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New data on Tectonics of Bolivian Andes from a photograph by Gemini 5, and field knowledges

by Luigi RADELLI

To my children, who will fly among the planets.

ABSTRACT : A photograph taken by Gemini 5 shows many of the basic geomorphologic units of Bolivian Andes, which are : the Western volcanic Cordillera; the Altiplano with the lakes of Titikaka and Poopo, and the Salt lakes of Uyuni and Coipasa; the Huayllamarca Range; the Eastern Cordilleras, including Cordillera Real; and the Sub Andean Zone. The whole of Bolivian Andes is cut by several tectonic lines, either parallel or transverse to the geographic trend of the mountain ranges, some ones of which were revealed first by the photograph taken from Gemini 5. The tectonic lines (Coniri, Ichilo-Achacachi, Poopo, Palca, Chacarilla, and Chiriquina) correspond to faults which were active ever since Paleozoic. Their existence is proved by precise both stratigraphic and tectonic remarks within the blocks separated by themselves. Of those, the Poopo Line crosses the Andean geographic trend; the Ichilo-Achacachi one does also that between the town of Santa Cruz on the East and the Cordillera Real on the West, but then it becomes parallel to this trend. The other ones are always parallel to it. Mutual movements of Andean blocks separated by the indicated intersecting faults occurred during geologic time are studied since Silurian, and they are summarized at § 18. Special attention is paid to both Hercynian and Nevadian tectonic movements. With regard to Bolivian Andes, the conclusion is attained that one Hercynian cordillera existed Eastwards of the actual Altiplano, another Westwards of it, and a minor third one in place of Altiplano itself, Eastwards of the actual Huayllamarca Range. The second one seems to have been engulfed, South of Poopo Line, during Nevadian tectonism, and North of that probably only during Miocene (or Pliocene), as well as the third one. The relationships between those blocks and the actual tectonics of Bolivian Andes are discussed. The tectonic features of each region have the same trend and the same bend of the nearest of the faults Coniri, Achacachi, Chacarilla, Chiriquina, and of those which limit the Sub Andean Zone. The tectonic outline of the cordilleras depends on vertical movements, along normal distensional faults, which in process of time can be bent towards sagging contiguous regions, to originate some overthrust, but it does not on external pressures. The resulting tectonic style is quite similar to that of the composite wedges suggested by C. Migliorini for the Apennines. The raising of such structures on the other hand originates pressures on neighbouring, gently raised, regions, where classic tectonic patterns (true folds) are recognizable.

RÉSUMÉ : Une photo prise de Gemini 5 montre la plupart des principales unités géomorphologiques des Andes Boliviennes, qui sont : la Cordillère occidentale, volcanique; l'Altiplano avec les lacs Titikaka et Poopo et les lacs salés d'Uyuni et de Coipasa; la Cordillère de Huayllamarca; les Cordillères Orientales desquelles fait partie la Cordillère Royale; et le Sub Andin.

Le système andin bolivien est recoupé par un certain nombre de lignes tectoniques, soit parallèles soit transversales par rapport à l'élongation de la chaîne, dont certaines ont été reconnues pour la première fois grâce à la photo prise de Gemini 5. Ces lignes tectoniques (Coniri, Ichilo-Achacachi, Poopo, Palca, Chacarilla, Chiriquina, et celles qui séparent le Sub Andin) correspondent à des failles, qui ont été actives à partir du Paléozoïque. Leur existence est prouvée par des observations précises sur la stratigraphie et la tectonique des blocs qu'elles séparent. De ces lignes tectoniques, celle du Poopo est transversale par rapport à la direction géographique de la chaîne; celle d'Ichilo-Achacachi l'est aussi entre la ville de Santa Cruz à l'E et la Cordillère Royale à l'W, mais ensuite elle devient parallèle à cette direction. Les autres lui sont toujours parallèles. Les mouvements mutuels des blocs andins séparés par le croisement de ces failles dans le temps géologique ont été étudiés à partir du Gothlandien, et ont été résumés au § 18. Les mouvements orogéniques hercyniens et névadiens ont fait l'objet d'une étude plus particulière. Pour ce qu'il en est des Andes boliviennes, il semble qu'une première cordillère hercynienne existait à l'E de l'Altiplano actuel, une deuxième à l'W, et une troisième à la place de celui-ci à l'E de l'actuelle Cordillère de Huayllamarca. Il semble que la deuxième ait disparu, au S de la Ligne du Poopo, au cours des mouvements névadiens, mais au N de cette ligne, seulement au Miocène (ou au Pliocène), en même temps que la troisième. Les relations entre les blocs et la tectonique actuelle des Andes boliviennes ont été aussi étudiées. Les lignes directrices tectoniques de chaque région présentent la même direction et les mêmes sinuosités de la plus proche des failles Coniri, Achacachi, Chacarilla, Chiriquina, et de celles qui limitent le Sub Andin. La configuration tectonique des cordillères dépend de mouvements verticaux le long de failles normales de distension, lesquelles par la suite peuvent être voûtées, jusqu'à donner des recouvrements, vers des compartiments voisins affaissés, mais sans intervention de pressions tangentielles externes. Le style tectonique résultant est semblable en tout à celui des « cunei composti » qui a été décrit par C. Migliorini dans les Apennins. Le soulèvement de ces structures donne lieu d'autre part à des pressions dans les zones voisines moins élevées, où se forment de véritables plis.

RIASSUNTO : Una fotografia presa da Gemini 5 mostra una gran parte delle principali unità geomorfologiche delle Ande boliviane, che sono : la Cordigliera occidentale con i suoi vulcani; l'Altopiano con i laghi Titikaka e Poopo ed i laghi salati di Uyuni e Coipasa; le Cordigliere orientali, tra cui la Cordigliera Reale; il Sub Andino. L'intero sistema andino boliviano è intersecato da un certo numero di linee tettoniche, parallele e trasversali alla catena, alcune delle quali rivelate per la prima volta dalla fotografia presa da Gemini 5. Dette linee tettoniche (Coniri, Ichilo-Achacachi, Poopo, Palca, Chacarilla, Chiriquina, oltre a quelle che separano il Sub Andino dalle Ande propriamente dette) corrispondono a delle faglie in parte profonde in parte affioranti, alcune delle quali furono attive fin dal Paleozoico. La loro esistenza è documentata da precise osservazioni stratigrafiche e di stile tettoniche nei diversi blocchi che esse con il loro incrociarsi individuano. Di esse, la linea Ichilo-Achacachi è trasversale alla catena tra la città di Santa Cruz e la Cordigliera Reale, quindi le diviene parallela; la Poopo è trasversale, le altre sono parallele all'allungamento della catena. I movimenti relativi dei diversi blocchi andini boliviani durante il tempo geologico sono studiati a partire dal Gotlandico, e sono riassunti al § 18. Particolare interesse è posto nello studio dei movimenti ercinici e nevadici. Per quanto riguarda le Ande boliviane, si conclude che una prima cordigliera ercinica esisteva all'E dell'attuale Altopiano, una seconda all'W, ed una terza minore al posto di questi all'E dell'attuale cordigliera di Huayllamarca. La seconda sembra essersi inabissata, al Sud della Linea del Poopo, durante i movimenti nevadici, ed al Nord di questa solo al Miocene (o al Pliocene) assieme alla terza. Si discutono le relazioni tra i blocchi e la tettonica attuale delle Ande boliviane. Le linee tettoniche principali di ciascuna regione hanno direzione parallela a quella della più prossima delle faglie Coniri, Achacachi, Chacarilla, Chiriquina e di quelle che delimitano il Sub Andino; e ne seguono le sinuosità. La configurazione tettonica delle cordigliere dipende da movimenti verticali lungo faglie normali di distensione, che possono in seguito flettersi verso zone contigue abbassate, dando luogo anche a dei ricoprimenti, ma non da pressioni esterne orientate. Lo stile risultante è in tutto simile a quello dei cunei composti del Migliorini. Il sollevamento di queste strutture induce delle pressioni nelle zone limitrofe più basse, dove si sviluppa una classica tettonica a pieghe.

