PRELIMINARY REPORT ON THE GEOLOGY OF THE UPPER LA PAZ VALLEY, BOLIVIA

by

Ernest Dobrovolny

Geologist, U.S. Geological Survey

Cooperation Between the U.S. Operations Mission to Bolivia

and

The Municipality of La Paz, Bolivia

La Paz, Bolivia, February 1955.

55-42

PRELIMINARY REPORT ON THE GEOLOGY OF THE

UPPER LA PAZ VALLEY, BOLIVIA

CONTENTS

Content - continued -

INTRODUCTION

Purpose

The purpose of this preliminary report is to provide a geologic map and a background of general knowledge to serve as a basis for special investigations. They involve study of landslides which affect urban development, ground water as a potential source for city use and a general plan for city zoning. Much of the basic data for these special investigations is contained in the following report and attached map. The basic data need to be interpreted and certain additional information must still be collected.

This report and map are preliminary. At a later date when the results of laboratory tests on selected samples are available the report will be revised for publication. Another topographic map, prepared from aerial photographs taken in 1948, will be used as a base on which to represent the geology.

Location and Topography

The area mapped is a part of the upper La Paz Valley situated between the Altiplano on the west and the Eastern Andes. La Paz, the administrative capital of Bolivia, is located in the central part of the map. A total of somewhat more than 100 square kilometers are shown on the attached map.

The topography in the vicinity of the map has been well, and often glowingly, described in many books and publications. To the traveler approaching overland from the west, the deep valley in which La Paz is situated makes a profound impression because the valley cannot be seen until the margin is reached. A deep and narrow gash cut 600 meters or more into the Altiplano in front of the Eastern Andes and parallel to the trend of the range is indeed unusual. The expectable would be to see the Altiplano extend as a piedmont to the mountain front as it does north of the La Paz area.

The Altiplano is a high plain between the Eastern Andes of Bolivia and Perú and the Western Andes of Chile and Perú. In the vicinity of La Paz the Altiplano is a mature surface that slopes upward toward the Eastern Andes. In the southwestern part of the map it has an altitude of approximatlt 4040 meters and in the northwestern part more than 4300 meters. Between the Choqueyapu and Chuquiaguillo Rivers in the northern part of the map is a remnent of the Altiplano which was once continuous with the plain of the western side.

The La Paz River and its tributaries, the Choqueyapu, Chuquiaguillo and Irpavi Rivers have incised the Altiplano to depths ranging from 200 to 800 meters. Clearly definable terraces with steeply inclined gradients in the direction of the stream flow are present along the lower margins of the major rivers. Vestiges of higher terraces, alluvial cones, mud flows and landslide blocks break the monotony of an evenly sloping profile from the edge of the Altiplano to the rivers.

At Finca Aranjuez in the southeast corner of the map is a northwest trending ridge through which the La Paz River flows in a narrow and steep sided canyon. Between Finca Aranjuez and Alto de Sopocachi is a small expanse of weak sedimentary rocks that have been sculptured into spires, pinnacles and other spectacular erosion forms. This intricately eroded area, called "Bad Lands" in Bolivian literature after similar topographic features defined in the western part of the United States of America, extends westward into the Achocalla Valley.

Previous Work

Only a few of the more significant contributions to the geological literature of the La Paz Valley are included in the bibliography of this report. Most of the previous investigators could spend but a few days in the area and they had no maps on which to record their findings. Nevertheless, many keen and penetrating observations were made. Some of the hastily concluded concepts have been varified by this more detailed survey.

Conway (6) was in and near La Paz for several months. On a trip down the La Paz River on his way to climb Mt. Illimani, he recognized the mud flow which originated in the Achocalla Valley. Hauthal (4) considered the upper part of the La Paz Formation to be early Pleistocene. In his report on ground water for the city of La Paz, Felsch (7) indicated that the La Paz Formation might be late Tertiary.

Troll (11) spent several years in Bolivia during which time he extensively investigated Tertiary and Pleistocene deposits and made at last two topographic maps. Unfortunately his geologic map of the La Paz area was destroyed before it could be published, so he tried to explain his concepts of the geology by more lengthy discussion. Troll recognized three periods of glaciation. The till which Troll considered to represent the first period of glaciation is called Calvario Till in this report. He also recognized the mud flow which originated in the Achocalla Valley.

Berry's (5) suggestion that the last major deformation of the Andes may have taken place in the early Pleistocene has been verified by this more detailed investigation. Ahlfeld's (1 - 2) reports on the area are a resume and compilation of previously published information dealing with the origin of the La Paz Valley. He included many of his own observations relating to structural history. All mayor differences between his published comments and those contained in this report were reconciled after Ahlfeld spent two days in the field with the author.

Method of Investigation

Stratigraphic sections were measured with a stadia rod in many parts of the area of the map and a few beyond its borders. After sufficient information had been assembled to differentiate mapable units, the units were delineated on aerial photographs. The delineations on the photographs were transferred to the base map by use of a sketchmaster. As the aerial photographs do not cover the entire area of the map, a part of the geology was placed on it directly.

Definitions

Many kinds of maps of La Paz and vicinity have been printed. A wide discrepancy in names and in spellings of names of streams and localities is noted on them. Some rivers not only have several different names, but also have specific names for certain stretches of their courses. As an example, the Irpavi Valley has five names from its mouth to its origin in the Eastern Andes. With few exceptions, names and spellings as appearing on the attached base map are used in the report even though they disagree with later maps. Among some of the terms that need clarification are the following:

1, Aranjuez Constriction refers to the deep and narrow valley at Finca Aranjuez where the La Paz River has cut a gorge transverse to the structural alignment of the oldest rocks in the area.

2, Upper La Paz Valley is used to refer to the drainage system located above the constriction in the valley at Finca Aranjuez. The lower La Paz Valley or the La Paz gorge is below the constriction at Finca Aranjuez.

3, "Aranjuez Ridge" is the name given to the partly exposed Pre-Tertiary alignment of hills that are crossed by the La Paz River at Finca Aranjuez. The ridge coincides with an alignment of deformation called Aranjuez structure.

4, Kenko Structure refers to the northwest-southeast trending zone of faulting and folding that is well exposed below the Altiplano near Kenko.

5, "Basin" is used in reference to a structural depression.

6, Chocayapu - Choqueyapu. Local critics have felt so strongly about the spelling of this word that Choqueyapu is used even though it does not agree with the spelling found on the attached map.

7, Buildings shown on the map as Colegio Militar are now the University of San Andrés. In the text reference is made to the University instead of Colegio Militar.

Base Map

For this report the topographic map published in Germany by Troll, Finsterwalder and Biersack in 1935 is used as a base on which to represent the geology. Field work for the base map was done between 1927 and 1929 so it is out of date in its representation of cultural features. Also, the altitudes shown on the map do not agree with the more accurate levels of later surveys. However, the map has several advantages. It is a fairly good portrayal of the configuration of the valley; it covers the area of primary interest; and it is a convenient size on which to show the relevant geology.

Acknowledgment

So many people have aided in this work that all of them cannot be mentioned. They are sincerely thanked for their help. A few must be mentioned by name: Dr. Federico Ahlfeld, former Chief Geologist, Dirección General de Minas y Petróleo de Bolivia, spent two days in the field with the author and contributed many constructive opinions. Jorge Muñoz Reyes, Professor of Geology at the San Andrés University, reviewed the geological map in the field and made his large geological library available for reference; references included copies of reports on site investigations by Prof. Muñoz made in the vicinity of La Paz during the last two decades. Messers Humberto Lozada, Jorge Crespo and Arturo Zalles, engineers of the Municipalidad, took the author on many tours of inspection during which they pointed out problems affecting city levelopment and explained their approach to solving them. Gregorio G. Ortega V., engineering student at San Andrés University, was a helpful guide and interpreter. Mario Rada, chauffeur, almost intuitively understood where and when the author wanted to be picked up at the end of the many walking tours.

The Spanish version was carefully read by Juan Luis Gutierrez Granier, the mayor of La Paz, through whose efforts the project was initiated. It was also reviewed by Prof. Jorge Muñoz Reyes, Dr. Federico Ahlfeld, Jorge Crespo and Humberto Lozada. Rene Paz Prado, architect for the city of La Paz, and Raul Valdez, Municipality water supply engineer made significant suggestions. All the critics made constructive comments that have helped to make the report more easily understandable and readable.

DESCRIPTIVE GEOLOGY

As used here, descriptive geology is an explanation of the units of rock that have been delineated on the attached map. The explanation includes statements about their age, thickness, lateral continuity, composition, properties and other features distinguishing one unit from another.

Pre-Tertiary Rocks Undifferentiated

Pre-Tertiary rocks are shales, sandstones and conglomerates. A direct neasurement was not made, but the exposure in the mapped area is estimated as representing a total thickness of about 1000 meters. Individual beds range in thickness from about 20 to 150 meters. Althought it would be possible to do so, the various lithologic units have not been separately mapped.

The rocks are strongly folded and faulted. Just off the southern edge of the map one conglomerate bed is over-turned to the southwest. In general the crests of the folds and the alignment of the faults trend northwest. The Aranjuez ridge and structure separates two sub basins: the Choqueyapu sub basin to the north and the Achocalla sub basin to the south. The ridge is believed to continue northwestward as a structural trend much beyond Alto de Sopocachi beneath the younger sediments.

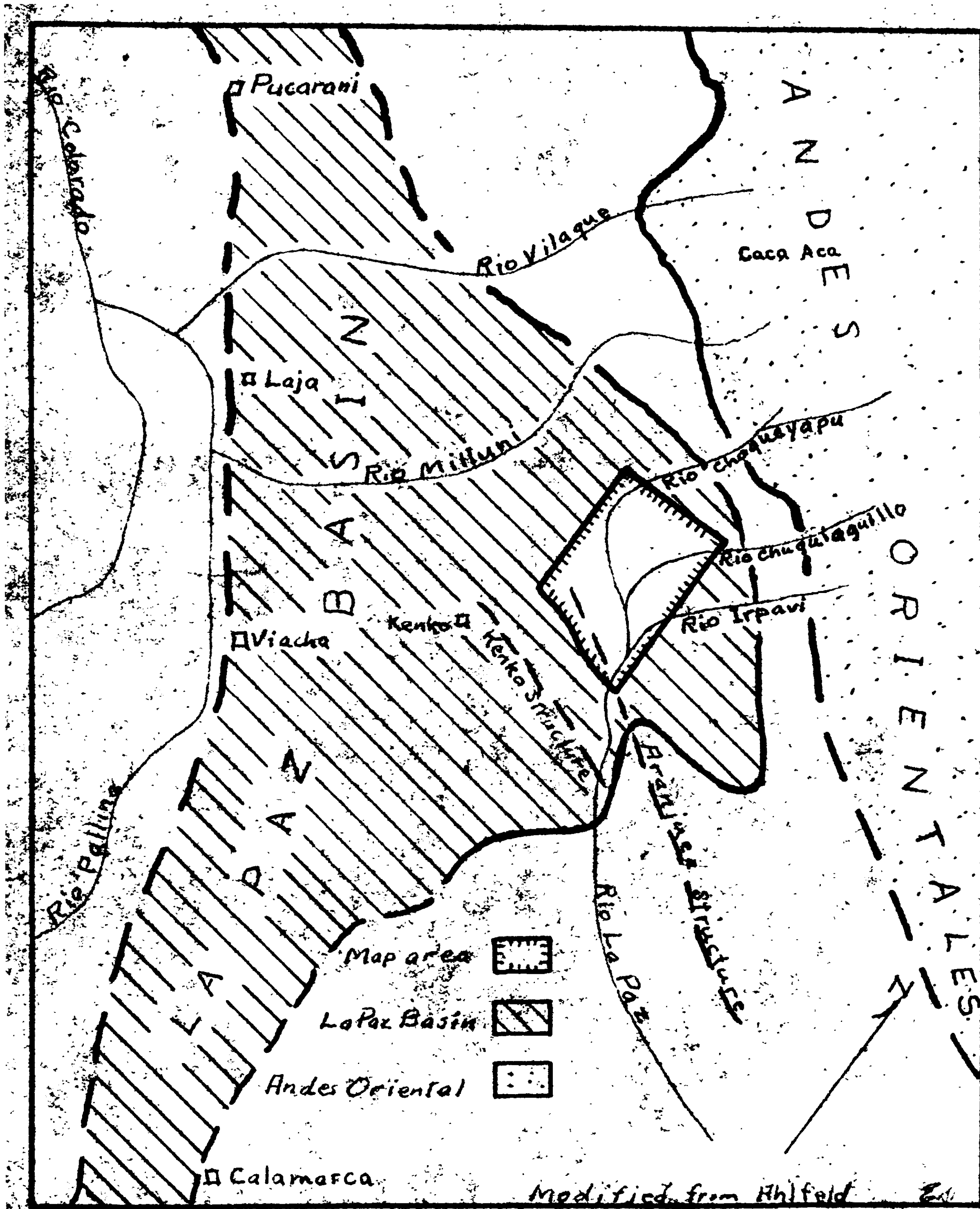
The Pre-Tertiary rocks are by far the oldest in the area mapped. Primarily on the basis of regional correlations, previous workers estimated their age as middle Paleozoic or late Mesozoic. Some rocks of the Upper Puca Formation (Ahlfeld,2) may be present, but in the absence of more definitive information they are here collectively called Pre-Tertiary. Fossil evidence that would help determine a more precise age has not been found. For the purpose of this report, the age of these rocks is not very important. However, it is important to understand the larger structure of these rocks because their configuration controls the outline of the major part of the La Paz Basin. This control, in turn, also determines much of the localization of ground water.

