GEOLOGICAL INVESTIGATIONS AROUND LAKE TITICACA.[1]

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A GEOLOGICAL SURVEY covering some 40,000 sq. kilometers has just been completed by the writer around Lake Titicaca. In addition, a reconnaissance was made along the

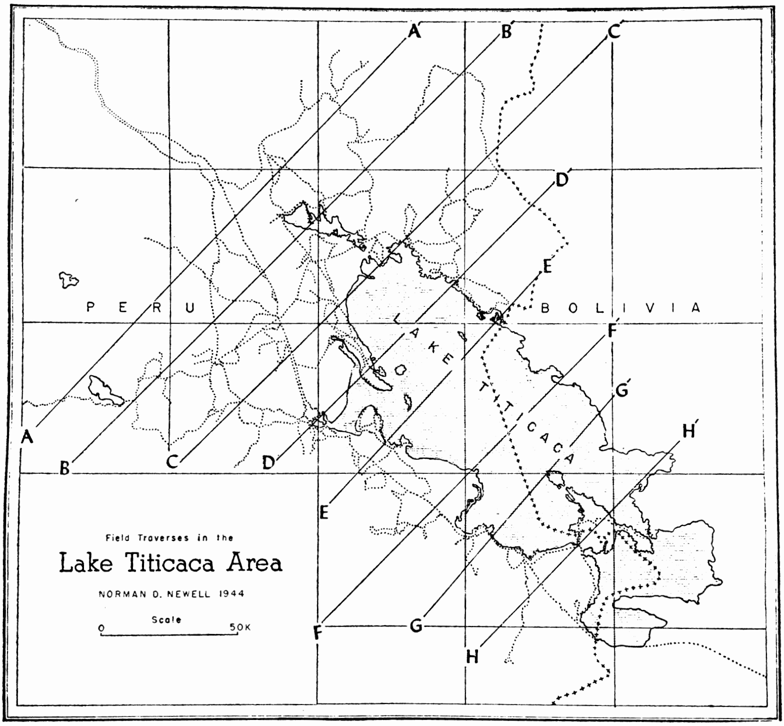

Fig. 1. Field traverses and location of structure sections. Traverse routes are indicated by dotted lines.

route of the Southern Railway, northwestward from Lake Titicaca to Cuzco, Peru. This survey was made for the Departamento de Petroleo, Cuerpo de Ingenieros de Minas, of the Peruvian Ministry of Development (Ministerio de Fomento). A general areal map was prepared at a scale of 1:200,000, and a small area of some 200 sq. kilometers around

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Pirin, northwest of the Lake, was mapped in detail at a scale of 1:10,000. Numerous structural profiles have been prepared, and detailed measurements of stratigraphic sections were made at many places, so that an adequate understanding of the regional stratigraphy might be obtained.

Although most of the work was done in Peru, some observations were also made in the Bolivian part of the Lake basin. Close collaboration with Dr. Federico Ahlfeld, State Geologist of Bolivia, has resulted in a general accord, with respect to geologic problems of the Peruvian-Bolivian frontier.

Stratigraphic Succession, Titicaca.

		Meters
Pleistocene	Outwash, moraines	20
Tertiary system	Río Azángaro clays (deposits of old Lake Ballivián, ancestor of Titicaca)	100
	Sillapaca volcanics: andesite and basalt flows, tuffs, breccias, which form cover of Western Cordillera of the Andes	500
	Angular unconformity: Underlying beds are folded and broken by thrust faults, and are truncated by erosional "Puna" surface of the last general peneplanation of the Central Andes.	
	Tacaza volcanics: Basalt flows and red arkoses below; andesite agglomerates and dacite tuff above	3,600
	Angular unconformity: Extensive overlap of volcanic rocks over older formations.	
	Puno group: Sandstone, red to chocolate, arkosic, and locally tuffaceous, andesite and quartzite conglomerates common, with interbedded chocolate shales (equivalent to Corocoro beds of Bolivia)	7,000
	Angular unconformity: Extensive overlap of Puno group on older rocks.	
Cretaceous system	Muñani formation: Brick-red to reddish-buff arkosic sandstone without volcanic material ..	800
	Vilquechico formation: Dark olive-gray shale, siliceous, with several beds of white quartzite	680
	Cotacucho group: Pink and red massive sandstone overlain and underlain by red, gypsiferous shales; contains persistent sandstone unit of probable eolian origin	1,096
	Disconformity and regional overlap: In the Eastern Cordillera the Cotacucho group rests locally on rocks as old as Devonian.	