§ 1. — The mission of Gemini 5 (NASA) was photographing large areas of the earth's surface. Many of these photographs were published by the popular press. The present note on the geology of the Bolivian Andes is based upon one of these photographs (fig. 1). Because of my extensive field work in this part of Bolivia, I was able to recognize in this photograph some important known and also some previously unknown geologic features. I realized that some of these features could help me improve my knowledge of the overall geology and of the basic tectonics of the Bolivian Andes. Through USIS, Paris, Nasa provided me with original photographs. I thank both NASA and USIS for their courtesy. I think that the study of this kind of photographs will be useful not only in providing more objective knowledge of the geology of the earth, but also to enable us to understand the future photographs of planets. I have written this note in order to prove these assumptions, and also to continue to collaborate with the friends I have in Bolivia.

§ 2. — Figure 1 shows the principal geomorphologic units of the northern and central Bolivian Andes. These are, from left to right : the Western Cordillera, the Altiplano or Puna, and the Eastern Cordilleras. In the Altiplano Lake Titikaka, Lake Poopo, the Salt Lakes or Salares, and the Huayllamarca Range are shown. Between the Eastern Cordilleras, the Cordillera Real and the Cordillera of Quimsa Cruz can easily be recognized by their snowy peaks. The picture does not include the Sub Andean Zone or foot-hills zone which divides the Andes from the Eastern Plains (Llanos Orientales). The unit of the Western Cordillera, chiefly constituted by Cenozoic volcanics, corresponds to a defined geological one, but the other geomorphologic units do not coincide with the main geological and geotectonic units of the Bolivian Andes.

§ 3. — The existence of some geotectonic units was indicated previously (L. Radelli, 1964) on a stratigraphical and tectonic style basis only. A study of the NASA photograph of the Bolivian Andes confirms the attempted conclusions. This study, associated with field knowledge, enables us to give more exact details on the extension, geological history, and evolution of each part of the Bolivian Andes.

The picture shows two still unknown tectonic features (fig. 2 and 3). The first of these is a line which crosses the country with a nearly NE-SW trend North of Lake Poopo, that I call Poopo Line. The following pages of this report will demonstrate that this line corresponds to a dip screen between two different geologic blocks. The second unknown feature is a NW-SE fault (Achacachi Fault) which is recognizable from Lake Titikaka to the valley between the Illimani and the Mururata peaks of Cordillera Real. This fault seems to prolong the Ichilo Fault Zone suggested and discussed by E. Rod (1960), which would cross the country first with a E-W trend, North of both the towns of Cochabamba and Santa Cruz and which would have produced, on the East, the NW-SE Chiquitos Graben. The nature of both Poopo Line and Ichilo Line will be discussed later.

The Sub Andean Zone is divided from the Andes by a fault zone, as indicated in the geological map of Bolivia by F. Ahlfeld (1960).

The western boundary of the Cordillera Real is an important fault (Palca Fault), which is demonstrated by a number of reverse strata and overthrusts. The NASA photograph indicates that this fault continues on the South along the western border of the Cordillera of Quimsa Cruz.

The eastern boundary of the Cordillera Real is a recognizable fault zone only East of Ancohuma-Illampu Massif, where the overthrusts of Candelaria and Yani were discovered by myself. Elsewhere the crystalline rocks of the Cordillera Real disappear gradually under the sedimentary beds of the Yungas region. The line drawn in the photograph (fig. 2) on the East of both Real and Quimsa Cruz Cordilleras indicates the approximate boundary between the metamorphic rocks of these Cordilleras and the sedimentary rocks of Yungas.

A very important fault has been followed by both geological and geophysical work in the Altiplano. That is the Coniri Fault, which is believed to continue both North- and South-wards (Peru, Argentina). In the northern part of Bolivia, approaching of the Lake Titikaka region, two other faults, which quickly take a NW-SE trend, branch out from the Coniri Fault. They are indicated here by geomorphologic features, which are recognizable also in the NASA photograph.

West of the Coniri Fault, is the Chacarilla Fault. This is a low angle reverse fault, which moved

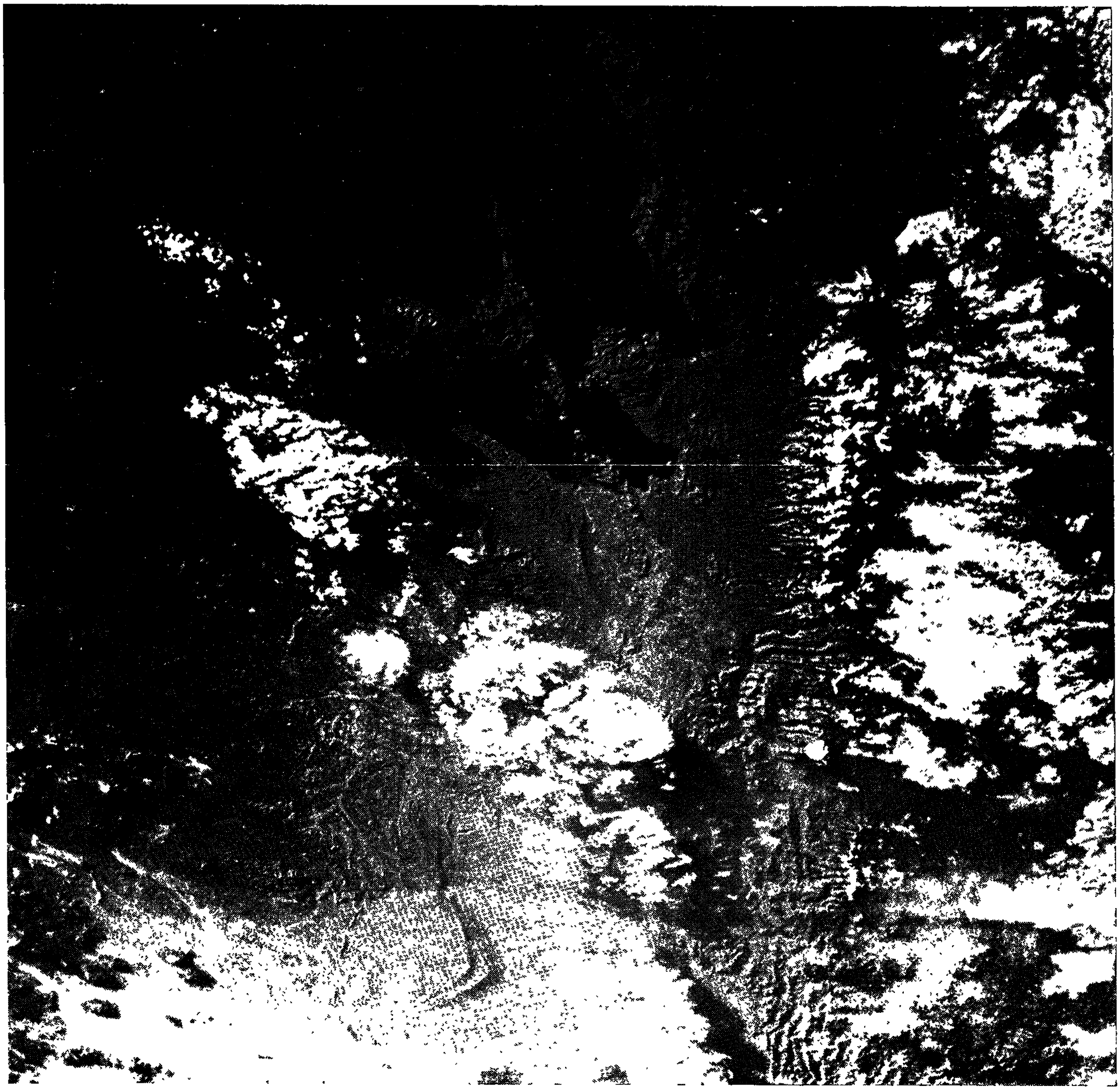

Fig. 1. — NASA view of central and northern Bolivia (for scale see fig. 2).

(Photo USIS)

beds from West to East (P. LJUNGGREN and H. MEYER, 1964). Along it numerous gypsiferous diapiric domes have been formed. This fault is also recognizable on the NASA photograph, because it lifts, on the East, the Huayllamarca Range. On the western border of this Range, there is another reverse fault, the Chiriquiña Fault, which moved beds from East to West.