Tertiary Rocks

Earlier workers divided the Tertiary rocks of the area into the Lower and Upper La Paz Formations and placed the boundary between them near the base of the prominent ash bed. As a till is present below the volcanic ash bed, rocks that have been previously assigned to the late Tertiary and called "Upper La Paz Formation" are Quaternary in age. Therefore the term "Upper La Paz Formation" will not be used in this report. However, La Paz Formation is retained to name the entire sequence of poorly consolidated sediments of Tertiary age that unconformably overlie the Pre-Tertiary rocks.

La Paz Formation

The La Paz Formation underlies the entire area of the map north of the Aranjuez Ridge. It consists in lensing and discontinuous beds of poorly consolidated sand, silt, gravel, clay and some thin seams of lignite. Individual beds range in thickness from a feather edge to about 20 meters. In this investigation many partial sections have been measured. From these measured sections it is estimated that the total thickness is inexcess of 600 meters. Most of the beds are



Location map and diagrammatic outline of the La Paz Basin gray; a few lenses of tan and red sand are found in the vicinity of Obrajes and San Jorge. Individual beds cannot be traced more than about one kilometer.

In exposures west of Pico de Pampajsi the upper beds of the La Paz Formation are coarse. In lithology and texture they resemble the Pleistocene deposits. East of the mapped area in the Irpavi Valley where the Pleistocene volcanic ash marker beds is absent, the contact between the Tertiary and the Pleistocene is gradational and, for mapping purposes, would fall within a zone of sediments more than 75 meters thick. Though gravel beds are present in the La Paz Formation in the western part of the mapped area, they are thin and the proportion of fine grained material is much greater than in the eastern part. The upper boundary of the formation was drawn at the base of the volcanic ash bed except in the one locality where a till underlies the ash marker bed.

Many normal faults of displacements ranging from a few meters to about 100 meters are present. The general direction of these faults is parallel to the structural lines of the Pre-Tertiary rocks. However, a large fold and zone of faulting observed near Kenko (see Fig. 1) has a strike somewhat more westward than that of the older structural trend. Some of the larger faults are exposed in the upper Chuquiaguillo Valley, west of Pico Pampajsi and in the Patapatani area. Many smaller faults can be observed along the Choqueyapu and Horcohahuira rivers for approximately one kilometer upstream from Obrajes. On the attached map only the larger faults are shown.

A late Tertiary age for these rocks is accepted on the basis of the following: 1. a report by Posnansky (9) in which he mentioned finding two Pliocene vertebrate fossils in a brick quarry in Miraflores and a recent find of similar fossils by Branisa (3), 2. the correlation of the La Paz formation with other similar basins containing known Tertiary sediments, made by previous workers, some of whom are listed in the attached abbreviated bibliography and 3. because there appeared to be continuous deposition from the Tertiary into the Pleistocene.

Quaternary Rocks

Quaternary rocks in this area are unconsolidated clays, silts, sands, gravels, tills, one ash member and, locally, lenses of lignitic peat. In origin most of these sediments are associated with glaciation. With some exceptions, they are 1, mixed debris left by the glaciers, 2, sorted stream deposits laid down in front of advancing glaciers, 3, sorted stream deposits laid down in front of retreating glaciers. The ash member, a significant horizon marker, obviously is not related to glaciation.

Patapatani Till

The Patapatani Till is an unsorted mixture of large boulders, gravel, silt and clay. It is well indurated and oxidized throughout the total thickness of the exposure. Seven meters are well exposed along the north edge of the map on the east valley wall of the Choqueyapu River but the total thickness is estimated to be about twenty meters. The type locality of the Patapatani Till is on the first ridge about 400 meters north of the exposure shown on the map and 75 meters above the road leading to the Milluni mine - Chacaltya area. Patapatani is the local name unwittingly given the topography formed by the terminal moraines of the Choqueyapu Valley. In the Aymara Indian language it means "One thing over another".

The base of the Patapatani Till marks the separation between the Tertiary rocks and the Pleistocene deposits. Because the lower part of the till is concealed by colluvial deposits, a good description of the contact with the La Paz Formation cannot be given. In the Choqueyapu Valley downstream from the type locality where the rocks are better exposed, this till is not present and no obvious criteria were found that could be used to separate the Tertiary from the Pleistocene. It is possible that coarse grained sediments mapped as part of the upper La Paz Formation are an outwash facies of the Patapatani Till. This till is thought to represent the time equivalent of the first Pleistocene Glacial Stage in North America and Europe.

Volcanic Ash and Gravels

This unit is composed of two distinct lithologies. The lower part is a volcanic ash and the upper part is a well sorted gravel with some sand and clay. The ash member is conspicuously exposed in the upper parts of the walls of the Chuquiaguillo and Choqueyapu Valleys and, as a distinctive marker bed, below the brow of the Altiplano from El Alto to Alto de Sopocachi.

The volcanic ash is white in the lower 2/3 and pink in the upper 1/3. The lower part contains a few scattered pebbles of rounded granits, hard shale and quartzite, while the upper part is generally a clean ash. In some places the ash is very soft and friable; in other localities it is ledge forming and comparatively hard. Though the ash is soft, it is somewhat more resistant to erosion than the coarse unconsolidated material above and below it; for this reason it crops out in more localities than the beds above and below it. In thickness it ranges from about two meters to 12 meters.

The upper part of the unit is composed of well sorted white granite gravel and some sand and clay. The exposure west of the Cemetery is the only locality where thin beds of reworked ash were observed. Few of the well rounded pebbles are larger than 5 cm. in diameter. Individual beds range in thickness from a few inches to about 2 meters and are well graded. In the valley wall above the Cemetery is a bed about one meter thick that is composed mainly of flat pebbles that give the appearance of having been formed on the shore of a lake. The part of the unit above the ash member ranges in thickness from about one half meter to 25 meters.

Calvario Till

The Calvario Till is composed of a mixture of clay, silt, sand, gravel and boulders. It contains many fragments of a hard purple shale; these fragments give the unit as a hole a purple cast which can be seen better from a distance than on the outcrop. In most places the upper half of the till is oxidiaed. It ranges in thickness from a feather edge to about 85 meters.

The Calvario Till is present above the Volcanic Ash and Gravel unit north of a line drawn between Alto de Potosi and Finca Chuquiaguillo. On the ridge between the railroad tracks leading to the Yungas and Calvario del Norte observation station the till is well exposed and characteristically developed. This exposure, where the till is 33 meters thick, was selected as the type locality. The name was taken from the observation station.

The structure that was mentioned in the part of this report dealing with the La Paz formation involved this till and the intervening older beds. Deformation younger than that represented by the Calvario Till could not be found. For this reason it is surmised that the last period of active faulting and folding took place after the Calvario Till had been deposited.

White Granite Gravel

In the northwestern part of the area where the Acueducto de Milluni descends the wall of the Choqueyapu Valley, the white to gray granite gravel unit is best developed in its most distinctive form. There it is composed mainly of remarkably well rounded white to gray granite gravel of stream origin derived from the area around Caca Aca (Huayna Potosi) and the headwaters of the Choqueyapu River. The individual pebbles range in size from particles so small as to be hardly recognizable as granite to boulders about 1/2 meter in diameter. By far the greater number of pebbles are from 5 to 15 cms. in diameter.

Within the mapped area, the White Granite Gravel ranges in thickness from about 50 to over 100 meters. It is exposed high on the west wall of the Choqueyapu Valley from Alto de Sopocachi to the north boundary of the map, in the Palomera area between the Choqueyapu and Chuquiaguillo Valleys and north of Pico Pampajsi.

Northward from the acqueduct locality near the edge of the map, the gravel thins rapidly; though the unit is there composed of about 1/2 sand and clay, it is still distinctive for its content of white to gray granite gravel. Southward from the acqueduct locality the preponderance of white granite gravel decreases. In the valley above the Cemetery several lensing beds of lignitic peat are present. Beyond Alto de Sopocachi quartzites, gray slates and sandstones are so abundant that the presence of white granite is no longer a distinguishing feature. However, the unit as a whole can still be differentiated, though the position of the upper boundary is obscure.

Milluni Till

The Milluni Till is a mixture of silt, clay, sand gravel, and boulders. It contains more large quartzite boulders than the older tills. It is distinguished from the other tills by stratigraphic position rather than by composition. Locally an impervious red to gray and black soil zone has been developed on top of the till.

The Milluni Till is found in the northwestern part of the mapped area. Its greatest development is beyond the limit of the map along the road to Milluni and Chacaltaya. It ranges in thickness from a feather edge to perhaps over 100 meters.

The thickest exposed section of the Milluni Till is high on the west side of the Choqueyapu Valley where the Acueducto de Milluni decends toward the river. Though partial exposures are much better along the railroad tracks in the vicinity of Alto de Lima, the one adjacent to the aquoduct was selected as the type section because it is thicker and because the lower contact with the White Granite Gravel is quite distinct. The name is taken from the name of the aqueduct and road leading to Milluni.

Outwash Gravels of the Altiplano

The Outwash·Gravels of the Altiplano are coarse stream gravels with some silt and clay. These were deposited in part in front of the Milluni Till and, as the Milluni ice retreated, on top of the Milluni Till, in fairly well defined broad and narrow channels. In the area mapped this unit ranges in thickness from a feather edge to more than 70 meters.

The term "gravels of the Altiplano" is found in the geological literature of Bolivia. It is restricted in this report to include only those water layed materials that were deposited in front and on top of the Milluni Till. The word "outwash" is used as a modifier because it so well describes that much of the material was deposited by stream water in front of the ice.

