica.

CONCLUSIONS

In the fresh-water-bearing alluvial clays, silts, and silty sands in the San Joaquin and Santa Clara Valleys of California, the loss in pore volume that results from compaction by effective overburden loads in the range between 3 and 70 kg per cm² averages about 0.3 void-ratio units or about 15 percent of the bulk volume of the fine sediments. When one allows for the lesser compaction of the interbedded coarser sands and gravels, the reduction of the total volume of the alluvial sediments amounts to about 12 percent between 10 and 70 kg per cm² on the west side of the San Joaquin Valley and about 10 percent between 3 and 33 kg per cm² in the Santa Clara Valley.

The factors that directly influence the pore volume of the alluvial and shallow-marine sediments under these loads are the average particle size, the particle sorting, the large proportion of montmorillonite, the proportion of exchangeable sodium relative to exchangeable calcium and magnesium, and the presence of diatom skeletons. Although not shown by direct evidence, the proportion of mica probably also influences the pore volume. Factors having at least indirect influence, if not direct influence, are the acidity of the sediments and the concentration of interstitial electrolytes. The relative importance of all these factors is not easily evaluated because (1) their interrelations are often complex and (2) some of them are too constant (the proportion of montmorillonite, for example) to show variable effects on pore volume within this group of sediments. But one can distinguish with a fair degree of certainty the factors of primary importance from those of subsidiary importance.

The average particle size and the content of diatom skeletons are certainly primary factors. Under these overburden loads, a sediment that has a median diameter of 1 micron can be expected to have a void ratio greater by at least 0.2 (about 7 percent of the total sediment volume) than a sediment whose median diameter is 100 microns. Diatom skeletons, where they are present, increase the pore volume markedly.

In sands and silts, the influences of the particle sorting and the proportion of mica flakes on the pore volume are probably of subsidiary importance. Whether particle sorting is a primary or subsidiary factor is not clear. Rather uncertain statistical correlations suggest that one might expect a difference in void ratio near 0.2 between sediments whose QD_{ϕ} values are 1 and 3; but the relation of pore volume to sorting is probably less important and almost certainly less pervasive than the relation to average particle size. The ranges of mica content and overburden loads in the sediments and the experimental work carried out in previous studies indicate that the differences in the mica content probably do not cause differences in void ratio much greater than 0.1.

In the more clayey sediments, the content of montmorillonite and the proportion of adsorbed sodium become important. Judging mainly from the previous experimental work, the large proportion of montmorillonite must be a primary influence on the pore volume. No numerical estimates are made of the range of its possible effects, but the sediments of the San Joaquin and Santa Clara Valleys are certainly more porous than they would be if their principal clay-mineral constituents were illite or kaolinite. The proportion of adsorbed sodium relative to the other exchangeable cations is probably of subsidiary importance because (1) it is closely related to the pH and concentration of the interstitial electrolytes and (2) its total effect depends on the amount of clay-mineral surface available for cation sorption—the amount of montmorillonite, in these sediments.

The degree of preferred orientation of the montmorillonite particles parallel to the bedding direction is consistently related to the depositional types of the fine sediments. Lacustrine sediments show the greatest degree of orientation; alluvial-fan sediments, the smallest degree; flood-plain and shallow-marine sediments show intermediate degrees of orientation. However, there is no clear identification of the specific properties of the sediments or characteristics of the depositional environments that control the degree of orientation.