These intersecting faults divide the country into a patch-work pattern, each part of which is indicated in figure 3 by a letter (A, B...) and in this text as block A (= $A_1 + A_2$), B, C... Letter a

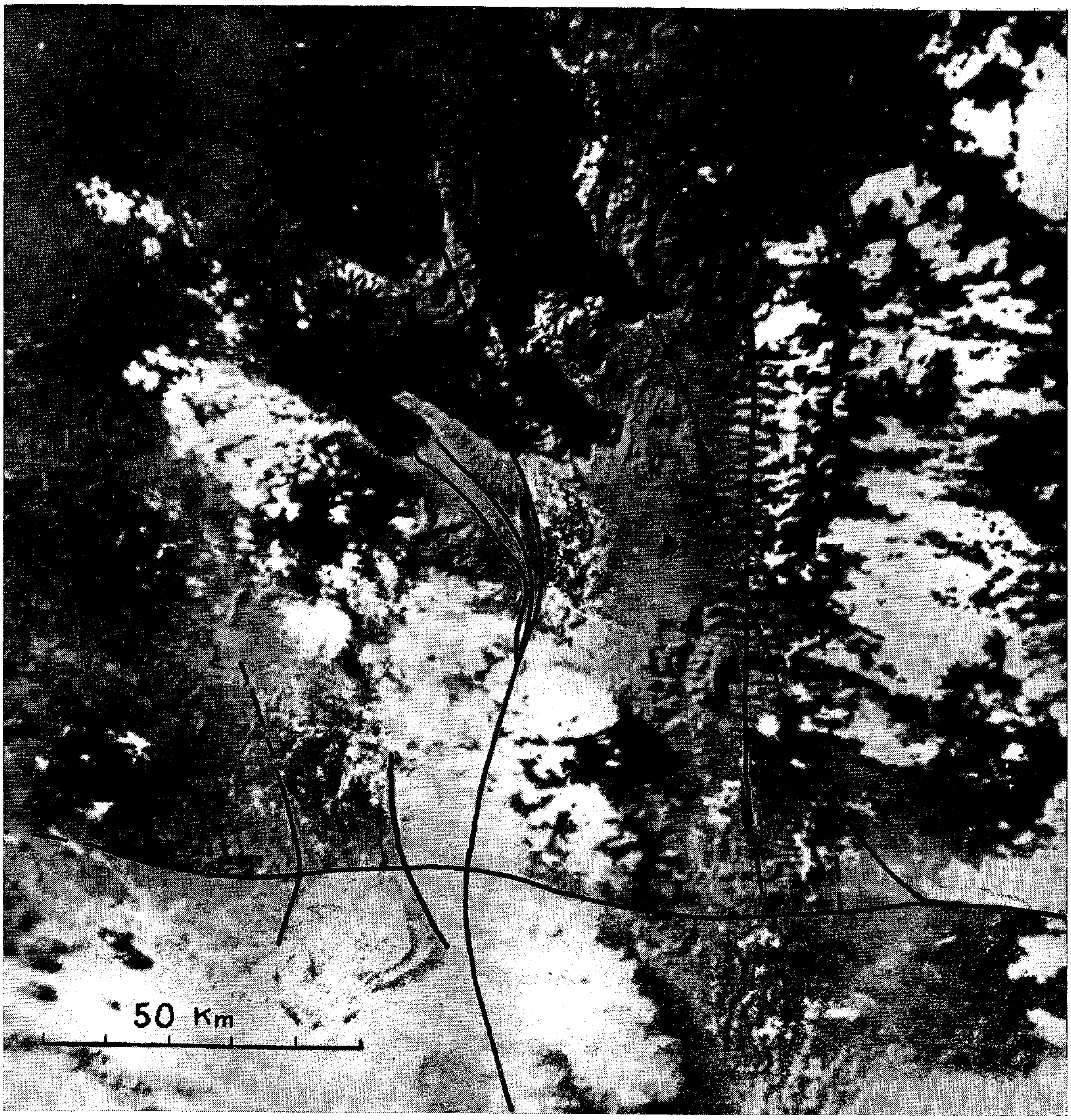

Fig. 2. — Tectonic boundaries and main faults of northern central Bolivian Andes (for their names and precise location see fig. 3).

(*Photo USIS*)

indicates the Huayllamarca Range of block A (A_1 + A_2), and letter h another minor part of block A, which has an independent history.

In the following pages I will demonstrate that each block differs from the other ones in geological constitution and history, and that mutual movements of these blocks can be recognized.

§ 4. — In blocks B (C?), D, and F the Silurian (Gothlandian) begins with the Zapla Formation. That consists of a fine groundmass of massive

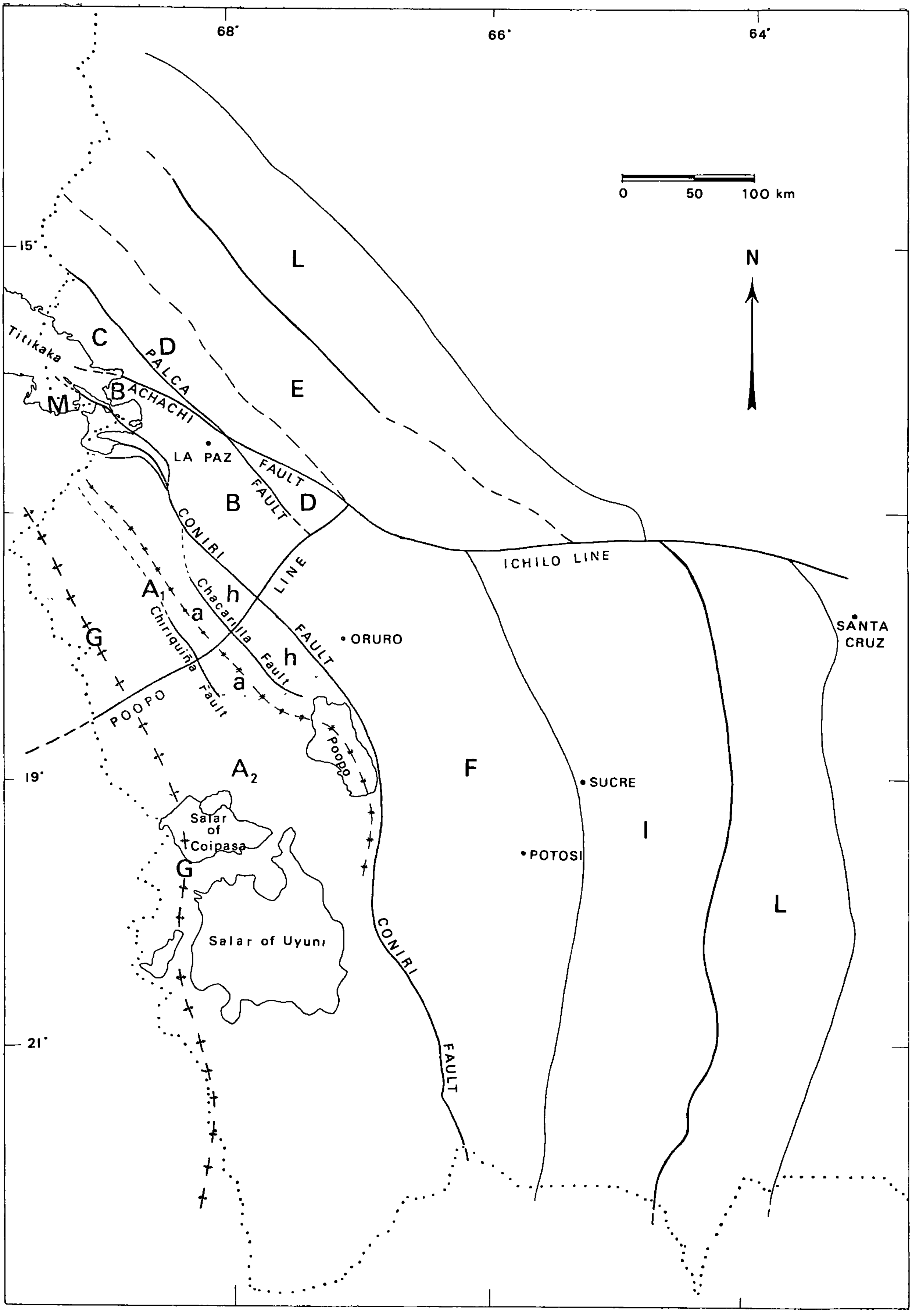

Fig. 3. — The main blocks and their tectonic boundaries of Bolivian Andes
(supposed axis of G block is also indicated, as well as the axis of Poopo-Huayllamarca synclinorium).