		Meters
Pleistocene	Outwash, moraines	20
Cretaceous system	Moho group: Mainly shale; upper part dark olive-gray, with gray quartzite beds, lower part variegated or brick red, containing persistent Ayavacas limestone of marine origin, not far above base	800
	Huancané sandstone: Coarse, light-brown to red, with persistent eolian bed, ranges from 60 to	500
	Muni shale: Dark reddish-brown or maroon shale, with thin, fossiliferous marine limestones	135
	Sipín formation: Limestone, very sandy and shaly, unfossiliferous	20
	Angular unconformity and overlap.	
Jurassic system	Lagunillas group: Dark gray to black shale, dark-gray limestone, and gray quartzite, grades upward into redbeds, entire sequence fossiliferous, marine	1,200
	Angular unconformity.	
Permian system	Copacabana group: Massive gray, cherty limestones interbedded with gray and red shales; at base lies a sequence of dark-gray and black shales of partly non-marine origin; locally a massive, unfossiliferous red sandstone lies at the top (Tiquina sandstone)	800 to 1,800
	Disconformity without angularity	
Devonian system	Cabanillas group: Shale, and minor amounts of quartzite of black to greenish-gray color, basal contact of Devonian unknown	3,000
	Aggregate thickness	20,281 M.

Fossil collections adequate for purposes of age determinations were obtained from the Cabanillas, Copacabana, Lagunillas, Muni, Moho, and Vilquechico divisions.

Stratigraphy.—In spite of the fact that the Titicaca region has been visited by a number of geologists in the past, no extensive geological study has heretofore been attempted. Consequently, it is not surprising that some unanticipated discoveries were made, during the course of the present investigation.

The aggregate thickness of the sedimentary section is enormous, more than 20,000 meters, exclusive of the nearly unknown sequence of Early Paleozoic (Cambrian, Ordovician, and Silurian) of the area north of Lake Titicaca. Naturally, it is not to be implied that the entire sequence is present at any single locality, because there are many unconformities.

A noteworthy innovation includes discovery of Lower Permian (Wolfcampian-Sakmarian) fusulines[2] in "Upper Carboniferous" rocks at several localities, within the region. Undoubted Pennsylvanian, or Mississippian fossils were not discovered. A thick sequence of fossiliferous marine Jurassic rocks, probably of Late Jurassic age, occurs in an area west of Puno, and near Lake Lagunillas, west of Lake Titicaca.

The most surprising stratigraphic find, however, is an enormous section of Cretaceous rocks ("Middle" and Upper Cretaceous) immediately to the northeast of Lake Titicaca. These rocks, measuring some 3000 meters in thickness, had never been previously examined in detail, and had been classed as Paleozoic by other geologists.

According to Ahlfeld (personal communication), the basal sandstone of the "Puca" red-beds terrain of Bolivia correlates with the uppermost division, Muñani sandstone, of the Titicaca region. According to this correlation most of the Cretaceous section of Titicaca is older than the much-discussed Puca beds of central Bolivia and northern Argentina.

The enigmatic sequence of unfossiliferous red sandstones and shales noted by all previous geologists to the northwest, west, and southwest of the Lake are found to be equivalent to the Tertiary Corocoro group of Bolivia. In Peru these beds, the Puno group, attain an astonishing thickness of 7000 meters. They had been classed by various writers as Permian, Jurassic, Cretaceous, and Tertiary. The relationship between the Puno group and the Puca beds of Bolivia is not clear. The two are lithologically unlike, but are in all probability partial equivalents.

Two series of volcanic extrusive rocks cover the high plateau surface of the western cordillera, southwest of Lake Titicaca. These are: a thick sequence of older, folded and faulted rocks, the Tacaza formation, and a younger group of horizontal volcanics, the Sillapaca formation (names suggested by Dr. Wm. F. Jenks, University of Arequipa). The great volcanic cones of the western cordillera, such as those at Arequipa, belong to the last great phase of volcanism responsible for the Sillapaca volcanics.

[2] Dunbar, Carl O., and Newell, N. D.: 1945, Early Permian Rocks of southern Peru and Bolivia. Amer. Jour. Sci., 243, p. 218.