Exposures in the vicinity of Alto de Potosi and north of the Palomera area are examples of sediments deposited in front of the Milluni Glacier. Sediments present in the northwest corner of the map were deposited in channels cut into the Milluni Till as the glacier retreated. Near El Alto at the southern terminus of the Milluni Till a gravel lense about 4 meters thick is present within the till. Though it was not possible to trace the gravel bed definitly into the Outwash Gravel of the Altiplano, the gravel bed is interpreted as representing deposition in front of the Milluni Glacier during a minor retreat of the ice and illustrates partial contemporaneous deposition of the two units.

Pampajsi Terrace Gravel

The Pampajsi Terrace Gravel is composed of coarse gravel and very little sand and clay. The gravel pebbles are rounded to subrounded and consist of quartzite, slate, sandstone and granite. The average diameters of the pebbles are about 3 inches. The unit ranges in thickness from a feather edge to about 50 meters. Along the southern edge of the terrace the gravel appears to be thicker than 50 meters; this is attributed to the steeply inclined surface upon which the gravel was deposited.

Irpavi Terrace Gravel

In all respects observed, the Irpavi Terrace Gravel is similar to the Pampajsi Terrace Gravel except that it is located at a lower altitude. The gravel ranges in thickness from a feather edge on the inner part of the terrace to about 30 meters on the outer edge. The terrace is found in only two places; one on the east side of Pampajsi Terrace and the other on the west side.

Choqueyapu Moraine

The Choqueyapu Moraine is an unsorted and unconsolidated mixture of sand, silt, clay, gravel and boulders. Located in the upper Choqueyapu Valley where it once filled the valley to a depth of over 200 meters, it is a classical example of a terminal moraine. The same symbol is used to identify the morainic material that is found in the upper Chuquiaguillo Valley. The moraine in the Chuquiaguillo Valley is thought to have been deposited at the same time as the one in the Choqueyapu Valley, but it was never as large or well developed.

Miraflores Terrace Gravel

The Miraflores Terrace Gravel is a white to gray granite gravel with a discontinuous clay bed in the middle. It contains some rocks of other composition but they are in the smaller fraction and superficially inconspicuous. The white to gray granite was derived from two kinds of sources. One source was from large bedrock exposures in the upper part of the Choqueyapu Valley and also from some smaller exposures in the headwaters of the Chuquiaguillo Valley. The second source was from reworking of the White Granite Gravel and other units containing smaller amounts of the granite.

The Miraflores Terrace Gravel forms the prominent terrace on which much of the city of La Paz has been constructed. Troll (11) used the term Miraflores Terrace to define the well developed topographic feature in the borough of Miraflores. As used in this report, the term Miraflores Terrace Gravel refers to the material rather than the topographic surface.

The lower part is a coarsely bedded white granite gravel with some clay and sand. Some boulders as large as 1/2 meter in diameter lie along definite planes of stratification. The sand and clay along with the smaller pebbles have been so tightly packed and somewhat cemented that the material will quite safely stand in vertical cliffs. Of course, some sloughing takes place from the face of such vertical cliffs, but other kinds of failure was not observed in the material itself. It was observed that where the material beneath the gravel was weakened by water saturation or undercutting that the gravel failed for lack of support. This part of the unit ranges in thickness from a feather edge to 20 m.

The middle part of the unit is a discontinuous and lensing clay bed that in some places contains thin layers of gravel. It is well exposed south of the Hipodromo on the ridge between the Choqueyapu and Horcohahuira rivers. It ranges in thickness from a feather edge to about 8 meters.

The upper part of the unit is a granite gravel with about 50 percent clay, silt and sand that ranges from a feather edge to 18 meters. It too contains some large boulders. This part of the unit is not as resistant to erosion as the lower part. In many places cliff faces must be protected by walls to control sloughing and slumping.

Recent Deposits

Recent deposits are sediments that in large part have been formed since the last retreat of the ice. The distinction of time of formation is arbitrarily drawn as some of the deposits were in their first stages of formation in the late Pleistocene. The significant fact about the Recent deposits is that their formation represents processes of erosion which are active today.

Lacustrine Deposits

Lacustrine Deposits contain peat, clay, silt, sand and gravel. They are found at three levels which represent deposits in three different lakes that are not differentiated on the map.

The lake deposits highest in altitude are up stream from the Choqueyapu Moraine. The deposits are bedded peat, sand, clay and gravel. This lake was in existence along enough to cut a well marked beach into the confining Choqueyapu Moraine.

The next lower lake deposits are found north of Finca Aranjuez in the southeast corner of the map. The sediments are well bedded and evenly sorted sands and gravels that in part overlie an older mud flow and in part overlie pre-Tertiary rocks. In a few places the slight inclination of the bedding gives the appearance of a delta deposit from which the bottomset and foreset beds have been removed.

The lowest lake deposits are found in the same locality at a lower altitude. They include sand, silt, clay and gravel. These deposits may represent a lower stage of the same lake that was mentioned in the previous paragraph.

Landslides

This unit includes individual and multiple blocks of sediments that have moved down slope. In places the dislocated blocks moved down slope in combination with mud flows.

These downward displaced blocks are clearly a surface phenomena. For this reason, in this report, the word "fault" is reserved for deep seated separations and the words "slip plane" is used to refer to the plane along which the landslides moved. None of the landslides observed moved as an unfractured single block. Many separate slip planes are present and movement was, and is, differential along these planes; more fractures are found in the lower part of the slides than in the upper parts.

It was recognized that the landslides are not all of the same age. An age would be difficult to assign with certainty to a landslide that has moved intermitently since the last advance of the ice. An example of this is the landslide between the University region and the borough of Miraflores. This landslide first moved down slope about the time the clay bed of the Miraflores unit was deposited. One part of the block has long been stable, but, as the Choqueyapu River deepened its channel, the outer surface of the stable block failed, and still fails, in a series of smaller landslides.

Mud Flows

Mud Flows are a heterogeneous mixture of clays, silts, sands, gravels and recognizable blocks of parts of bedded sediments and tills. They include any or all of the materials that are found in place higher up the slope of the valley. All of the mud flows observed were found to conform to present tributary valleys.

The mud flow which innundated the stadium of "Club Strongest" in Sopocachi is recognized, but not differentiated from the larger landslide area shown on the map. This mud flow, which took place in 1953, is obviously much younger than the one underlying the lake deposits in the vicinity of Finca Aranjuez. Differentiation as to age was not shown because some of the areas are too small to be indicated on a map of this scale.

Colluvium

Colluvium as represented on this map includes two kinds of deposits that had somewhat different origins. One kind is composed primarily of fairly well sorted gravels and the other is a mixture of all the material found on the slope above. This latter is properly termed "slope wash".

The sorted gravels of this unit are found just below the brow of the Altiplano in ice-abandoned cirques extending from Alto de Sopocachi to the northern limit of the map and also along the railroad to the Yungas in the Chuquiaguillo Valley. On the margins of many of the cirques these sorted gravels are mingled indistinguishably from slope wash. This concealing blanket of gravels was derived from local material higher up the slope and sorted by meltwaters from the small snow and ice fields that occupied parts of the sides of the main valleys when the level of the rivers was higher than it is today. The blanket ranges in thickness from a feather edge to more than 20 meters.

Slope wash, the other part of this unit, is found in all parts of the mapped area. It is also composed of locally derived materials from up slope. However, in this case, gravity played a more dominant role in deposition than water. It is this part of the unit that cannot always be distinguished from landslides and mud flows because the forces that formed them were in part the same.

Alluvial Fan Deposits

Alluvial Fan Deposits are mainly coarse gravel in the upper part of the fans, gravel and sand in the middle part, and sand and silt in the lower part. The materials are derived from the upper parts of the valleys and in composition reflect the parent lithology.

In the Chijini district the Alluvial Fan Deposits include some small landslide blocks. The fan forming process was in part contemporaneous with the sliding of these blocks of sediments. Alluvial fan material is found to underlie and also overlie some of the blocks. For this reason the landslide blocks were mapped with the Alluvial Fan Deposits.

In the Purapura district some gravels that might be stream terrace deposits were included with the Alluvial Fan Deposits. Alluvial Fan Deposits are prominent features of the two principal river valleys of La Paz because the Miraflores Terrace forms a base on which the material can be spread out by the intermitent streams.

Recent Terrace Gravels

Recent Terrace Gravels include gravel, sand, silt, and clay. These were deposited by the major streams before the last entrenchment took place. In some areas these gravels form clearly distinguishable levels between the Recent Flood Plain Deposits and the Miraflores Terrace; in other areas the contact is indistinct and the line separating them was drawn arbitrarily.

Recent Floodplain Deposits

These deposits are mainly gravel, but locally contain some sand, silt, and clay. They mark the approximate upper limit of materials that are moved during times of high water of the rivers. Channelizing the lower parts of the main streams has aided greatly in stabilizing these materials.

GEOLOGICAL HISTORY

Geologic history is a record of the events of natural pysical forces that acted upon the land in producing the configuration of the landscape as we see it today. Like every other history, the more ancient the record, the more vague and unreliable does the information become. In geologic history much of the older record is either lost by erosion or has been concealed by younger deposits.

Events in Pre-Tertiary Time

The Pre-Tertiary rocks were not studied in detail. To unravel the major events of their history requires a comprehensive study of a much larger area than the La Paz Basin. They are treated by Ahlfeld in his "Geology of Bolivia" (2).

The Pre-Tertiary rocks shown on the map are an interbedded sequence of shales and conglomerates that appear to represent alternate continental and marine deposition that took place long before the Andean Mountains existed. After deposition of the sequence, the rocks were uplifted, folded and faulted. In the ensuing erosion cycle the area was again reduced to a near level plain. No direct evidence was observed in the area studied that would indicate subsequent invasion of marine waters of thick accumulation of continental deposits. However, the red sandstone and gypsum series exposed in the upper Choqueyapu and Irpavi Valleys beyond the northern and eastern boundary of the map are deposits that may be much younger than those shown on the map. Assuming a long period of erosion following the first deformation of the Pre-Tertiary rocks, the next period of significant deformation did not take place until early Tertiary time before the oldest beds of the La Paz Formation were deposited.

Tertiary Period

The outline of the present Andes began to take shape sometime during the Tertiary period prior to the deposition of the La Paz Formation when there was large scale tectonic movement that produced three major topographic and geologic provinces. These provinces are: 1, the Western Andes, 2, the Central Altiplano, and 3, the Eastern Andes.

One might think of these provinces as a rising block that was squeezed from two sides (see Fig. 2). The edges of the block, where pressure was applied, would be crumpled, distorted and higher while the central part would be comparatively undeformed. In the analogy, the distorted edges would be comparable to the Eastern and Western Andes and the central part of the Altiplano.

Little is known about the history of the Western Andes because much of the area was later covered by volcanic material. The central Altiplano, though it was a comparatively stable block, was warped into broad gentle anticlines and synclines. Closer to the Eastern Andes the warpings become more sharply defined, closer together and bloken by faults. The Eastern Andes were very strongly folded, faulted, fractured, and in many places, overthrust.