black graywacke, which contains pebbles to small granules of granite, gneiss, quartzite, and particularly of quartz. Because several pebbles are striated, Bolivian geologists believe that the Zapla Formation is a marine tillite. I do not completely accept this hypothesis. I think that the presence in it of striated pebbles is not sufficient to conclude that a formation is a tillite : « striated pebbles » are well known also in formations which were deposited during tropical climatic conditions. The thickness of the Zapla varies quickly especially across its tectonics trends (axes of folds). Very rare fossils are recorded in it, and that is not in accord with our knowledge of the actual cold seas, where a wide spread life occurs. So that I think that Zapla Formation was most probably deposited by turbidity currents, to which the terrigenous materials could have been supplied by glaciers. Anyway, stratigraphic and microtectonic studies enabled H. H. LOHMANN (1961, 1964) to recognize that Zapla was deposited in blocks B, (C?), D, and F from the West ; and in the southern part of block F (outside the region represented in the NASA view) from the South also. There is no Zapla on the West of the Coniri Fault, but it outcrops widely on the East of it. Consequently, during at least the Lower Silurian, block A (A_1 + A_2) must be considered as a continental (glaciated) land (Zapla Land), where granites and metamorphic rocks were cropping out ; and the Coniri Fault (its paleogeographic boundary) as a very old fault which at this time raised block A.

§ 5. — Devonian rocks do not exist in block F, which corresponds to the Proto Puna of BONARELLI (1921). I indicated previously (L. RADELLI, 1964, p. 845, fig. 3) the Bolivian boundaries of this block, which continues in Argentina (fig. 3). The then suggested northern limit coincides exactly with the Poopo Line shown by the NASA photograph.

On the contrary, Devonian marine rocks are widely represented in blocks A_2, B, C, and perhaps in block E. Consequently, block F can be considered as a raised, and probably continental, region, during Devonian time. Its western boundary coincides with the southern part of the Coniri Fault, as its northern one does with the Poopo Line. That seems to indicate clearly that during Devonian time block F was raised along them.

But North-wards of the Poopo Line the movements occurred in the opposite way. That is, block A_1 remained raised, and block B moved down. In fact, the Devonian of block B near the Coniri Fault is constituted (R. ASCARRUNZ and L. RADELLI, 1964) by quartzitic sandstones (Aigachi Formation), which are cropping out immediately South of the Lake Titikaka (Cumana Syncline).

§ 6. — Carboniferous is represented by continental rocks, often of a Gondwana facies. Excluding Sub Andean Zone, these are found only in the western border of block B, near the Coniri Fault (Vilaque, Island of Cumana, and Copacabana Peninsula), and East and North of block F (Zudañez, Challhuani, and Comarapa). In block B Carboniferous rocks are generally arkosic sandstones with fossil plants (Kasa Formation, R. ASCARRUNZ and L. RADELLI, 1964), but in the Island of Cumana the Carboniferous begins with the Cumana Formation, which probably consists of deltaic graded hematitic sandstones, shales, and conglomerates (R. ASCARRUNZ and L. RADELLI, 1964). As indicated previously by H. H. LOHMANN (1964), the Carboniferous rocks were deposited in block B from the West, that is from block A_1 ; and those around (North and East) block F from this block itself. There were not very important tectonic changes during this time ; the depositional areas passed from a marine to a continental environment, but the already formed blocks continued to move in the same way as during Devonian time.

§ 7. — During Lower Permian new mutual movements of the indicated blocks cannot be recognized. Fossiliferous limestones of the Copacabana Group (N. D. NEWELL, 1949), Wolfcampian in age, have been found, with nearly same both litho- and biofacies, North-, North-East-, and South-East-wards of the Coniri Fault, except in block F. Several both arkosic, and chloritic sandstones interbedded in the limestones of the Copacabana Group at Copacabana Peninsula (Lake Titikaka) seem to indicate a contemporary tectonism. This tectonism (Permian Pulsation) is believed to have produced the synkinematic ultrametamorphic metasomatic Kutikucho granite of Cordillera Real, block D (P. LJUNGGREN and L. RADELLI, 1964). Copacabana Group is not known, west-wards of the Coniri Fault, in blocks A_1 and A_2, but it is not possible to affirm that it does not exist in the subsurface of them. The arkosic sandstones interbedded in the Copacabana Group of the Titikaka region may indicate that the Bolivian Lower Permian marine basin was limited on the West by an uplifted land (H. J. HARRINGTON, 1962, fig. 14).

§ 8. — Very important both tectonic and paleogeographic changes occurred during the Hercynian orogenetic uplifts, between Lower Permian and Upper Permian or Lower Triassic. Then Paleozoic strata were folded and faulted, and intrusive postkinematic granitic bodies were squeezed into block D, that is in both Cordillera Real and Cordillera of Quimsa Cruz (P. LJUNGGREN and L. RADELLI, 1964; L. RADELLI, 1964). Permo-Triassic gypsiferous marles, Campana Formation (H. MEYER and J. MURILLO, 1961) or Chuquichambi Formation (S. KRIZ and al., 1962) are known in blocks A (A_1 + A_2), B, C, and on the western border of block D. In block A these Permo-Triassic rocks constitute diapiric bodies which intrude Cretaceous strata (block A_2) and the red beds of the Huayllamarca Range. In blocks B and C they rest with a gentle unconformity, or conformably on the Lower Permian Copacabana Group. In block D, the gypsiferous strata, with some beds of lacustrine (?) limestone, rest unconformably on the Silurian Milluni Formation (low-grade metamorphic sericitic slates).

The gypsiferous Chuquichambi-Campana environment following the marine one of the Copacabana Group seems to indicate a generalized descent of blocks A, B, and C, in comparison on the one hand with blocks D, E, and F on the East, and on the other hand, with a western block (block G), in place of the actual volcanic western Cordillera. This suggested raised western block is believed to have possibly originated the evaporitic Chuquichambi-Campana environment, by closing all oceanic circulation. This suggested block G cannot be directly observed within the Bolivian Andes, because of extensive covering of Cenozoic volcanics. Consequently one cannot establish here its boundaries, nor its precise geological constitution. Only regional comparisons can supply such information. South of Bolivia, in northern Argentina, along the same trend of suggested block G, W. C. STOLL (1961) was able to demonstrate the existence of a western Hercynian Cordillera, mainly constituted by Hercynian granites, and post-Hercynian chiefly Mesozoic continental rocks. SW of the Salt Lake of Uyuni, and between that and Chuquicamata an Hercynian batholith is known in the Andes of Chile. Again on the same trend, but now to the North of Bolivia, in Southern Peru, the post-Hercynian Mitu Group (N. D. NEWELL and al., 1953) is known on the west side of the Vilcanota Valley. Because of that, I think that the suggested block G, closing oceanic circulation during at least Upper Permian, was raised by the Hercynian orogeny.

This orogeny is recognizable all over the Eastern Bolivian Andes and the Bolivian Altiplano when Paleozoic strata are cropping out, but its intensity was not the same in each part of the country.

All over the country the Hercynian orogeny is revealed by the folding of Paleozoic strata, over which Mesozoic ones rest unconformably. But in block D, during Hercynian orogenic conditions, primitive Paleozoic sedimentary rocks were transformed into highly metamorphic rocks, ultrametamorphic metasomatic Kutikucho-type granite, and finally into intrusive magmatic Huayna Potosi-type granitic bodies (P. LJUNGGREN and L. RADELLI, 1964), what did not occur elsewhere. It is very interesting to note that the southern boundary of this highly orogenic block D coincides exactly with the Poopo Line, that is with the northern boundary of block F, which corresponds to the Devonian Proto Puna. Generally speaking, the Bolivian geologists believe that only one formation, the Chuquichambi-Campana Formation, was deposited after Lower Permian and before Cretaceous in the Bolivian Andes. Consequently they suggest a great hiatus. I have discussed this point previously (L. RADELLI, 1964), and I have suggested a different interpretation. The discussion concerns the geological age of the ToroToro Formation, and of the Huayllamarca Group. I shall discuss that again, after I have dealt with fossiliferous Cretaceous Bolivian rocks.