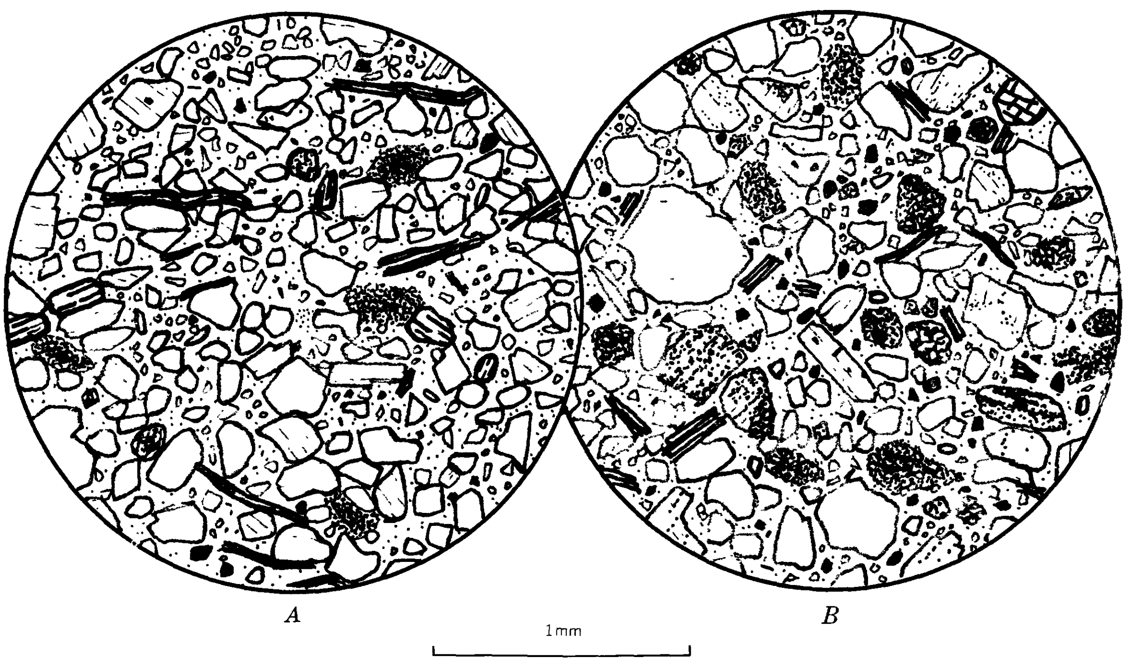

FIGURE 22.—Sections of micaceous sands from Mendota core. Sections cut normal to bedding, which is parallel to top of page. *A*, Flood-plain sand from 833 feet; Sierra Nevada source. Mainly quartz, potassium feldspar, twinned plagioclase (light cleavage), biotite, shale fragments (strippled), and a little hornblende. *B*, Flood-plain sand from 1,076 feet; Diablo Range source. Mainly quartz, potassium feldspar, "dirty" twinned plagioclase (light cleavage), shale and other rock fragments (strippled), biotite, chlorite, and dark accessory minerals. Optical relief of grains exaggerated in both sections.

Experimental work by O'Brien and the inferred post-depositional histories of the sediments suggest that the water content of the sediments during the very early stages of compaction may be a critical factor. A limited regression analysis suggests that the development of preferred orientation in the shallow-marine sediments may be favored by decreasing particle size, decreasing concentration of interstitial electrolyte, and increasing proportion of sodium adsorbed by the montmorillonite. Only the influence of electrolyte concentration is well supported by experimental studies.

The most certain conclusions from the study of clay fabric are negative: the degree of preferred orientation of the montmorillonite does not increase with decreasing pore volume or with increasing depth of burial beneath overburden loads as great as 70 kg per cm^2.

GLOSSARY OF STATISTICAL TERMS

Most of the statistical terms used in this report and in another report (Meade, 1967) in this series are defined below. Many of these definitions were taken, with little or no modification, from James and James (1949). References to further explanation and discussion are given after most of the definitions.

Coefficient of determination. The percentage to which the variance in the dependent variable is determined by the independent variable or variables. The square of the coefficient of linear correlation.

Correlation coefficient or **coefficient of linear correlation.** A number between −1 and +1 that indicates the degree of linear relationship between two or more sets of numbers. See **Coefficient of determination.** The simple correlation coefficient (r) indicates the degree of linear correlation between two sets of numbers. The multiple correlation coefficient (R) indicates the degree of linear correlation between one set of numbers (values of the dependent variable) and a combination of two or more sets of numbers (values of the independent variables). The partial correlation coefficient indicates the degree of linear correlation between the dependent variable and one of the independent variables, while eliminating the linear tendency of the remaining independent variables to obscure the relation. See Ezekiel and Fox (1959, p. 127–129, 190–197), Fisher (1950, p. 175–210), Moroney (1956, p. 271–320), and Waugh (1952, p. 446–449, 508–509).