Between the more stable part of the central Altiplano and the intensely deformed Eastern Andes, the uplift produced long and narrow basins and ridges about parallel to the trend of the present day

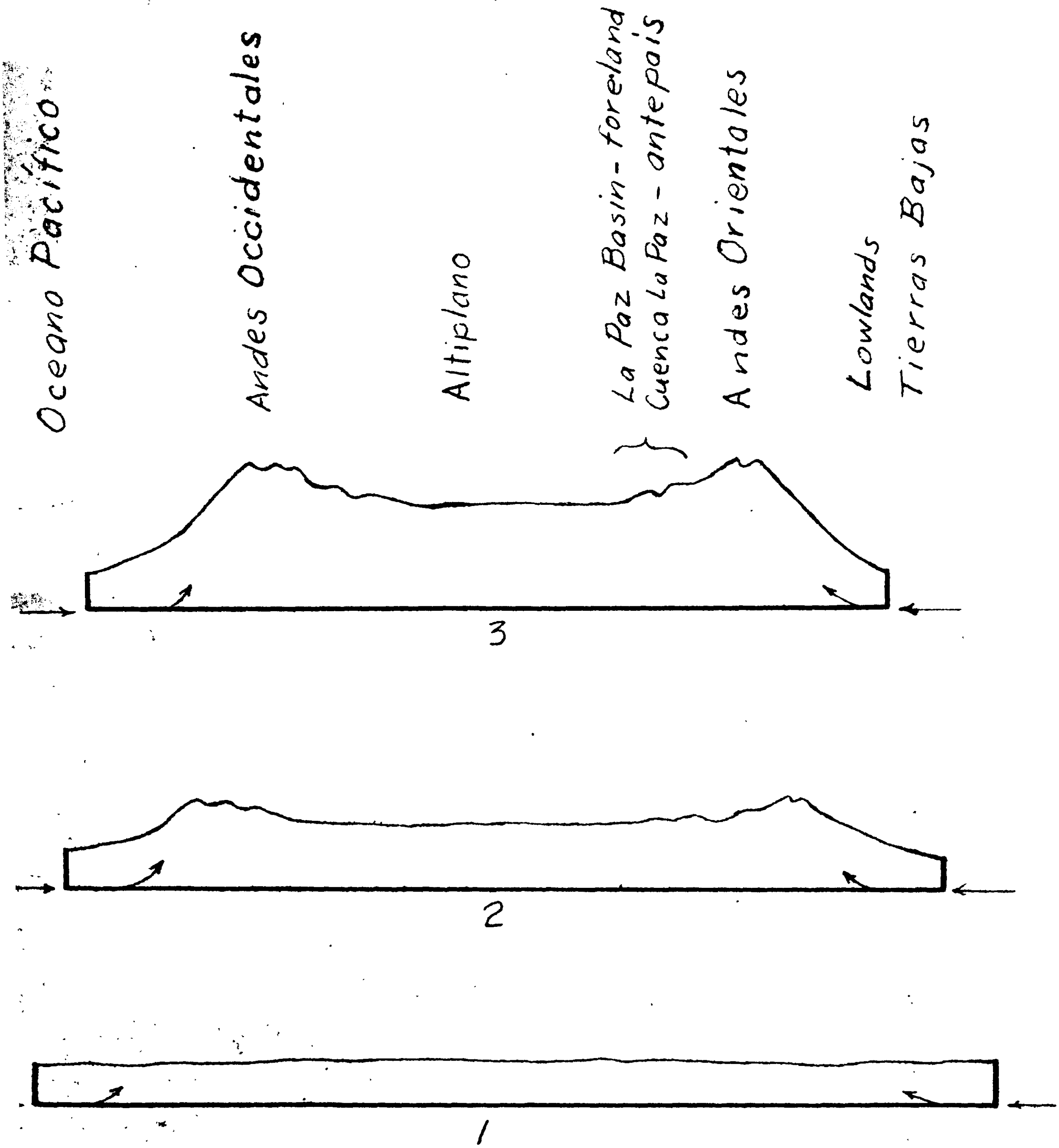


Fig. 2. Simplified sketch illustrating stages of uplift and formation of the Altiplano

Fig. 2. Esquema simplificado ilustrando los grados de solevantamiento y formación del Altiplano

Andes. The La Paz Basin is but one of several such basins that were formed in Bolivia and Perú.

As the mountains began to rise, materials eroded from them were deposited in the foreland depressions. Streams heading in the rising Eastern Andes, flowed westward. They deposited most of their coarse sediments near the mountains and the finer ones farther west. Even in so short a distance as between the Finca de Chuquiaguillo and Calvario del Norte this gradation from coarse to fine is remarkably evident.

Filling of the foreland structural basins was in part contemporaneous with the development of the basins. Some of the foreland basins were completely filled, and sediments derived from the eastern mountains spilled over into basins still farther west. This happened because the foreland basins were not deepened at a pace equal to the amount of sediment that was supplied from the more rapidly rising eastern mountains. Two such basins can be seen from the constriction at Finca Aranjuez. In this place the Aranjuez Ridge separates the basins. The northwest basin is deeper and contains more Tertiary material than the basin to the southwest. These basins are secondary depression in a larger syncline. Another still smaller depression is indicated farther south.

The term "La Paz Basin" is used to define the large depressed area along the western front of the Eastern Andes in which late Tertiary sediments were deposited. In the same latitude but beyond the edge of the attached map, its eastern boundary is between km. 7 and 8 on the Yungas Road, and its western boundary near Viacha. Its northern boundary may have been Lake Titicaca and its southern boundary south of Calamarca. Three divisions within the La Paz Basin are recognized. They are the Choqueyapu Sub-basin on the northwest side of Aranjuez Ridge, the Achocalla Sub-basin on the southwest side of Aranjuez Ridge and an obscure third unnamed sub-basin south of the Kenko structure.

When the La Paz Formation was being deposited, the climate was milder than it is today. Evidence for this statement is based also on the recent excavation of vertebrate fossils found above the abandoned railroad west of the Aranjuez Ridge. The fossil was identified by Branisa (3) as Plohophorops sp un., family Daedicuridae, an extint variety of giant armadillo. Vertebrates of this kind could thrive only in a warmer and moister environment.

Though the La Paz Basin in its entirety was probably never covered by water, small fresh water lakes did exist. In places these lakes had fairly well defined shore lines. Adjacent to some of the lakes and along the rivers, vegetation was supported. However, no evidence was uncovered to verify that forests of large trees existed.

Following the deposition of the La Paz Formation, there may have been regional uplift. Certainly there was a climatic change which altered the character of the sediments from water layed deposits to ice and ice associated deposits.

Quaternary Period

The Quaternary Period refers to the entire time span from the end of the Tertiary Period to the present. For convenience the Quaternary Period is further subdivided into the Pleistocene and Recent Epochs. The Pleistocene Epoch, commonly called the "Ice Age", refers to the time when glaciers advanced and retreated over parts of the larger continents of the world. The Recent Epoch refers to the events which took place since the last major retreat of the ice.

Pleistocene Epoch

Probably more is known about the chronology of the Pleistocene Epoch than any of the preceding periods of geologic time. The span of time covered is shorter and more of the record in terms of deposits is preserved. In Eurasia and North America these deposits have been studied in some detail because so much of the works of man exists on them and because so much agricultural produce is grown on them. In Bolivia too, much of the agriculture is practiced on either the sediments that were deposited during the Pleistocene Epoch or on soils that were in large part formed during that time.

Within the boundary of the attached map is a fairly complete record of four advances and four retreats of the ice. In a general way they can be correlated with the advances and retreats in Eurasia and North America. A new terminology, based on observations made in the vicinity of La Paz, will be used in this report for the chronology of the Pleistocene in Bolivia.

First Glacial Stage:

The first major advance of the ice in the eastern Andes of Bolivia is represented by the Patapatani Till. Only the upper part of this till is exposed in the small locality where it was found. Though the contact between the Patapatani Till and the La Paz Formation was not seen, the unexposed interval is less than 20 meters.

Like the glaciers of the two succeeding stages, the Patapatani was a piedmont glacier. It may have extended as far as Alto de Lima from the mountain front. During the time of the existance of the Patapatani Glacier a valley was present at about the place where the Choqueyapu of today has its headwaters in the mountain front. However, that valley was not as deep as the present day valley. During the existence of the Patapatani Glacier the Eastern Andes were not so high as they were during a later stage, though they may have been as rugged as they now are. The white granite that today is well exposed 15 to 20 km. up the Choqueyapu Valley beyond the limit of the map was just being incised. The purple shale which constitutes the diagnostic inclusion in the Calvario Till was also just being exposed.

Westward, beyond Alto de Lima, water from the Patapatani Glacier deposited a sheet of outwash gravel. As the outwash gravel cannot be distinguished with certainty, it was mapped with the Tertiary deposits.

First Interglacial Stage:

Materials of the first interglacial stage are represented by the volcanic ash and the overlying gravel.

After the retreat of the Patapatani Glacier, a period of erosion followed that removed most of the till and its water deposited facies. The surface was exposed long enough to oxidize the Patapatani Till. Upon this eroded surface the volcanic ash was deposited.

The precise location of the eruptive volcanos that contributed the volcanic ash is not known. However, the source was probably the western Andes in an area which has long been intermittently active volcanically. The ash fall covered quite uniformly a land surface that looked very much like the Altiplano does today.

The contact between the volcanic ash and the overlying gravel is slightly undulating. Sharp incisions that would mark the course of a stream channel cut into the ash were not observed. The streams which deposited the overlying gravel were aggrading and scoured the surface very little. The gravel may represent outwash developed in front of the Calvario Glacier as it began to spread westward from the mountains.

Second Glacial Stage:

The second glacial stage is represented by the Calvario Till. The hard maroon shale on the western flank of Mt. Chacaltaya was broadly exposed and much of the till was derived from that locality. Farther up the valley now occupied by the Choqueyapu River, white granite was plucked by the glacier and carried towards the Altiplano.

Presumably the Calvario Glacier was not as well developed south of the Chuquiaguillo River as it was to the north. Till of this age is not recognizably present in the Pampajsi area, but gravel that represents the outwash stream phase is thought to exist in the thick gravel sequence there exposed. During its retreat the surface of the Calvario Till was rather evenly planed by water. If a soil was developed on the till, it was later removed. In most places the upper 1/3 to 1/2 of the till was oxidized.

Second Interglacial Stage:

The Second Interglacial stage is represented by the White Granite Gravel. Some time between the retreat of the Calvario Till and the earlier deposition of the White Granite Gravel, the Eastern Andes and the basin of La Paz were again structurally deformed. As during previous periods of deformation, the mountains were more intensely disturbed than the plains areas. It was at the end of this period of deformation that the Eastern Andes probably reached their greatest height.

Faulting and folding, more or less parallel to the mountains, took place in the La Paz Basin. Generally the western part was uplifted in a series of enechelon faults ranging in displacement from a few meters up to 100 meters or more. Locally, as near Finca de Chuquiaguillo, some blocks were down faulted in the form of a graben.

Just off the western limit of the map in the Kenko area, Tertiary and early Pleistocene deposits of the Achocalla sub-Basin were broadly folded upward. The west central part of the fold was broken by several faults. This line of faulting extended southward down the La Paz gorge. Displacement of this faulting in the La Paz gorge near Mallasilla is more than 200 meters.

The landscape of the plains fronting the mountains did not long remain a series of block faulted hills, low anticlines and synclines. With the greater uplift of the Andes, streams became more active. In this general vicinity they carried their sediments of predominantly coarse white granite gravel to the depressions, filled the depressions and aided in planing the projecting fault blocks and folded hills. By the end of the second interglacial stage the surface was again a broad plain inclined to the west.

Third Glacial Stage:

The third glacial stage is represented by the Milluni Till. The Milluni Glacier spread out over a broad plain inclined to the west. Isolated remnants of its deposits are found about 10 km. beyond the western limit of the map. In front of the ice a well defined outwash plain was deposited.

During the third glacial stage the La Paz River had cut its valley headward to perhaps below the present location of Mallasilla. Meltwater from the southern part of the Milluni Glacier may have gone down the La Paz Valley.

Third Interglacial Stage:

The third interglacial stage is represented by the Outwash Gravels of the Altiplano, the Pampajsi Terrace Gravel and the Irpavi Terrace Gravel.