§ 9. — Cretaceous rocks differ in facies and thickness from one to another of blocks which are separated by intersecting Coniri, Palca, and Achacachi Faults and the Poopo Line. South of the Poopo Line, there is the typical Cretaceous of

Bolivia, which includes several calcareous marine formations. Cretaceous stratigraphy of the region between Sevaruyo on the West (Eastern border of the Altiplano) and Potosi on the East was established previously by C. CHERRONI (1963) as indicated in fig. 4.

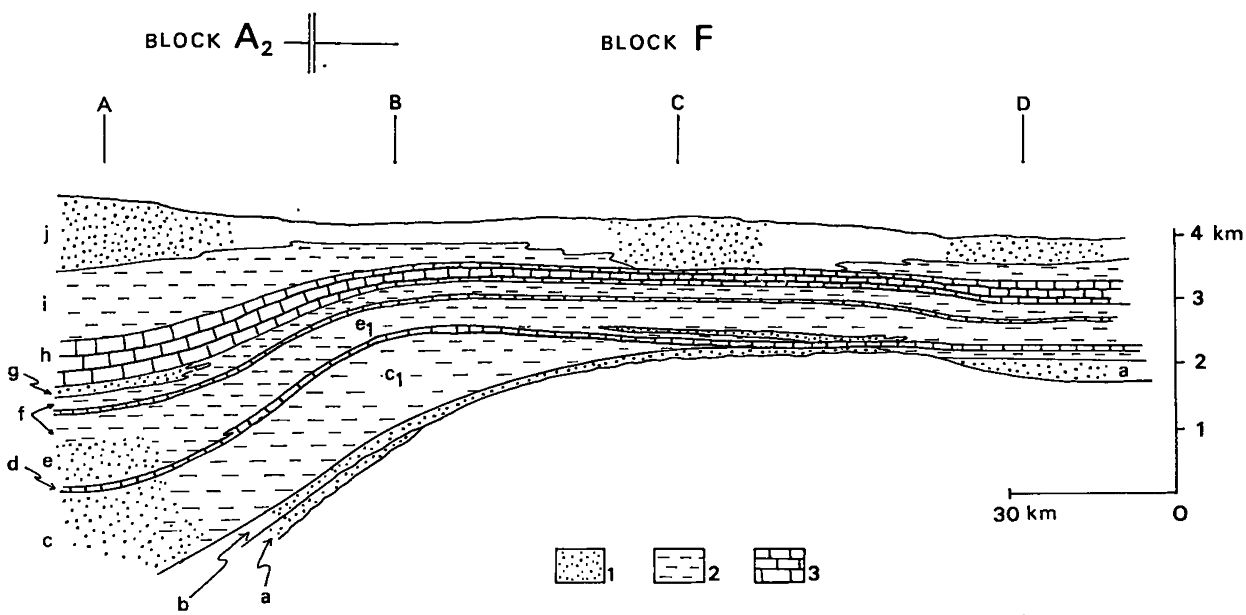

Fig. 4. — Cretaceous stratigraphy of blocks A2 and F.

A, Sevaruyo Tambillo; B, Huari; C, Lagunillas; D, Miraflores (Potosi); 1, Sandstones; 2, Shale and marl; 3, Limestone. Formations : a, ToroToro; b, Condo; c, Lower Orinoca; c_1, Kosmina; d, Anta = Miraflores; e, Upper Orinoca; e_1, Aroifillia; f, Mulasi; g, Croma; h, Molino = Pahua; i, Candelaria = Santa Lucia; j, Suticollo, Cayara, and Tusque.

The marine Cretaceous formations disappear from the Rio Caine-Rio Pilcomayo line East-wards : this line corresponds to the eastern shore of the Cretaceous marine basin (L. RADELLI, 1964.)

The thickness of Cretaceous rocks varies greatly from the Altiplano (± 5 000 m) to the Eastern Cordilleras (< 2 000 m), that is from West to East of the Coniri Fault. The facies of Cretaceous rocks also varies in the same way : Cretaceous formations are more arenaceous on the West that on the East (compare : Lower Orinoca Formation and Kosmina Formation ; Upper Orinoca Formation and Aroifillia Formation, etc.). Besides, near the western border of the Eastern Cordillera (Huari, Peñas, Lagunillas) during Lower Cretaceous, the conglomeratic Condo Formation was deposited. These facts indicate a generalized raising of block F in comparison with block A_2, that is a synsedimentary activity of the southern part of the Coniri Fault. The Coniri movements were accompanied by several parallel faults on the East, which finally produced local fairly independent basin, like those of the Kosmina and Condo Formation of Huari (C. CHERRONI, 1963).

Also West-wards of Lake Poopo the thickness of Cretaceous rocks varies, and in Andamarca it is reduced to some 1 700 m. West-wards of both Andamarca and Salares regions, other Cretaceous outcrops are known, but I do not known their thickness. Furthermore on the West, in Tarapaca Province, Chile, Cretaceous rocks are known (G. CECIONI and A. GARCIA, 1960), which unconformably rest on layered Jurassic rocks, and on « Nevadian » Andean Diorite. The oldest post-« Nevadian » formation of Tarapaca Province is the Atajaña Formation (*ibidem*), which consists of some 1 400 m of continental, probably lacustrine, sandstone, conglomerate, and red siltstone, coming from a western land. This formation is overlapped conformably by the marine Blanco Formation, and there is a gradual transition between them. The Blanco Formation is Berriasian in age, and consequently the Atajaña Formation seems to belong to Tithonian. On the other hand, South of the Tarapacà Province, in the Atacama Province, Chile, the younger marine formations are jurassic, and generally Oxfordian in age (G. CECIONI, private communication).

A land existed here during Cretaceous, closing oceanic circulation towards the East. These observations seem to indicate that : (a) the marine Cretaceous Bolivian basin South of Poopo Line was connected west-wards, in the region of the actual Salares, with the Pacific Ocean ; (b) the western Tarapaca basin was separated from the Bolivian one by a submerged ridge, which might explain the facies and the changes in thickness of discussed Bolivian Cretaceous rocks ; (c) this marine Cretaceous Bolivian basin was originated by « Nevadian » movements ; (d) the Condo Formation of Huari, Lagunillas and Peñas, which unconformably rests on the ToroToro Formation, but which is conformably overlapped by the following partly marine, Cretaceous formations, should also be post-« Nevadian », and Tithonian in age.

The hypothesis expressed in (a) is completely contrary to the ideas pointed out previously, for example by H. J. HARRINGTON (1962) and myself (L. RADELLI, 1964), which suggested that all Cretaceous Bolivian rocks were deposited in an internal marine tongue (or embayment), coming from the North. The importance of this new point of view on the paleogeographic environment, and tectonic framework of the marine Cretaceous Bolivian basin also for oil deposits researches is self-evident.

§ 10. — What is the geological age of the red beds of the ToroToro Formation, which rests under the surely Cretaceous ones of block F, and particularly unconformably under the Lower Cretaceous conglomeratic Condo Formation ? Until 1962 there was no doubt for the Bolivian geologists that ToroToro was Lower Cretaceous in age. During 1963 C. CHERRONI published his geologic map of Huari region and the annexed explanatory note. Because he recognized that ToroToro rests unconformably both on Paleozoic strata folded by a post-Permian and pre-Cretaceous orogeny, and under Cretaceous ones, which begin with the Condo Formation, he indicated that the Cretaceous age of ToroToro is dubious. Nearly at the same time (report published on March, 1964) I expressed my view that ToroToro was originated by the Hercynian orogeny, and that it is probably Upper Permian to Triassic and perhaps Jurassic in age.