Structural geology.—Of significance in the understanding of Central Andean geology is the discovery of extensive over-

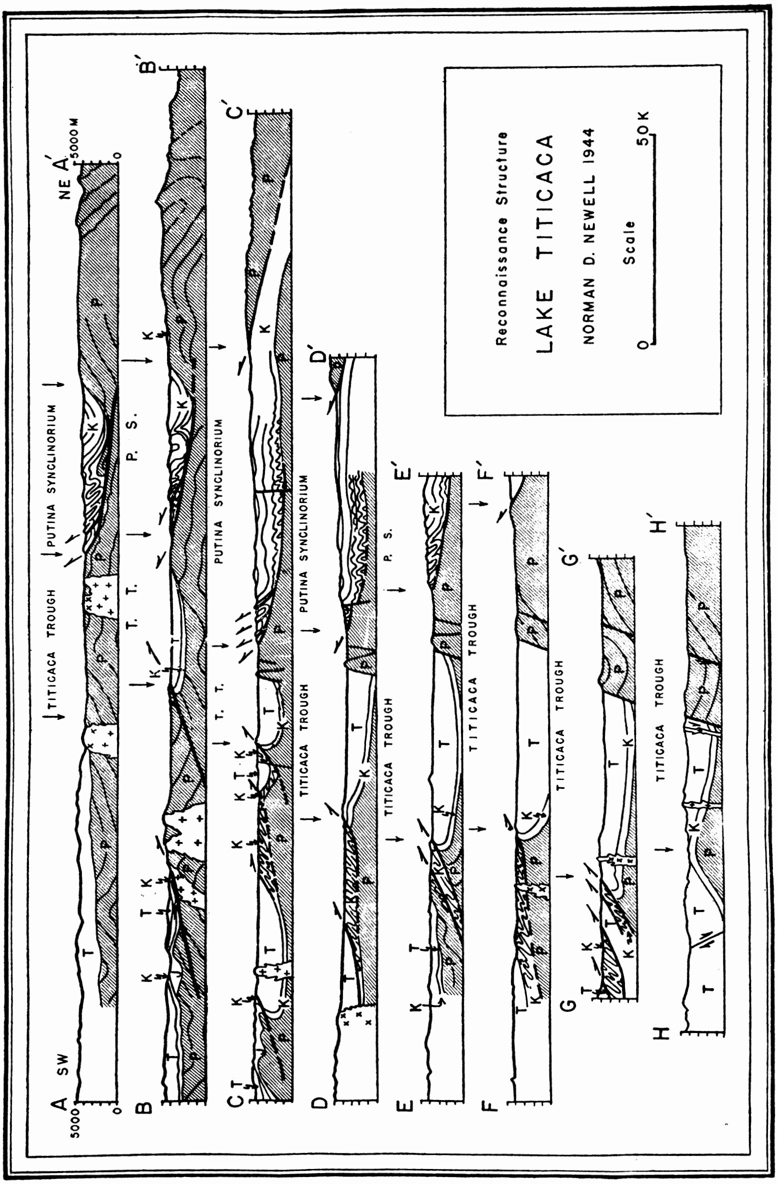

Fig. 2. Structure sections. P, Paleozoic; J, Jurassic; K, Cretaceous; T, Tertiary and Quaternary.

thrusting on both sides of Lake Titicaca. Although large-scale overthrusts have not been generally recognized in the

Central Andes, the evidence is overwhelming that the basin of Lake Titicaca lies between two opposed sets of overthrusts. Compression was directed toward the axis of the Lake, that is, from the northeast and from the southwest. Not only is the evidence for these opposing movements expressed in overthrust faults, but also in very common overturned and recumbent folds, in which the axial planes commonly dip away from the axis of the basin at angles of 45 degrees and less.

An interesting feature of the tectonics of the region is the great difference in structural competency of the Devonian as compared with the "Middle" Cretaceous (Moho formation), which generally overlies the Devonian in thrust-fault relationship. Because of the occurrence of soft shales, gypsum, and locally some salt, in the Cretaceous, thrusting has been localized along, or near the upper surface of the resistent Devonian rocks. Consequently the Cretaceous rocks are highly folded and faulted, in extreme disorder, often with extensive development of overturned isoclinal folds, having been pushed along the top of competent Devonian beds which reveal relatively simple structure.