The gravel deposited in front of the ice during the maximum extent of the Milluni Glacier is, of course, in part contemporaneous with the till. However, as the Milluni Glacier retreated, gravel was deposited in broad channels, and in narrow channels within the till, and in its westernmost extent, was a blanket that almost entirely covered the distal extremities of the till.

The headward working La Paz River and its tributaries soon incised the plain on which the Outwash Gravels of the Altiplano were deposited. It is probable that glaciers remained in the higher mountains through out the third interglacial stage. Water from these glaciers contributed to the headward working La Paz river system. Above Finca Aranjuez many large tributaries flowed more or less directly westward from the mountains. In each case these rivers had, and still have, their origins in valley glaciers that occupied the higher altitudes.

Early in the erosion cycle, the Irpavi River contributed most of the water entering the La Paz gorge. It is quite likely that the Pampajsi Terrace Gravel is a deposit formed by an early Irpavi River when it flowed in a broad arc that crossed over Tembladerani and Achocalla. As the Choqueyapu worked headward, it began to capture more and more of the water from the Milluni area. It became the dominant stream and deflected the course of the older Irpavi. After the deflection, the Irpavi Terrace Gravel was deposited and the Aranjuez constriction was deeply incised in its present position. All the valleys that are present today were well established by the end of the third interglacial stage.

Fourth or Valley Glacial Stage:

The fourth glacial stage is represented by the Choqueyapu Moraine, the moraine in the upper Chuquiaguillo Valley that has also been called Choqueyapu, and the Miraflores Terrace Gravel.

Glaciers of the fourth or last glacial stage were not as large as those of previous stages. They occupied the valleys of existing streams and only locally did the ice spread over the plains in front of the Eastern Andes. There were two major advances of the valley glaciers. Associated with them were several minor fluctuations. The principle activity during the stage was erosion and down cutting of the La Paz Basin.

As there is acceptable evidence that during the fourth or valley glacial stage there were at least two major advances of the valley glacier, this stage will be treated under three subheadings: 1, the first substage, 2, the first interglacial substage and 3, the second substage.

First substage: The material shown on the map as Choqueyapu Moraine probably represents the deposits left by two separate valley glaciers that had a stationary front at approximately the same place in the Choqueyapu Valley. There is no apparent distinction between the nature of the material of the two moraines. The upper or older moraine is found above the 4000 meter contour while the lower or younger moraine is below the 4000 mater contour. The Choqueyapu Valley is markedly narrower above these moraines than it is below them. That two valley glaciers had their termini at about the same place is indicated by two lines of evidence that are more clearly revealed in the Choqueyapu Valley than elsewhere.

The first line of evidence is the presence of two alignments of kettle lakes at different levels. The lower alignment is shown on the map while the higher one, which is about 100 meters above the lower, is just off the edge of the map on the north side of the valley. The second line of evidence is the presence of terraces, spurs with topographic closures and prominent shoulders on ridges that project into the valley. Terraces are illustrated by the level in the Llojeta and Picos de Sopocachi district in the southwestern part of the map. Other terraces exist, but cannot be recognized on a map of this scale because the contours cannot show them very well. Spurs with topographic closure are illustrated on the valley slope above Purapurani, north of Purapura, below the railroad leading to Alto de Lima. Shoulders high or ridges that project into the main valleys are prominent up stream from the confluence of the Horcohahuira and Choqueyapu Rivers.

If a line is projected down the Choqueyapu Valley from the higher alignment of keetle lakes on a gradient somewhat less than that of the Miraflores Terrace, the line traces along the spurs with topographic closure, shoulders on ridges and terraces at the level of the one at Llojeta. This combination of data is accepted as evidence for the existance of the first valley glacier.

When the first valley glacier advanced to its stationary front, the floodplain of the Choqueyapu River was wide. In the Purapurani area it extended from approximately the 4000 meter contour interval on one side to the same interval on the other, a distance of about 2 kilometers. Farther south in the Llojeta area it may have been twice as wide. Meltwaters from the glacier widened the valley. Some of the material observed on the Llojeta flat is what remains of the outwash material from the main glacier.

At the time of the maximum development of the first valley glacier, small glaciers and ice fields were formed in the short ravines along the western side of the Choqueyapu Valley. The largest of these was in the Apumalla Valley. Glaciers and snow fields of the short tributary ravines which enter the Choqueyapu Valley at nearly right angles were not connected with each other or the Choqueyapu Glacier.

First Interglacial Substage: During the interval between the retreat of the first valley glacier and the advance of the second one, the rivers deepened their valleys. The valleys were excavated from the level of Llojeta to the Miraflores Terrace, a depth of about 300 meters. With this entrenchment and the formation of steep valley walls, landslides and mud flows became a common form of erosion.

It was during this substage that the Aranjuez Ridge was deeply entrenched. The Aranjuez Ridge was not a great barrier to streams after the beginning of the Pleistocene. Once the course through the ridge was established, the material carried by the rivers easily cut the bedrock without even developing strong rapids.

Second Substage: The second advance of the valley glacier is represented by part of the material mapped as Choqueyapu Moraine and the Miraflores Terrace Gravel.

When the ice of the second valley glacier reached its maximum development, small glaciers and ice fields may again have existed along the western side of the Choqueyapu Valley and in short ravines that enter the main valley at right angles.

The ice of the second falley glacier may have advanced farther down the valley than is indicated by the Choqueyapu Moraine. If it did advance farther south, it soon retreated to the locality represented on the map by the moraine. A temporary advance would explain two large erratic boulders that were observed in the vicinity of Obrajes.

As the Miraflores Terrace Gravel is not found up stream beyond the front of the Choqueyapu Moraine, it is considered to be the outwash facies of the moraine. The lower gravel member of the Miraflores Terrace was deposited by stream water mainly derived from ice shortly before the second Choqueyapu Glacier reached its stationary point. Continuous deposition of the gravel was interrupted by a landslide and mud flow. A large block of rock was loosened in the area between Calvario del Norte and Cerro Killi Killi. Associated with the loosening and downward displacement of the slide block were several mud flows. The mud flows are represented by the discontinuous clay member in the Miraflores Terrace Gravel. The top of the mud flows were truncated by the succeeding deposition of the upper member of the Miraflores Terrace Gravel. The upper member was deposited as the second valley glacier began to retreat. With the retreat of the glacier, the Recent Epoch or 4th interglacial stage began.

Recent Epoch

The Recent Epoch is represented by Lacustrine Deposits, Landslides, Mud Flows, Colluvium, Alluvial Fan Deposits, Recent Flood Plain Deposits and by erosion. Erosion took place in many ways. It was during this epoch that the river channels were excavated from the Miraflores Terrace level to their present position. For convenience in discussion, the various deposits are grouped as follows: 1. Lacustrine Deposits, 2. Deposits and Erosion Processes occuring on Valley Slopes, and 3. Terraces.

Lacustrine Deposits:

As represented by sediments in the upper Choqueyapu Valley and in the La Paz Valley above the Aranjuez constriction, three lakes existed during the Recent Epoch.

The lake highest topographically was located up stream from the Choqueyapu Moraine. It owed its existence to the presence of the moraine. Sediments of this lake were deposited shortly after the second valley glacier retreated. As a lake it was not in existence very long. Soon the impounded water overtopped the moraine and cut a channel through the till. The channel it cut is the present course of the Choqueyapu River. However, the lake was in existence long enough to cut a well marked beach line into the till. Into this body of water were carried fine and course grained sediments. Part of the time the margins were marshy and supported vegetation.

The lakes that occupied the area upstream from the Aranjuez constriction were caused by the impounding of the La Paz River when a mud flow damned the stream below the constriction. For a short time the lake stood at an altitude of about 3360 meters. Once shore line sediments were more extensive than those still preserved on the north east side of the Aranjuez ridge, but they have since been removed by erosion. There is evidence of a later but smaller mud flow below Aranjuez. It impounded the La Paz River long enough to allow accumulation of the lower lake sediments at an altitude slightly above the 3250 meter contour. Part of these lower lake sediments may, of course, have been deposited when the higher lake was in existence.

The mud flow which caused the higher lake above Aranjuez was by far the largest one that affected the area. This mud flow had its origin in the upper part of the Achocalla Valley. It deposited its debris down the La Paz gorge for a distance of over 24 kilometers. When it stopped flowing, it had filled the La Paz gorge below the Aranjuez constriction to a depth of nearly 100 meters. The filling of the valley dammed the La Paz River above the Aranjuez constriction and formed a temporary lake that extended from the constriction to the vicinity of San Jorge. The natural reservoir was soon filled. In a short time the dam was breached. The upper La Paz River quickly eroded a channel through the mud flow and established a slightly altered course from what it previously had. This mud flow which made the lake took place in the early part of the Recent Epoch before the recording of local historical legends.

While the lake was in existence, many of the landslide blocks on the hills below Obrajes were developed and moved part way down the slope. Water from the lake saturated materials adjacent to the shore. As the lake probably receded rapidly once the mud flow was breached, it left high unstable banks. These banks of water-laden sediments soon failed for lack of support that had been supplied by the lake water. Failure took place in the form of mud flows and landslides.

Deposits and Erosion Processes Occurring on Valley Slopes:

These deposits include Landslides, Mud Flows, Colluvium, and Alluvial Fan Deposits. In many ways these deposits are related to each other. They are the result of processes that take place when a valley has been deeply cut into weak material. The processes occur primarily on valley slopes and contribute to valley widening. The processes began to take place soon after the present stream courses were established. They have been going on at an ever accelerated rate because the valleys of these youthful streams are being continuously more deeply incised.

All of the landslide areas shown on the map have been active in the Recent Epoch. Many of them have been temporarily arrested. Most of the landslides in the La Paz area are complex. Their present features are the result of several periods of movement. They have caused minor changes in the direction of river channels. From the historical record it has been established that they are most active at the end of rainy seasons.

Mazamorra, the Spanish word for porridge, is an apt term for describing mud flows in action. The mud flow of largest areal extent shown on the map is east of the Hipódromo across the Horcohahuira River. It covers the upper part of the Miraflores Terrace.

Alluvial fans were formed on the Miraflores and other terraces. They were formed in such places because there is a sharp decrease in the gradient of the tributary streams as they flow out from the short and steep side valleys onto the terraces or other level areas. During rains the tributary streams have high velocities up stream and can carry large quantities of material. When the stream arrives at the more level ground, its velocity is reduced and material is deposited. The coarser and heavier material is deposited near the point of gradient change and the finer material is dropped farther out. The shape of the fan is made as the depositing streams wander back and forth in an arc below the point of gradient change.

Colluvial material moves down steep and moderate slopes and covers the exposures of previous erosion scars. By this process particles such as individual stones, soil or tussocks of vegetation move down slope under force of gravity. Downward migration takes place during the dry season as well as during the wet season. During the wet season the weight of water accelerates the downward movement of soil and tussocks. These slopes characteristically have the appearance of a wide stairway with treads of varying width and risers of irregular hight. The stairway effect is the result of separations that takes place parallel to the slope along the risers at the two margins of the individual treads. The amount of downward displacement of the individual blocks or treads can be measured and ranges in movement from one to 20 centemeters or more. In the dry season, individual stones move down as the enclosing soil shrinks and no longer holds the stones tightly.

Valley Terraces:

These deposits include Recent Terrace Gravels and Recent Flood-plain Deposits.

The erosion process of downward cutting by streams was accompanied by lateral cutting that resulted in the formation of terraces. Terrace development in the Recent Epoch has not been strong because most of the energy of the streams was directed to deepening of the channels rather than valley widening. However, where the channels were temporarily constricted or deflected and meandering started, the streams deposited materials in such a form as to be classes as terraces. These are sediments that were deposited by the streams in their flood plains. When the base level was lowered, the streams incised their flood plain leaving deposits above them in the form of terraces.