This view is based on the following facts. ToroToro was deposited in a continental and chiefly desertic environment, as indicated by its conspicuous cross-bedding (fig. 5). ToroToro rests unconformably upon folded Lower Permian, Devonian, Silurian, and Ordovician rocks. Rapid changes in thickness both along and across their tectonic trends indicate that ToroToro was deposited in separate, intramountain basins. I observed in the Caine Valley, near ToroToro Village, that, when such post-Lower Permian basins were filled up by ToroToro sediments, an orogeny occurred, which caused faults in ToroToro beds before the sedimentation of the typical Cretaceous formations. H. LOHMANN and L. BRANISA (1962) suggested that the unconformity recognizable under La Puerta (= ToroToro) Formation of Miraflores (Potosi) syncline was produced by the same orogeny which originated folding and granitic batholiths of Cordillera Real before Cretaceous time, and that younger tectonic movements occurred between the ToroToro sedimentation and the deposition of the Miraflores Formation (Aptian-Albian). In fact they recognized that in a marginal conglomeratic facies of the calcareous Miraflores Formation there are antimony-bearing pebbles, which were deposited from antimoniferous veins cutting the underlying La Puerta (= ToroToro) Formation. Nevertheless, because they did not recognize that the first orogeny was the Hercynian one (that was demonstrated only on 1964 by P. LJUNGGREN and L. RADELLI), they continued to include the ToroToro Formation in the Cretaceous system. Actually the remarks of H. LOHMANN and L. BRANISA (1962), C. CHERRONI (1963) and L. RADELLI (1964) clearly indicate that the ToroToro Formation was deposited after post-Lower Permian Hercynian orogeny, but before a pre-Aptian-Albian orogeny. The only known orogeny of this time is the Nevadian orogeny, which in the

Fig. 5. — Cross-bedding in ToroToro Formation, Rio Pilcomayo (Potosi).

Central, northerly trending, Andes occurred during Tithonian (G. CECIONI and A. GARCIA, 1960 ; G. CECIONI, 1961). Consequently the ToroToro Formation is older than Cretaceous, probably Upper Permian to Jurassic in age, and partly correlative with the Chuquichambi-Campana Formation of block A_2.

§ 11. — In block B Cretaceous is represented only by unfossiliferous continental red beds, including conglomerate, sandstone, and siltstone (Formations Aranjuez and Peñas, L. RADELLI, 1964). The pebbles of the conglomerates consist of pre-Devonian schist, Devonian quartzite, Permian Copacabana limestone, quartz, and at Aranjuez (La Paz Valley) of igneous rocks, including basalt and metasomatic microcline granite (P. LJUNGGREN, private communication). Because the granitic batholiths of Cordillera Real were not exposed until Miocene, granitic pebbles of the Aranjuez Formation indicate that the sediments were accumulated, at least partly, from the West. That suggests an uplifted region west-wards of block B, and it furnishes a way to approach the problem of the geological age of the Cretaceous rocks of block B. The precise geologic age of these rocks cannot be defined. However, their petrographic constitution and general relationships seem to indicate that they can be tentatively correlated with the Saracocha Formation of Peru (W. F. JENKS, in N. D. NEWELL, 1949), of oldest Cretaceous (post-Nevadian, and probably Neocomian). In fact, as pointed out by N. D. NEWELL « roots of Nevadian mountains still formed rugged topography » during this time.

§ 12. — In block C the Cretaceous has a different development and a different facies (Southern Peruvian facies). N. D. NEWELL (1949) suggested here the following stratigraphy :

Upper Cretaceous :

Munani Formation : Red sandstone, 800 m;

Vilquechico Formation : Greenish-gray siliceous shale and thin persistent beds of white quartzitic sandstone, 680 m;

Cotacucho Group : Red beds and gypsum above and below, massive pink sandstone near the middle, 1 096 m.

Discordance.

Middle Cretaceous :

Moho Group : Upper part lithologically similar to Vilquechico; Formation, lower part red beds, with persistant Ayavacas limestone near base, 800 m.

(Lower ? Cretaceous) :

Huancané Sandstone : Pink to maroon, ranges from 60 m SW of Lake Titikaka to maximum of 500 m.

(Upper Jurassic ?) :

Muni Formation : Dark red shale, with thin fossiliferous limestone near middle, 135 m;

Sipin Limestone : variegated limestone and inter bedded coarse sandstone, few to 20 m.

The stratigraphy, and consequently the tectonics, of the Peruvian part of the Lake Titikaka region, as established by N. D. NEWELL has not received general agreement. For example, S. KRIZ (fide F. AHLFELD and L. BRANISA, 1960, p. 108) affirms : « In the Munihorco anticline, the Huan cané Sandstone rests conformably under the Moho Formation. The Sipin Horizon constitutes the top of the Cretaceous series ». The same idea was exposed by A. HEIM (1948). The correlations between the formations of Newell ant those of the Cretaceous of central Bolivia are not yet well established. Because the Pucalithus was found in both them, H. LOHMANN and L. BRANISA (1962) suggested that the El Molino (= Pahua) Formation of central Bolivia would be correlative with the Vilquechico Formation of Newell. On the other hand, El Molino belongs to the Cenomanian, and, after NEWELL, in the Titikaka region the Cenomanian would be represented by the Ayavacas limestone. In any case, and apart from other differences (for example : the discordance between Middle and Upper Cretaceous, which does not exist in the Cretaceous of blocks A_2 and F), the older (Miraflores) of two calcareous Cretaceous fossiliferous formations of central Bolivia (Miraflores = Anta ; El Molino = Pahua) would not exist in the Lake Titikaka region, and the Ayavacas Formation would be correlative with the El Molino one, as it seems to be indicated by some outcrops of the northern part of block A_1 (see below). It is not possible to give more details.

§ 13. — In blocks D, and E Cretaceous rocks are not known. In the Bolivian part of block A_1 Cretaceous rocks are scarcely represented. They are known only on the northern slope of the Tiahuanacu Range (between Guaqui and Desaguadero), South of Tiahuanacu Village, and near Jesus de Machaca. The Cretaceous is much reduced in thickness here (no more than 120 m), and it consists of shales and quartzitic sandstones, with limestone near the base. It is Cenomanian in age (L. BRANISA, private communication). It corresponds to the Moho Group of Newell, and it is correlative with the El Molino (= Pahua) and Chaunaca Formations. Its base is exposed only South of Tiahuanacu (Cerro Chilla), where it rests on Paleozoic metamorphic slates and limestones. It is everywhere covered by red beds (Huayllamarca Formation or Puno Group). The age of these red beds and the nature of their contact with Cretaceous rocks will be discussed afterwards.

§ 14. — In short, Cretaceous rocks are very different North- and South-wards of Poopo Line. South of Poopo Line there was the main marine Cretaceous Bolivian basin, which was divided at least in two principal parts : the first one, West of Coniri Fault, corresponded to a true trough (block A_2), the second one to a shelf depositional zone (block F). North of Poopo Line, Cretaceous is known in the Bolivian Andes only West-wards of Palca Fault (East-ward of which it does not appear again until Sub Andean Zone). Besides, block B (between the Coniri Fault and the Achacachi Fault), with only continental Lower Cretaceous, divides the remaining blocks C and A_1, where a marine Cretaceous with Peruvian facies is known, but reduced in thickness in block A_1. Therefore, block B seems to have constituted, after Nevadian movements, an intermediate horst, which probably included also the Island of Soto and other actually submerged lands in place of the Lake Titikaka (see also N. D. NEWELL, 1949, p. 21). The paleogeographic value of the indicated blocks dividing intersecting faults and Poopo Line appears from the preceding stratigraphic descriptions.

§ 15. — Important movements did not occur in the boundary Cretaceous-Tertiary, so that it is impossible to affirm whether the unfossiliferous of the top of the indicated Cretaceous series (Tusque, Suticollo and Cyara Foormations) really belong to the Cretaceous. There is only a conventional boundary. But movements which occurred during Tertiary enable us to recognize the continuing independance of the indicated blocks. In block F during Miocene the Kari Kari (Potosi) batholith [1] (granodiorite, quartz-latite, and latite)

[1] The geologic age of the Kari Kari batholith was established through numerous K/ Ar determinations by Prof. J. EVERNDEN, Berkely University (S. KRIZ, private communication).

was originated through the melting of Paleozoic strata under orogenic conditions (P. LJUNGGREN, 1964). Successively, unconformably over folded Cretaceous and older strata, the conglomeratic Mondragon Formation (Miocene ? Upper Miocene ?) was deposited. During Pliocene an intense rhyolitic volcanism occurred in the same block (Los Frailes rhyolites). In block A_2, apart from the Huayllamarca Group, which will be studied afterwards, Tertiary is chiefly represented by the Potoco Formation (red sandstone and shale). The Potoco Formation rests conformably on the top of Cretaceous. Both Cretaceous and Tertiary are cut by generally small subvolcanic and volcanic intrusive bodies, probably Pliocenic in age.