Five major thrust zones and several local thrusts have been recognized and mapped. Others will no doubt be discovered whenever more detailed investigations are made. These are: 1) Suches thrust, in the vicinity of Cojata, where Devonian rocks are pushed southwestward over Upper Cretaceous rocks. Near the international boundary with Bolivia the trace of the thrust disappears beneath Pleistocene deposits of the Suches river. According to discussions with Ahlfeld it appears quite possible that the Aplobamba fault continues to the southeastward along the front of the Cordillera de Muñecas and the Cordillera Real, in Bolivia. 2) The Azangaro thrust was mapped for more than 100 Km. from the vicinity of the village of Azangaro, along the northeast shore of Lake Titicaca to Conima and Puerto Acosta. Here, "Middle" Cretaceous rocks, in highly disordered state are shoved to the southwestward over Devonian rocks of simple structure. The Cretaceous rocks are thrown into persistent isoclinal folds near the trace of the fault zone. 3) Pirin-Juli thrust, extending from Pirin, at the northwest end of the Lake, along the southwest shore to a point beyond Juli. The fault originates near Pirin, where it is a high-angle thrust, but it changes a short distance to the southeast to a very flat thrust of 25 to 35 degrees, and the Cretaceous section is clearly pushed over Tertiary rocks (Puno), which have been completely overturned in the process. 4) The Sara thrust, north of Juliaca, is clearly

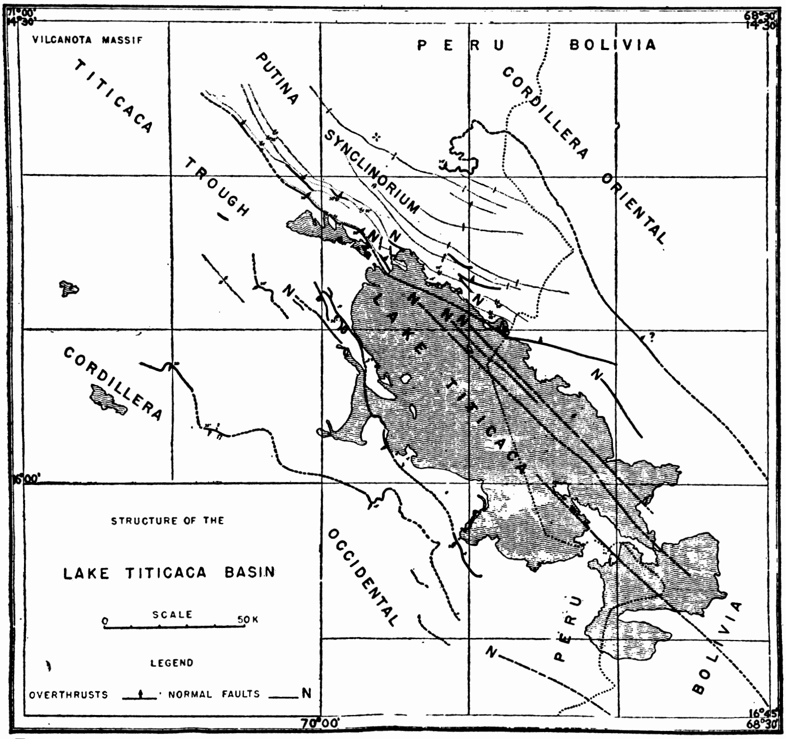

Fig. 3. Main structural elements in the Titicaca region.

exposed along the Juliaca-Cuzco railway. Devonian rocks are thrust toward the northeast over Tertiary rocks for a distance of 10 Km. or more along the strike. 5) In the Maravillas-Acora thrust belt a variety of structural relationships are found. Near Maravillas, on the Arequipa-Juliaca railway, "Middle" Cretaceous rocks, in greatly disordered state, are thrust northeastward over comparatively simple Jurassic and Devonian, locally causing a structural overlap of the former. Near Mañazo, west of the city of Puno, badly crushed "Middle" Cretaceous and Jurassic rocks are shoved over overturned Tertiary red-beds (Puno). Near Acora, southwest of Puno, "Middle" Cretaceous rocks (Moho group) in highly deformed and broken condition have been pushed over Devonian rocks of relatively simple structure. Here the indicated movement was from the southwest.

In the hills immediately to the west of Pirin, northwest of the Lake, large complex recumbent folds, in which the overturned beds are essentially horizontal over great areas, are observable over more than 100 sq. kilometers.