An example of the effect of deflection on the formation of terraces is illustrated by the level on which Obrajes is situated. Just above the confluence of the Choqueyapu and Horcohahuira Rivers they flow southward. Below their confluence they flow southeast. In early Recent time the channel below the confluence was farther northwest over Obrajes. It was held there by the Tembladerani landslide. The stream cut into the landslide debris at the bend in the channel where the water was deflected southeastward. Erosion on the west side shifted the position of the channel. At the same time that the position of the channel was being changed, it was also being deepened. Because the channel "slipped" to the westward, the material it left on the slope inclined toward the stream is called a slip-off terrace.

Recent Floodplain Deposits are mainly the materials being carried down stream today. In places these materials are clearly distinguishable from the Recent Terraces by low but sharp banks. In other places, where the streams are actively eroding the bottom of their channels, these deposits are no wider than the stream at low water stage and their thickness is measured in centimeter rather than meters. The significant thing about these materials is that they are transitory. An individual stone found on one place beside the stream today may be found one or more kilometers down stream after the next high water stage of the rivers.

APPLIED GEOLOGY

Several other terms in current literature could be used as a title to describe the content of the last part of this report. The word "economic" was abandoned because it implies and relates to mineral resources. "Engineering", another good term, was discarded becaue in common usage, it implies geology with reference to structures such as dams, roads, tunnels, and other similar works that are made by engineers. The word "applied" is employed in the sense of its dictionary definition, "using and adapting abstract principles and theory in connection with concrete problems".

So far this report has dealt with facts describing the rocks, some theories concerning their origin and a few principles or laws relating to geologic processes. What follows will be a general discussion about the resources, problems and planning in the upper La Paz Valley.

Ground Water

In every community water is a resource. This may not be recognized in places where there is an abundant supply of good water and the only problem is one of providing the engineering works to make it available. However, in areas where the usable water supply is small, it is often the factor limiting the magnitude of the activity, be the activity city expansion, industrial growth or irrigation for agricultural purposes.

Although the city of La Paz has by no means exhausted the water resources of its environs, the larger water supply necessary for future development of the city requires the construction of additional facilities to supply more water. These new facilities will cost more than installations in the past because the water must come from greater distances or from the ground. To meet the requirements imposed by a growing population and an expanding industry necessitates extensive and intensive studies of all potential water supply sources. To be complete, the entire hydrologic cycle should be studied. In this area a complete study would also include measurements of the water yielded by the retreating glaciers.

Limited studies of surface water have been carried on by engineers of the La Paz Municipality for several decades. They are less expensive to make than are studies of ground water. There are few wells in the area. Water from the ground is now pumped from two wells in Calacoto. Wells in other localities have been used, but the quantity of water yielded was so low they have been abandoned. One well near Finca Caiconi above Miraflores was abandoned because of the high content of bacteria. With such meager data available the general geologic map can serve only as a guide to the localization of the search for ground water. By interpretation the map can indicate where water might or might not be found, but valid predictions of quantity and quality of water cannot be made.

Water bearing units of the mapped area are parts of, 1, Recent Terrace Gravels, 2, Miraflores Terrace Gravel, 3, Alluvial Fans, 4, the La Paz Formation, and 5, the White Granite Gravel. Some of these units warrant more extensive exploratory drilling than others. As used here, exploratory drilling means drilling in favorable localities with the intent of proving or disproving the presence of sufficient potable water to serve as a basis for deciding whether the aquifer should be developed.

In the Calacoto area the Recent Terrace Gravels have yielded sufficient water to wells for the needs of individual dwellings, but the majority of the homes are supplied from a city distribution system which derives its water from surface streams. The composition of the Recent Terrace Gravels in other areas is thought to be too dense and too small in extent to investigate in more detail.

Springs issue from the base and from the top of the clay member of the Miraflores Terrace Gravel in several locations. The largest spring observed is on the northeast side of the curve of the road in the Choqueyapu Valley southwest of the Hipodromo. Other springs exist in the landslide area across the Choqueyapu River from the University and along the Horcohahuira River below Finca Caiconi. Using these observations as a crude basis, it is estimated that wells would yield sufficient water for individual domestic use, but not sufficient for the larger quantities needed by the city.

Water is probably present in the distal extremities of all alluvial fans during a part of the year. Alluvial fans deriving water from springs will yield water as long as the springs flow. Alluvial fans deriving water only from rains and from the intermittent streams that form the fans will yield no water during dry seasons. The two localities where additional investigations might be made are in the vicinity of Finca Caiconi and Chijini. Though the chemical content was well within allowable specified limitations, the Caiconi district was abandoned as a source of potable water because the bacteria content was high in samples taken from springs issuing near the base of a large fan. Nevertheless, the district could be investigated farther as it is probable that the high bacteria content is the result of surficial contamination introduced not far above the point of issue of the springs. In the course of exploring to determine the quantity of water, it is quite likely that the source of contamination would be found. If the quantity of water proves sufficient for consistent large yields, it might be economically feasible to eliminate or control the contamination responsible for high bacteria content. The coarse deposits of the alluvial fan area of Chijini between the San Pedro and Apumalla Rivers might yield a constant flow of water as the source is from permanent springs in the White Granite Gravel.

Evidence that the La Paz Formation would be a large yield producing aquifer was not observed. Producing wells might be developed from the coarse sediments in the eastern part of the area. However, the sediments in the western part of the area are considered too fine grained to yield water rapidly and therefore do not warrent more than cursory examination.

The White Granite Gravel is the most significant aquifer in the vicinity and should be more thoroughly investigated because available evidence indicates it will yield large quantities of potable water. Many facts relative to the White Granite Gravel, such as water transmissibility and thickness of the water table are, of course, not known. However, the unit is composed of poorly compacted coarse material so there is space between the rocks which, in the lower part of the unit, is probably filled with water. Porosity, the ratio of the volume of interstices of the material to the volume of its mass, may be as high as 10 or 15 percent.

That the White Granite Gravel contains large quantities of water is not questioned. All the springs in the west valley wall of the Choqueyapu River from Acueducto de Milluni to Alto de Sopocachi flow from the lower part of the unit. Though the springs fluctuate in volume somewhat, they flow the entire year, and contribute to the flow of the Choqueyapu River. As is indicated by the presence of springs at different elevations on the valley wall, water reaches the surface from several zones within the White Granite Gravel. The unit in this area contains many discontinuous lenses of silt, clay and lignitic peat. These lenses are less permeable than the rest of the unit and therefore probably cause temporary local perched water tables. (See Fig. 3A) The perched water tables cause surfacing at different elevations where the valley wall intersects the confining lenses. In some places water may percolate through or around the less permeable lenses, but little enters the Calvario Till which acts as a baffle to any significant further downward migration.

The source of the spring water from Alto de Sopocachi to Alto de Lima is primarily from rainfall occuring on the Altiplano. Soil on the Altiplano westward from the edge of the valley is very thin and there is little run-off; much of the water falling as rain sinks into the ground and becomes a part of the ground water table. The area of recharge for the springs extends two or three kilometers west from the brow of the valley to the Kenko Structure. Water falling on the west side of the Kenko Structure that becomes part of the ground water table again emerges at the surface as springs in the north and west side of the Achocalla Valley.

Some of the water yielded as springs from Alto de Lima to Acueducto de Milluni may originate closer to the mountain front where the White Granite Gravel is near the surface. This is a surmise that can be proved by determining the position of the water table. The determination can be made only when wells are available for study.

Small springs, more properly called zones of seepage, were observed on the north side of many of the valleys in the Palomera area. The fact that no seepage zones were observed on the south side of these stream valleys indicates that the water contained in the White Granite Gravel has a southward gradient and originates farther north in the Altiplano. At least some of the water surfacing as springs in the lower part of the alluvial fans near Finca Caiconi is from this source. The water probably moves from the White Granite Gravel to the alluvial fans where they cross the Calvario Till and lower formations and then appears at the lower part of the fans.

Surficial Earth Movement Problems

In the city of La Paz and vicinity, mud flows, landslides and loosely compacted man-made fill areas have given rise to problems involving surficial earth movements. Problems associated with mud flows and landslides have existed in this valley since the founding of the city. There is, for example, the historical record by two priests about Hanco-Hancó, a community of 2,000 located between Llojeta and Kenko (Sanjinés, 10). This village, including all the inhabitants and dwelling structures, was completely wiped away by a large mud flow on April 2, 1582 leaving no evidence of its former existence. Landslide failures have not been quite so destructive because the movement is slower. Failures caused by settlement over fill areas did not take place until later on in the development of the city.

Landslides

Landslides are clearly near surface phenomena. With proper equipment their boundaries below the surface can be determined. In almost every landslide that has been studied, water has been found to be a major factor contributing to failure. In one sense this isolation of one contributing factor to failure is fortunate because of all the constituents of a landslide, water is the only one of them that can, under favorable conditions, be partly eliminated or controlled.

Water in a landslide contributes to movement or failure in two ways. First, under certain conditions of composition in landslides that have already started, water adsorbed by clay minerals along the slip plains may cause them to expand and become plastic, thereby making it easier for the mass to move downward under force of gravity. Second, and much more important, water adds to the weight of the unstable block. In some landslides that have been studied in detail water accounts for 25 percent or more of the weight contained in the unstable mass.

In general, the most effective method of controlling landslides has been to take out a part of the contained water. It would be an illusion to think that all the water can be drained from a landslide. However, if enough water is eliminated and no more is permitted entrance, the loss of the water will help to keep the landslide mass on the side of stability.

Methods used to control the entrance and to eliminate part of the water in landslides are surface drainage which deflects the water from the unstable area and by internal drainage. Controlling the entrance of surface water by drainage deflection canals has not been very effective where the method was tried. This may not be an accurate appraisal because, so far, there has been no good way in which to measure the effectiveness. The fact remains that where the method has been tried, subsequent failure took place. Of course, surface drainage may have helped, but it was not enough to prevent failure. One kind of internal drainage is by nearly horizontal holes drilled into the landslide and the other by vertical bore holes. Where near horizontal bore holes are used, the water flows from the penetrated area under force of gravity. The same result can be obtained by tunnels. Vertical drains function by pumping the water to the surface and discharging it beyond the landslide or by drainage into deeper strata which will accept the water from the landslide area.

Before internal drainage of a landslide by internal drainage is attempted, the area should be studied in detail. It is advisable if possible, to locate the areas within the landslide that contain most of the water, where the slip plains are located, what the source of the water might be, and whether strata below the landslide are porous and dry enough to accept water rapidly. Often landslides contain large inclusions of highly porous material that are concealed reservoirs. Other surface failure areas receive water from underground sources. By this method the attempt is made to drain the water from (1) the concealed reservoirs, (2) the underground sources before the water reaches the unstable material, (3) the body of the

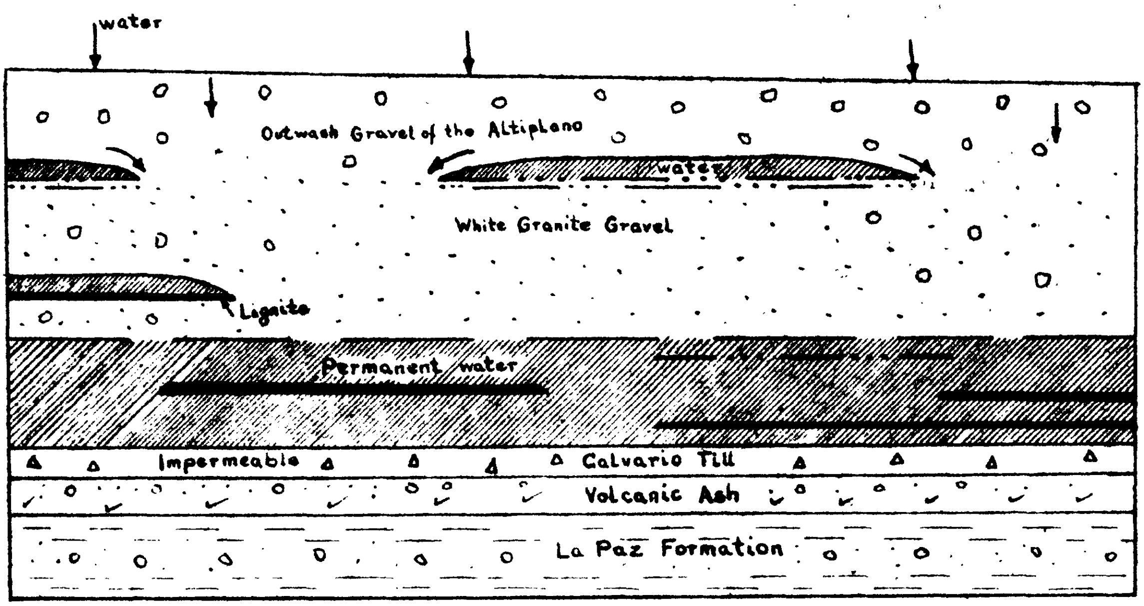


Fig. # 3-A

Diagrammatic sketch of lenses and path of water in the White Granite Gravel along valley wall above Chijini.