In block B during Miocene the lacustrine beds of the La Paz Formation (La Paz Valley) were deposited (E. DOBROVOLNY, 1962 ; L. RADELLI, 1964), with at the summit the Chijini volcanic ash. The La Paz Formation rests unconformably over Cretaceous (Aranjuez Formation) and Paleozoic rocks. Other Tertiary rocks of this block have been indicated by F. AHLFELD in his geologic map of Bolivia (1960) at Luribay, and near Cerro Pacuani, but no details of them are available. Also in this block, numerous Tertiary volcanic and subvolcanic intrusive bodies are known, but their age is not well established (Miocene ? Pliocene ?). In block C, continental Tertiary rocks (chiefly red beds) are exposed, which generally rests on the top of Cretaceous in synclines. Tertiary rocks are not known in blocks D, and E, nor East-wards of block F until the Sub Andean Zone. Concluding, a Miocenic discordance is recognizable in blocks F and B, but not in block A_2, nor in block C. Miocenic movements were stronger in block F than in block B, as indicated by the origin through the melting of Paleozoic rocks under orogenic conditions of Kari Kari batholith, which occurred in the first one. The presence in the La Paz Formation of granitic pebbles which came from the Hercynian batholiths of Cordillera Real (L. RADELLI, 1964) indicates that during Miocene this Cordillera was raised, that is, the Palca Fault was active.

Successively piedmont type sedimentation occurred during Pliocene and Quaternary.

§ 16. — To complete this study, we must now deal with the geology of the Huayllamarca Range, and of the Tiahuanacu Range. Both the Huayllamarca and Tiahuanacu Ranges are constituted by continental, chiefly unfossiliferous, rocks, including red beds and volcanics. From a lithostratigraphic point of view, these rocks are actually subdivided as follows (P. LJUNGGREN and H. MEYER, 1964) :

Umala Group : tuffs, and half-consolidated grey conglomerates ± 1 000 m.

Discordance

Crucero Formation : coarse-grained sandstones, and tuffs, ± 1 600 m.

Corocoro Group:

- Totora Formation
  - Vetas Member : friable, light grey coarse conglomerate and grey sandstones 1 500-2 500 m.
  - Ramos Member : violet to reddish brown sandy shales, with lenses of arkosic sandstones, and some evaporites, 1 500-2 000 m.
- Huayllamarca Formation
  - Chacarilla Member : massive, coarse grained feldspatic to arkosic sandstones, 200-1 000 m.
  - Coniri Member : very coarse conglomerate, 500-1 500 m.
  - Llanquera Member : massive red sandstones and sandy shales in lenses, 500-3 000 m.

The basic geologic problem is that of the geologic age of the formations of the Corocoro Group. Since 1841, the age of this group has been regarded as Carboniferous, Permian and Tertiary by successive geologists (H. MEYER and J. MURILLO, 1961). In fact a paleontological evidence for one age or another of each formation or member of the Corocoro Group does not exist. Only the age of the Vetas Member can be established. It belongs to the Miocene and probably it was deposited into a lacustrine environment as was the contemporary La Paz Formation of block B. That is not enough, of course, to assign a Tertiary age to all the formations of the Corocoro Group, as the modern Bolivian geologists tend to. The stratigraphic problem of the Corocoro Group can be stated as follows. The Corocoro Group appears only West-wards of the Coniri Fault. The Corocoro Group crops out both South- and Northwards of the Poopo Line, in the Huayllamarca Range, and in the Tiahuanacu Range to continue on the North, along the western shore of Lake Titikaka in Peru. That is, when the rocks of the Corocoro Group were deposited, block A was not completely divided into blocks A_1 and A_2.

There are no recognizable contacts between typical Cretaceous rocks and those of the Corocoro Group in block A_2. The only recognizable stratigraphic relationships here are the following ones. From the Sevaruyo zone (South of Lake Poopo) towards the Huayllamarca Range the thickness of Cretaceous and of Tertiary (Potoco Formation, which rests conformably on Cretaceous top) progressively lessens : ± 5 000 m of Cretaceous and 5 000 m of Tertiary (Potoco) at Sevaruyo, less than 1 500 m of Cretaceous and some 1 750 m of Tertiary (Potoco) at Andamarca. NW of Andamarca in the Huayllamarca Range, on the contrary, the Corocoro Group has a thickness of some 12 000 to 17 000 m, and W of Andamarca the Huayllamarca Formation shows a thickness of some 6 000 m. These facts would seem to indicate a geologic age older than Cretaceous for the lower part of the Corocoro, but, on the other hand, Cretaceous marine rocks have never been found in block A_2, in the synclinorium constituted by the beds of the Corocoro Group here. In the Tiahuanacu Range, and in its Peruvian prolongation, the recognizable relationships between Cretaceous rocks and those of lower part of the Corocoro Group (called here Puno Group) are as follows. In the Tiahuanacu Range, between Guaqui and Desaguadero, at first, near Guaqui, a low angle reverse fault is recognizable, which has moved from W to E Corocoro beds over Moho (Cretaceous) ones ; towards the North, this fault is truncated by a transverse one, and then the Corocoro beds seem to rest conformably on the Moho Formation, but a breccia exists at their base. SW of Guaqui, near Jesus de Machaca, a Bolivian geologist, R. Ascarrunz, has found a small outcrop of the Moho Formation under the rocks of the lower part of the Corocoro Group. The thickness of the Moho Formation is here less than 120 m, but the Huayllamarca one is about 5 000 m. On the same trend of the Guaqui-Desaguadero line, in the Peruvian prolongation of the Tiahuanacu Range, from Juli to Pirin, Cretaceous Moho Formation unconformably rests over Puno Group (= Huayllamarca Formation).