Cumulative frequency. The sum of all preceding frequencies, a certain order having been established.

Dependent variable. A quantity that takes on a value corresponding to every value or set of values of another variable or set of variables (called independent variables). For example, in the regression equations

$$y=a+bx,$$

or

$$y=a+bx+cz,$$

where y is the dependent variable, x and z are independent variables; and b and c are regression coefficients. See Ezekiel and Fox (1959, p. 47–48) and Fisher (1950, p. 129–130).

Independent variable. See **Dependent variable.**

Mean. The sum of observed values, divided by the number of values observed.

Measures of central tendency. Values loosely referred to as "averages". Measures of central tendency used in these reports are the mean, median, and mode. See Moroney (1956, p. 34–55), and Waugh (1952, p. 61–125).

Median. The midpoint of a group of measurements; the point in a distribution above and below which lie half the values.

Mode. The value that occurs most frequently.

Normal distribution or **normal frequency distribution.** The distribution is described by

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2},$$

where μ is the mean, σ the standard deviation of the distribution, and e is the base of Naperian logarithms. When graphed, the curve of the normal distribution is bell shaped, symmetrical about the mean, and extends infinitely far in both the positive and negative directions. See Dixon and Massey (1957, p. 48–66), Krumbein and Pettijohn (1938, p. 252), Moroney (1956, p. 106–119), and Waugh (1952, p. 155–186).

Percentiles. In a particle-size distribution, the 99 points that divide the distribution into 100 segments in such a way that the segments contain equal amounts (by weight) of particles. A given percentile is the value which divides the range of particle sizes into two parts such that a given percentage (by weight) of the particles is coarser than this value. See Waugh (1952, p. 77–78).

Probability of significance. Probability that the assumed model is correct; probability that the observed relation could not have occurred by chance. See Ezekiel and Fox (1959, p. 293–298) and Moroney (1956, p. 216–237).

Quartiles. The three points that divide a distribution into four equal parts. The 1st and 3d quartiles correspond respectively to the 25th and 75th percentiles. The 2d quartile corresponds to the 50th percentile, or median. See Waugh (1952, p. 75–76).

Quartile deviation. A measure of dispersion: one-half the distance between the first and third quartile. See Krumbein (1936, p. 102–103).

Regression coefficient. The coefficient of an independent variable in a regression equation. In simple regression (two variables only), the slope of the regression line. See **Dependent variable.** See also Ezekiel and Fox (1959, p. 134–140, 147–150) and Fisher (1950, p. 126–136).

Regression equation or **equation of linear regression.** The equation of the straight line used to estimate one variable (the dependent) from one or more other (independent) variables. It is computed by the method of least squares which minimizes the sum of squares of the residuals between the observed values of the dependent variable and the values computed by the regression equation. See Ezekiel and Fox (1959, p. 55–68, 170–187), Moroney (1956, p. 276–320), Waugh (1952, p. 301–316), and Williams (1959, p. 10–52).

Residual. The difference between the observed value of a quantity and the value predicted from the regression equation. See Ezekiel and Fox (1959, p. 119–121).

Skewness. A measure of the asymmetry of a distribution. See Waugh (1952, p. 200–206).

Standard deviation. A measure of dispersion: the square root of the arithmetic mean of the squares of the deviations from the mean. For a normal distribution, approximately two-thirds of the samples fall within one standard deviation, plus or minus, of the mean; approximately 95 percent fall within two standard deviations of the mean. See Moroney (1956, p. 61–62) and Waugh (1952, p. 135–147).

Standard error of estimate of the dependent variable. A measure of how close the observed values fall to the regression line: The standard deviation of the residuals between the observed values and the corresponding values computed by the regression equation. See Ezekiel and Fox (1959, p. 119–121, 147–150).

Variance. A measure of dispersion: the arithmetic mean of the squares of the deviations from the mean. The square of the standard deviation.