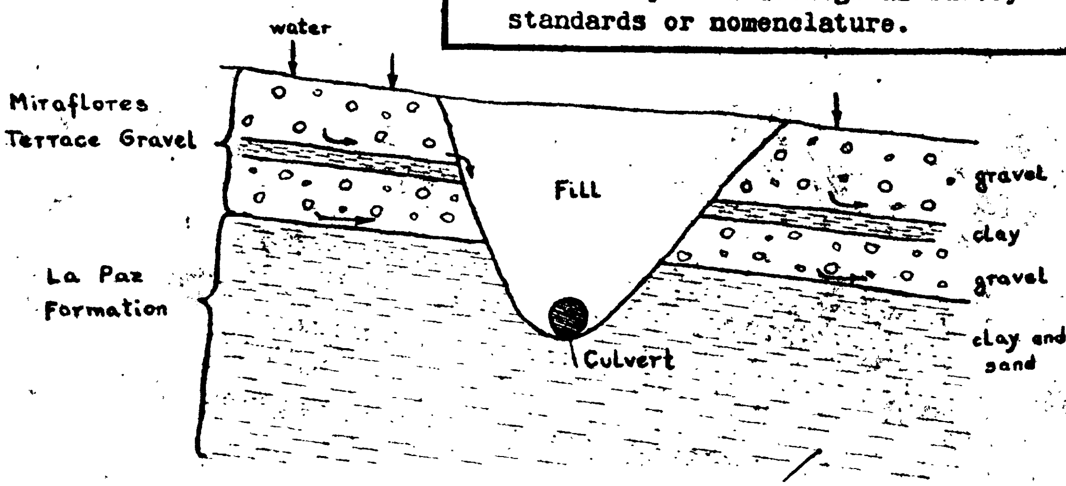


Fig. # 3-B

Diagrammatic sketch through fill section parallel to stream course near the University.

landslide to aid in eliminating weight.

The engineering part of the horizontal drain method consists of drilling near horizontal holes into the landslide. After the searched for place in the landslide has been penetrated, a perforated pipe is inserted in the bore hole. The perforated pipe serves as a drainage hole that will not easily become sealed if the flow of water is moderatly strong. Vertical bore holes drilled for the purpose of investigation can sometimes also serve as drains providing the rocks below the landslide will accept water. If it is determined from exploratory drilling that the same holes can serve also as drains, perforated pipe needs to be inserted to allow entrance of water and also prevent the hole from closing. However, small diameter holes are usually made for exploration and, because of the small size, they may not drain sufficient quantities of water to be effective in landslide control. Therefore, it may be necessary to drill additional holes of larger diameter.

Mapping has revealed facts about all the landslides. Only the landslide area between the University region and the Borough of Miraflores will be briefly mentioned here. The area of failure is complex because it contains three distinct parts. The eastern ridge, commonly called Laikakota, is an arrested landslide block which settled in its present position shortly before the clay member of the Miraflores Terrace Gravel was deposited. As a whole the original block is no longer subject to movement, but the side exposed to undercutting by the Choqueyapu River periodically fails for lack of support and because of saturation. The part of the landslide area extending northward to Cerro Killi-Killi is intermittently active. It fails because springs in the upper part continually supply water to the material which is inherently unstable. Construction that removed some of the material in the lower part of this segment has contributed to unbalancing the mass. Further, open sewers which follow some of the slip plains of the landslide contribute to failure by adding water. The part of the landslide near the University represents failure over a man made fill area. Water of the San Pedro River is conducted through the fill in a concrete culvert. (See Fig 3B) If the fill was placed over the valley using the same fill techniques as was observed in other parts of the city, the material was not well compacted. Failure may therefore be in part due to settlement resulting from compaction. It is also quite probable that water from the Miraflores Terrace Gravel seeps into the fill and contributes to failure.

Settlement over Fill Areas

Without a good record of the construction history of the city, it is difficult, in some places, to determine what material is man made fill and what is not. By referring to older maps and talking with engineers of the Municipalidad and residents, it has been possible to isolate some of the filled areas.

If material placed as a fill is not carefully compacted, it will settle with the laps of time. Where structure such as a house is contructed on fill and settlement is uniform, the structure will not be affected, though service facilities leading to it may be severed. Failure of structures on fill usually ocurrs because settlement in one part of the fill is greater than in another part.

Another cause for failure is that part of the structure has foundation on fill which settles and another part has foundation on bedrock which does not settle.

Problems of failure arising from settlement of fill material can best be averted by compacting the material carefully when the material is placed. This, of course, is of no help to the homeowner whose house is failing. Such existing problems can only be answered by investigating each failure area and, on the basis of the findings, follow specific recommendations. From previous experience, it might also be added, that, correcting failures over deep fill areas are expensive. There is no easy or cheap method.

Mud Flows

Aside from stating that mud flows occur during the latter part of a rainy season there is, in this area, no good way of predicting in which year they will take place and in what valley. Along certain stretches of the Bolivian R.R. (8) mud flows have been studied in some detail. Methods for protecting the railroad have been devised. For almost every mud flow the method is one whereby the flow is diverted rather than stopped.

On the basis of existing knowledge the best procedure to be followed in city planning is to avoid construction in areas where mud flows occur. Such areas where construction should be avoided are in stream valleys and on alluvial fans below the point of gradient change. The site of the stadium of "Club Strongest" is but one such locality below the brow of the Alto where development should be restricted.

City Planning

Comments on the relationship between city planning and geology are not entirely appropriate for this report. However, they are appended in abbreviated form because so many people have asked for them. More will be said about this subject in the later report dealing with a planning map for the city.

To begin with, one point should be made utterly clear. It is not the function of the geologist to write the terms of zoning regulations. It is within his province to describe the material and terrain in such terms and detail that they are clear to an intelligent and comprehending planning engineer.

Records of geological investigations as an aid to city planning date back to the Middle Ages. These investigations were not dignified by the term geological, but the results they produced were maps and reports that contained much geological information. Today some of the larger cities in Europe and New York in North America have permanent geological staffs. The duties of these geologists are many; among other things they: 1, continually revise and bring up to date geological maps of the city, 2, keep records of excavations and borings, 3, advice about properties of materials, 4, are consulted by planning engineers on zoning as it relates to foundation conditions and requirements.

Some closely related physical factors that must be considered in city planning are geology, topography and water supply. The attached map can provide some of the information needed if it is interpreted. Three major classes of sites are quickly discerned.

These are locations where ground conditions are: 1, favorable for construction, 2, unfavorable for construction, but can be corrected and 3, unfavorable for construction and can not be corrected.

With some qualifications, favorable sites for construction are generally represented by the area of the Miraflores Terrace Gravel, the Pampajsi Terrace Gravel, Gravels of the Altiplano, and for certain kinds of smaller structure, the Milluni Till.

To the class of sites that are unfavorable, but that can be corrected are parts of the areas of some of the landslides and colluvium. Corrective measures that need to be applied are mainly those of draining water from the unstable material and preventing entrance of additional water. Corrective measures of this kind must be applied on a large scale basis rather than by single house or factory site.

The third class of sites that are unfavorable for construction also include parts of landslide and colluvial areas. The topographic factor enters into consideration here because, no matter how good the foundation conditions, construction on slopes with an inclination of more than about sixteen degrees is undesirable.

"Fight with the Rivers"

"My fight with the rivers", was the expression used by one of the engineers of the Municipalidad to explain broadly the many structures he had designed and constructed to control stream erosion. Streams flowing through the city of La Paz are actively cutting down their channels and sapping their banks. As they deepen their channels the valley walls become steeper and are subject to failure. Long ago this process of stream erosion was recognized by the engineer from whose remark the little quotation was taken. Erosion control is being attempted by canalization of segments of the streams' courses and by construction of a series of small check dams.

Canalization of the streams can be quite successfully applied where both sides of the valley have material in situ. Examples of such conditions are found up stream along the Choqueyapu River from Obrajes to the landslide area near the University, and below Obrajes to the confluence of the Choqueyapu and Irpavi Rivers. Canalization will not be effective for very long if it is attempted along parts of the valley where one or both sides of the streams is composed of landslide material. As an example, the landslide west of Obrajes will destroy any unreinforced structure if it again moves as it did in 1945, and it is quite probable that the landslide west of Obrajes will move again.

Satisfactory locations for small check dams are similar to those for canalization. Check dams are being constructed in the rivers that flow through La Paz not only to check the flow of water, but also, by retarding the stream loads in the reservoirs, to build up the flood plain. In the first cycle of construction the top of the downstream dam has about the same altitude as the foundation of the next dam up stream. Over a period of years the height of the dams will be increased. Upon completion, the total height of each dam will be about 6 or 7 meters. A small rise in stream flow fills all the small reservoirs and the streams then flow over their retarded deposits. As the height of the dams is increased, the deposits retained in one reservoir act as a retaining wall in front of the next higher dam.

In the check dam system of control the last dam down stream is the key structure. Should the last dam down stream fail, the ones upstream from it would also fail soom afterward. Failure upstream from the key structure would take place because the deposits contained in the reservoir behind the last dam downstream would quickly be carried away by the stream, thereby eliminating the retaining wall influence of the deposits in front of the next dam upstream. Failure would take place for lack of support of the downstream face of the dam. Also, scour caused by the greater drop, would undermine it from the down stream side. If failure of the key structure should take place early in a long rainy season when it is impossible to make repairs, it is probable that almost all of the dams upstream would also fail.

The hard and well consolidated conglomerate in the Aranjuez constriction is the best location for the key structure. There may, of course, be leakage from the dam at this site, but leakage is of no importance to the purpose of these dams so long as it does not contribute to failure. The key dam is now being constructed in this location.

Deposits held in the lower part of the reservoirs of the check dams might be called dead storage as they will remain, but the upper part of the deposits will be transitory. When the reservoirs have been filled, the load the streams will carry past any given point along the system will be about the same as it was before the structures were placed. This means that clay, silt, sand, gravel and even boulders carried by the water will wear all dam and canal surfaces they contact. Even before the entire system has been completed maintenance of the spillways and the canals will be necessary. To preserve the structures and to keep them functioning properly will require systematic inspection and continual repair of the worn surfaces - truly an incessant "fight with the rivers".