The present topographic basin, now occupied by Titicaca, appears to be the end result of block faulting and stream erosion. Studies of the configuration of the Lake floor, from existing bathymetric maps, considered together with the surface geology, suggests that a high angle fault bisects the Lake along a northwest-southeast axis, into two approximately equal parts (Copacabana fault), bringing Devonian and Tertiary rocks in contact along the fault. Apparently this fault does not extend the full length of the Lake, because it is not recognized at the northwest end. Another fault, recognized at the Strait of Tiquina, probably passes northwestward under the Lake, since it is aligned with a southwestward-facing escarpment on the floor of the Lake. The islands of Campanario and Soto are surface expressions of this fault scarp.

The great depth of the Lake in front of the submerged scarp, 281 meters, as compared with the shallow depth to bedrock, 40 meters in the drowned gorge at the Strait of Tiquina, outlet for the Lake, suggests very recent faulting on the floor of the Lake. Had the faulting and subsidence of the lake-floor, along the northeast margin, been accomplished before the Pleistocene, the precipitous topography along the fault scarps should have been somewhat buried in lake sediments. Extensive erosion of Pliocene(?), nearly horizontal lake clays around the Lake indicates comparatively recent subsidence of the Lake level by more than 100 meters, and subsequent transportation of several cubic kilometers of these clays to the deeper part of the Lake.

History.—Although there is a great hiatus between the Devonian and Lower Permian, the contact is remarkably plane, and, in the area studied, without recognized angularity. The oldest observed discordance is found between Devonian and Jurassic rocks. Possibly the inferred orogeny occurred at, or near the close of the Paleozoic. A profound northeastward overlap of "Middle" Cretaceous (Aptian-Albian) over older rocks, down to the Devonian, indicates important orogenic movements prior to Middle Cretaceous time. That this orogeny may mave occurred at the close of Neocomian time is suggested by the fact that Neocomian and Upper Jurassic rocks are parallel in the nearby area of Arequipa. Neocomian rocks are entirely absent in the Titicaca region. In the middle of the Cretaceous section, presumably at the base of the Upper Cretaceous (Cotacucho group) there is a marked overlap towards the old massif of the eastern cordillera. In short distances the "Middle" Cretaceous sequence is completely truncated by Upper Cretaceous rocks. Angular unconformities and regional overlaps occur at the base of the Tertiary (Puno group) and at the base of the Tacaza group, but the last and most severe orogeny occurred after deposition of the Tacaza volcanics. The great thrusts of the region cut the Tacaza volcanics in a number of localities. Following this orogeny the entire region was peneplaned, producing the "post-mature" surface, or Puna surface, so conspicuous in Peru and Bolivia. Later volcanic rocks have been deposited over this old peneplain.

The dating of the various events of Tertiary history of the region is very difficult. Presumably, the Puno group embraces much of the Tertiary. Floras from Puno equivalents (Corocoro series) in Bolivia indicate that part of the group is of late Tertiary age (Pliocene). Nothing is known of the age of the Tacaza and Sillapaca volcanics, except that they are younger than the Puno group. The great volcanos of the Arequipa region are scored by cirques of vanished glaciers, so that presumably much of the Sillapaca formation was deposited before the close of the Pleistocene. Post-Pleistocene volcanism has also added its quota to the Sillapaca volcanics.

Most of the igneous activity of the region, intrusive as well as extrusive, occurred during the Tertiary, the types represented being chiefly diorite, dacite, trachyte, andesite, and basalt, with very minor amounts of more acid types. The majority of intrusives are hypobyssal, and judging from the field relations appear to be deeply eroded stocks and volcanic necks, probably associated with the Tacaza stage of volcanism.

Underlying a thin mantle of glacial outwash, and therefore older than the last stage of the Pleistocene, are extensive deposits of nearly horizontal lake clays rising topographically more than 100 meters above the present surface of Lake Titicaca. These beds are best shown west and north of Lake Arapa, along the Río Azángaro. They are interpreted as relics of the ancestral lake (Lake Ballivián). Together with elevated marks of wave erosion, they indicate a former level of the Lake somewhat above the 3900 meter contour.

Glaciation had no part in the formation of the basin of Lake Titicaca. Terminal moraines and cirques of small size are first encountered about 200 meters above the Lake, on the northeast side of the basin, and considerably higher on the southwest side. Even outwash deposits generally do not reach the shore of the present Lake, although they do reach the probable shore position of ancestral Ballivián. For a long time, probably since the Pleistocene the Lake has stood near its present level, as shown by a well defined strand line no more than 8 meters above the lake surface. Fluctuations of the Lake level, correlated with local precipitation, have reached a maximum of 3 meters within the past 15 years.

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