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APPENDIX A

Samples used in statistical studies

The groups of alluvial sediments shown in figures 11 to 15 consist of the following samples. The numbers were assigned by Johnson, Moston, and Morris (1967).

Group A:
- 57 CAL:
  - 8, 11, 27, 37, 40, 57, 62, 76, 78, 79, 81, 82, 84, 85, 90, 108, 113, 115, 136, 139, 142, 152, 155, 162, 176, 177, 186.
- 58 CAL:
  - 1, 4, 7, 28, 41, 47, 74, 75, 76, 81, 82, 93.

Group B:
- 57 CAL:
  - 7, 29, 31, 50, 64, 65, 83, 121, 130, 149, 154, 166, 168, 169, 174, 178, 181.
- 58 CAL:
  - 2, 20, 33, 42, 49, 52, 59, 65, 72, 73, 90.

Group C:
- 57 CAL:
  - 25, 39, 48, 51, 54, 55, 56, 58, 59, 61, 86, 88, 114, 123, 124, 146, 147, 150, 159, 161, 164, 167, 173, 175, 185, 187, 188, 189, 190.
- 58 CAL:
  - 5, 9, 10, 12, 26, 31, 50, 53, 64, 67, 84.

Group D:
- 57 CAL:
  - 9, 10, 12, 13, 14, 52, 107, 109, 111, 112, 131, 135, 137, 148, 151, 157, 163, 165, 183.
- 58 CAL:
  - 23, 30, 32, 38, 46, 48, 51, 57, 60.

Group E:
- 60 CAL:
  - 16, 17, 18, 23, 24, 29, 34, 35, 38, 42, 44, 48, 49, 57, 64, 72, 73, 74, 79, 83, 92, 93, 95.

Group F:
- 58 CAL:
  - 102, 104, 105, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 125, 126, 127, 128, 129, 131, 132, 133, 134, 135, 136, 137, 138, 140, 141.
- 59 CAL:
  - 350, 351, 352, 353, 354, 355, 356, 357, 361, 362, 363, 364, 365, 366, 367, 369.

APPENDIX B

Effective overburden loads at different depths in the cored sections at time of coring

[Computed by R. E. Miller (Mendota, Cantua Creek, and Huron), B. E. Lofgren (Pixley and Richgrove), and J. H. Green (Sunnyvale and San Jose)]

Depth below land surface (feet)	Effective overburden load	
	(psi)	(kg per cm²)
Mendota 1957		
120	104	7.3
625	308	21.6
700	475	33.4
1,500	832	58.5

Effective overburden loads at different depths in the cored sections at time of coring—Continued

Depth below land surface (feet)	Effective overburden load	
	(psi)	(kg per cm²)
Cantua Creek 1958		
192	170	12.0
565	305	21.4
575	475	33.4
1,720	970	68.2
2,000	1,090	76.6
Huron 1957		
120	105	7.4
730	305	21.4
747	540	38.0
1,640	915	64.3
2,200	1,155	81.2
Pixley 1958		
120	86	6.0
285	165	11.6
296	213	15.0
760	413	29.0
Richgrove 1959 [1]		
180	135	9.5
533	306	21.5
744	400	28.1
1,053	524	36.8
1,175	568	39.9
1,205	578	40.6
1,377	629	44.2
1,384	634	44.6
1,743	760	53.4
1,818	790	55.5
1,900	819	57.6
2,200	950	66.8
Sunnyvale 1960		
150	64	4.5
185	130	9.1
215	144	10.1
415	235	16.5
680	360	25.3
1,000	503	35.4
San Jose 1960		
137	120	8.4
245	166	11.7
475	270	19.0
785	418	29.4
815	432	30.4
865	449	31.6
895	464	32.6
930	481	33.8
1,000	513	36.1

[1] Pore pressures in fine-grained beds in 1959 were assumed equivalent to water-level conditions of 1921. This assumption probably is reasonable for pressures in the recently tapped (1946+), slow draining, thick marine siltstone beds between depths of 744–1,900 feet. However, computed effective loads between depths of 180–744 feet in the alluvial deposits may be as much as 15 percent low.

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