BIBLIOGRAPHY

1. Ahlfeld, Federico, "Reseña Geológica de la Cuenca de La Paz", Instituto Boliviano de Ingeniería de Minas y Geología, May, 1945.

2. Ahlfeld, Federico, "Geología de Bolivia", Univ. of La Plata, Argentina, 1946.

3. Branisá, Leonardo, personnal communications and report in the La Paz, Bolivia newspapers, El Diario and La Nación, Dec. 1, 1954.

4. Hauthal, R., "Reisen in Bolivien und Perú, 1908", Leipzig, 1911.

5. Berry, Edward W., "Sketch of the Geology of Bolivia", Pan American Geological Society, vol. 57, 1934.

6. Conway, A., "Exploring and Climbing in the Bolivian Andes", 1901.

7. Felsch, Johannes, "Reconocimiento Geológico de las Aguas Subterráneas en los Alrededores de La Paz", Junta Impulsora de Aguas Potables de La Paz, 1930.

8. Morum, S.F.W., "The Treatment of Mud-Runs in Bolivia", Institute of Civil Engineering Journal, Vol. 1, No. 3, Jan. 1936.

9. Posnansky, A., Bol. Soc. Geogr. La Paz, 28, 1920, Nos, 51 y 52.

10. Sanjinés, Alfredo G., "La Paz, Síntesis Histórica de la Vida de la Ciudad, 1548 - 1948", Imprentas Asociadas S. Ltda., La Paz, 1948.

11. Troll, C., & Finsterwalder, R., "Die Karten der Cordillera Real und des Talkessels von La Paz (Bolivien) und die Diluvialgeschichte der Zentralen Anden", Petermanns Mitteilungen, 81, 12. Heft, Dezember, 1935.

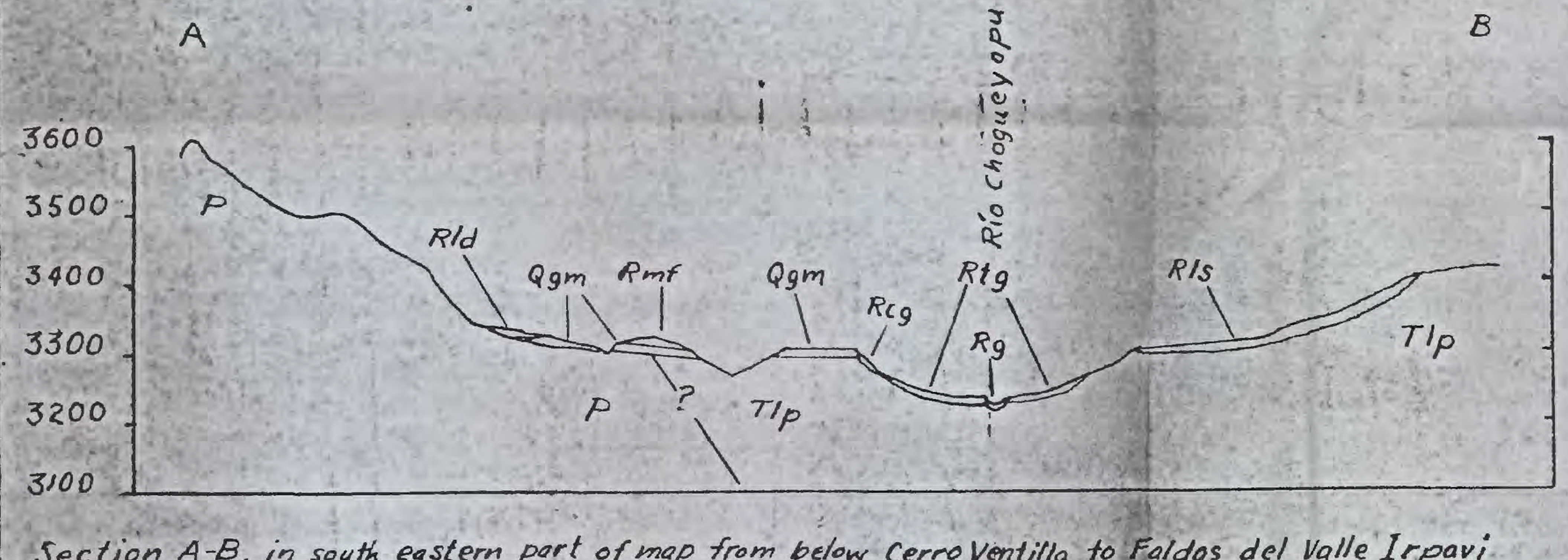
Fig 4

55-42

Section E-F, across north boundary of map

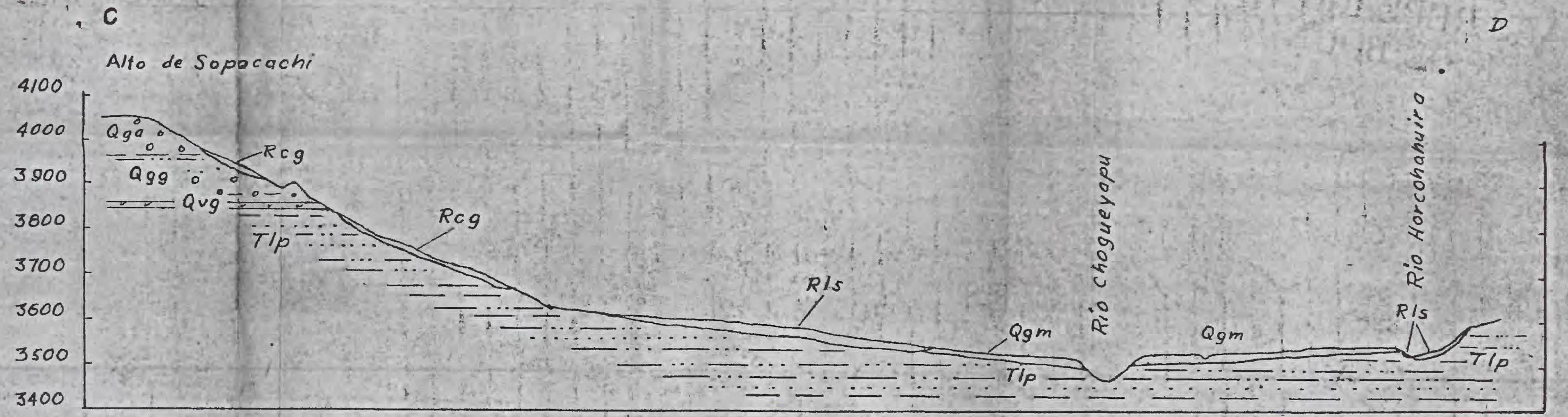
Seccion E-F, a través del límite norte del mapa

U. S. Geological Survey
OPEN FILE REPORT
This map or illustration is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.



Section A-B, in south eastern part of map from below Cerro Ventilla to Faldos del Valle Irpavi

Sección A-B, en la parte sud este del mapa desde abajo del Cerro Ventilla hasta las Faldas del Valle de Irpavi



Section C-D, from Alto de Sopocachi triangulation point through circle on Ave. Arce and across Río Horcohahuira

Seccion C-D, desde el punto de triangulación del Alto de Sopocachi pasando a través del circulo de la Ave. Arce y cruzando el Río Horcohahuira

Note: 1. Cross sections do not coincide in detail with the map because of differential paper shrinkage. 2. Lithology symbols are the same as used on corralation graph. 3. Vertical scale about 1/3 exaggerated

Nota: 1. Las secciones transversales no coinciden en detalle con las del mapa debido a la diferente contracción del papel. 2. Los símbolos litológicos son los mismos que se han usado en la correlación gráfica. 3. La escala vertical es más o menos 1/3 mayor respecto a la horizontal.

Fig. 4. STRUCTURE SECTIONS

Fig. 4. CORTES DE LAS ESTRUCTURAS

Fig 5
55-42

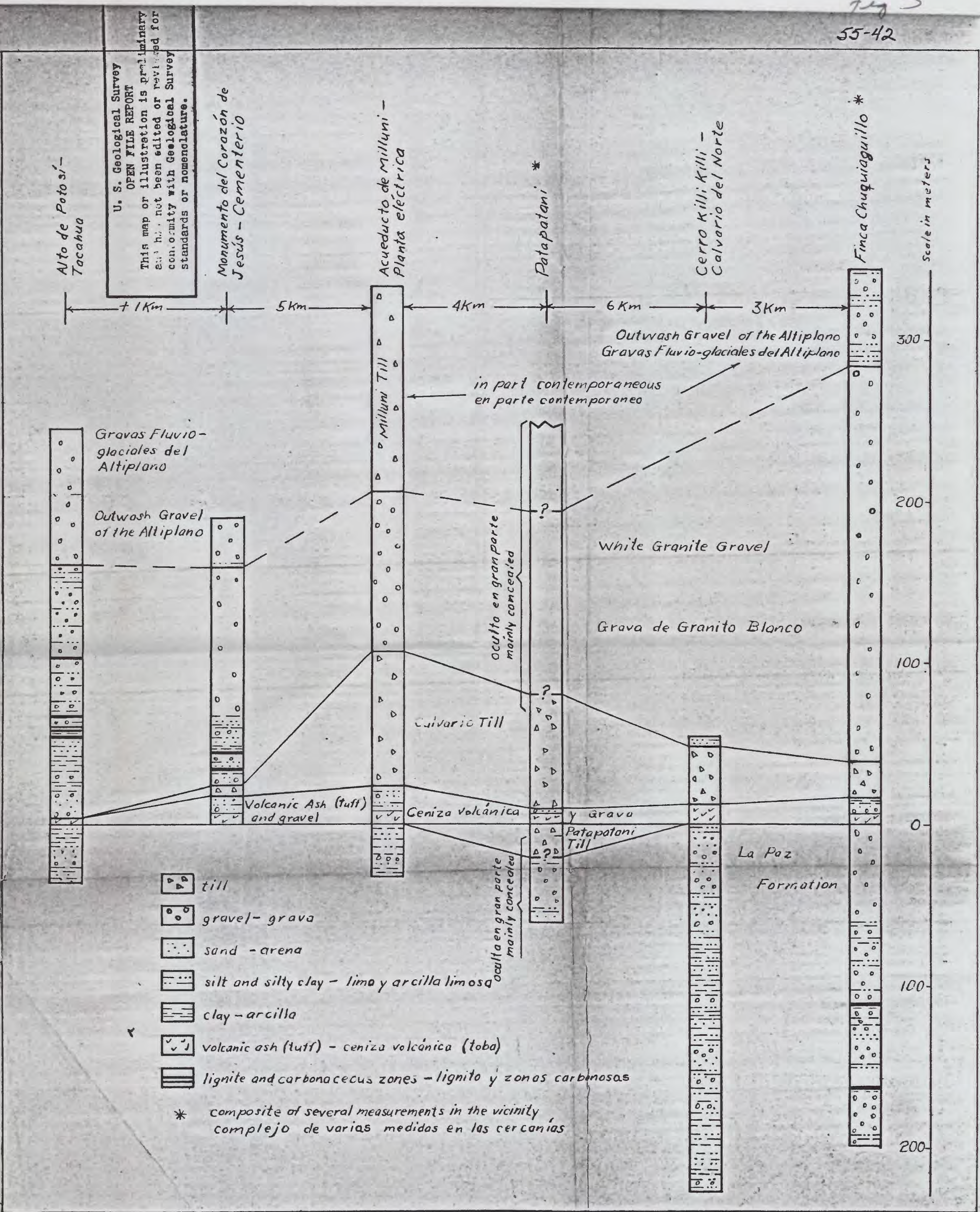


Fig. 5 Correlation of some of the major units in the Upper La Paz Valley
Correlación de algunas unidades mayores en el Valle Superior de La Paz