N. D. Newell, who postulated a Tertiary age for the Puno, explained this overlapping as an overthrust (« nappe de chevauchement ») of Alpine type. A. Heim (1948), who knew the manuscript of Newell (1949), did not accept his idea about the tectonic structure of the Lake Titikaka region. He wrote : « My conclusion was that... autochtonous unconformities have been confused with overthrusts, and that nothing similar to the so-called nappes of the Alps exists. » He demonstrated that the Locamalla Overthrust of Newell dit not exist and that it was postulated only because Newell was mistaken about the stratigraphical position of the Sipin Limestone, which would rest on the Moho Formation, but which was supposed by Newell to rest under Cretaceous. On the other hand, A. Heim accepts the Tertiary age of Puno (« ... Newell is to be credited for establishing the Tertiary age of border formations of Pusi, a series of sandstones and conglomerates, which were regarded by Peruvian geologists as Paleozoic »). Nevertheless, such an age for Puno involves the existence of one of those overthrusts which Heim chooses not to recognize. That is the Pirin Overthrust of Newell, the front of which would be recognizable along some 120 km, near the western shore of Lake Titikaka. However that may be, the following conclusion seems to be conceivable : either Puno is Tertiary in age and the Pirin Overthrust exists ; or the Pirin Overthrust does not exist, Puno is not Tertiary but older, the overlap of Pirin is stratigraphical, and then an extensive overthrust exists in the Tiahuanacu Range, which moved Huayllamarca beds (= Puno) over Cretaceous strata. From a sedimentologic point of view, the feldspatic and arkosic sandstones of the Huayllamarca Formation must have been accumulated from one or more granitic sources. They cannot have been accumulated from the Eastern Cordilleras : before Miocene, granitic batholiths existed only in place of both Real and Quimsa Cruz Cordilleras, but they were not eroded. On the other hand, paleocurrent measurements (P. Ljunggren and H. Meyer, 1964) suggest that the sediments of the Huayllamarca Formation were accumulated from the West as well as from the East, but the changing thickness from West to East indicates that the main source of sediments was located on the West. Before the Miocene, only the Hercynian orogeny can have originated an extensive granitization West- and East-wards of the actual Huayllamarca Range. A western Hercynian granitized zone has been suggested in this report before, in order to explain the origin of the evaporitic environment of Chuquichambi-Campana (Upper Permian to Lower Triassic); a minor one can be assumed to have existed around the Coniri Fault (part b, of block A), where the outcrop of metamorphic Paleozoic of Cerro Chilla, South of Tiahuanacu, might be regarded as a small remainder of such an orogenic zone. It could also explain the presence of granitic pebbles in the Nevadian Aranjuez Formation of La Paz Valley. That would indicate a likely Upper Permian to Triassic starting out for the Huayllamarca sedimentation. A remark made by P. LJUNGGREN and H. MEYER (1964) seems to confirm this idea. They noted that, when the Chuquichambi-Campana Formation (Upper Permian to Lower Triassic) is not diapiric into the Corocoro Group, this Group (Llanquera Member) rests on the Chuquichambi-Campana Formation. In this way it becomes possible to give a precise significance to the conglomeratic Coniri Member. It can be regarded as Nevadian in age, that is, as produced by the Nevadian tectonism in the boundary Jurassic-Cretaceous. In fact, in the Coniri conglomerates granitic, Devonian and older, and Permian (Copacabana Limestone) pebbles have been recorded, but Cretaceous pebbles have never been found in them. The Coniri Formation seems to be correlative with the Saracocha, Aranjuez, and Peñas Formations. Consequently, the Llanquera Member would be Triassic-Jurassic in age, and correlative with the ToroToro Formation of block F. Chacarilla and Ramos Member would be Cretaceous to Oligocene in age. The Vetas Member (Miocene) would be correlative, both in age and in facies, with the La Paz Formation, and the Callapa tuff with the Chijini volcanic ash of La Paz, and with the tuff which constitutes the top of the Mauri Formation of AHLFELD (1960), or Berenguela Formation of the geologists of the Geological Survey of Bolivia, which crops out in the north-western part of the Altiplano. The Crucero Formation would be Upper Miocene in age, and the Umala Group conventionally Pliocene, as indicated previously by P. LJUNGGREN and H. MEYER (1964). The attained conclusion on a Triassic-Jurassic age of the Llanquera Member, and on the existence of an important continental ridge west-wards of the actual Huayllamarca Range agrees with that of G. CECIONI (1963), who studied the Jurassic geosyncline of northern Chile. By means of a study of the turbidites of the Jurassic basin of Tarapaca Province, G. CECIONI was able to demonstrate the existence of a Jurassic land in place of the actual Western Cordillera of Bolivia (fig. 6). Another index of a at least pre-Tertiary age of the red beds of the Huayllamarca Cordillera seems to be furnished by recent mapping of the Geological Survey of Bolivia in the NW corner of the country. Here the Abaroa Formation, certainly pre-Tertiary,

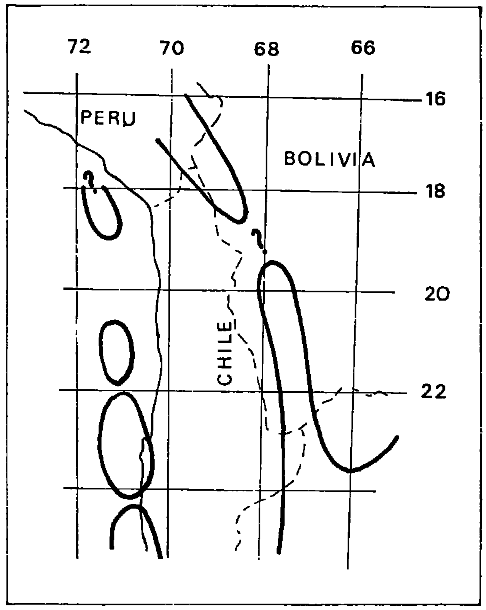

Fig. 6. — Paleogeography of Jurassic, after G. Cecioni, 1963.

Lands are indicated by thick lines. Cecioni suggested a strait on the East in order to explain the marine Miraflores Formation, the age of which he considered as Jurassic. In fact Miraflores is Cretaceous in age, and probably there was no interruption of the land in place of actual Western Cordillera of Bolivia.

has been discovered. It consists of basic lavas with interbedded red beds, which have the same facies of the Llanquera Member.

§ 17. — The suggested geological age of each formation, or member, of the Corocoro Group necessarily involves a paleogeographic control of the sedimentation, which must be discussed. It implies that block A_2 was gently tilted towards South during Cretaceous. Fortunately, that is proved by the changing thickness of Cretaceous in this block.

Furthermore, that implies that the southern part of the compartment, corresponding to the actual Huayllamarca Range, constituted a peninsula into the Cretaceous sea of block A_2. I acknowledge that there is a difficulty, but I think that it is only an apparent one. As pointed out previously (H. MEYER and J. MURILLO, 1961), the Huayllamarca Range, and the synclinorium of this, are limited by two longitudinal faults : the Chacarilla Fault on the East, and the Chiriquiña Fault on the West. The present study of the main Bolivian faults (Coniri, Achacachi, and Palca Faults, and Poopo Line) indicates that all these faults have a paleogeographic significance. It is not contrary to the scientific rule to suppose a similar history and value for the Faults Chacarilla and Chiriquiña. If these faults are regarded as old tectonic features, it is possible to think that during Cretaceous they prevailed over the movements along the Poopo Line which probably were discontinuous (see below § 19 and § 22), and they raised, as a whole, the compartment of the actual Huayllamarca Range on both sides of the Poopo Line itself. On the other hand, movements along this line occurred later, probably from Upper Miocene, when numerous volcanic and subvolcanic intrusions occurred into the Corocoro Group (as well as in the Western Cordillera), producing several metalliferous mineralisations by removing the sedimentary dispersed metallic contents (chiefly copper) and concentrating it into appropriate tectonic features, chiefly along the flanks of anticlines (P. LJUNGGREN and H. MEYER, 1964). The Bolivian geologist (S. KRIZ, many private discussions) do not agree with my idea of an old age of a part of the Corocoro Group (L. RADELLI, 1964). They oppose that the tectonic axis of the main folds of Cretaceous + Tertiary Potoco of block A_2 exactly coincide with those of the Corocoro Group, and that consequently this Group must be considered Tertiary in age as well as the Potoco Formation. This idea is not without reason. Experience teaches that the axis of folding are always axis of isopachs. But this relationship between the axis of folding and the isopachs does not concern the age of the folded rocks. It only concerns the thickness of the rocks included between the same discordances. The geometric concepts must remain separated from the chronostratigraphic ones. In this actual case, as generalized folding did not occur between Upper Permian and Miocene [2], the Corocoro Group and the Cretaceous + Tertiary Potoco are anyway included between the same discordances, Hercynian at the bottom, Miocenic or Incaica at the top, their coinciding tectonic axis do not implicate that the Potoco is correlative with the Corocoro Group as a whole. On the contrary, the whole lot of Cretaceous + Tertiary Potoco + eventually the buried Llanquera Member (or its equivalent Toro-Toro Formation) of block A_2 is correlative with the Corocoro Group.

More difficulties appear if one considers that the Corocoro Group belongs to the Tertiary. The relationships between the thickness of the Corocoro Group and that of the Cretaceous rocks becomes incomprehensible : the maximum thickness of Tertiary sediments would have been accumulated in places of minimum thickness of Cretaceous, that is on the borders of the Cretaceous basin, and that without any folding in the boundary Cretaceous-Tertiary. An accumulating thickness of some 10 000 to 17 000 m [3] of Tertiary sediments should be assumed in the Corocoro basin, when, in the deeper part of the Cretaceous + Tertiary Potoco one, only some 5 000 to 6 000 m Tertiary Potoco sediments were accumulated during the same time. Furthermore, if the Corocoro Group was Tertiary, the fact would have to be explained that, in the Huayllamarca Range, a stratigraphic boundary between the Permo-Triassic Chuquichambi-Campana Formation and the Corocoro Group has been observed (H. MEYER and J. MURILLO, 1961) but a similar boundary between fossiliferous Cretaceous rocks and the Corocoro Group has never been found here.

From a strictly tectonic point of view, as I have indicated above, a pre-Cretaceous age of two lower members (Llanquera and Cooniri) of the Huayllamarca Formation (Puno Group of Peru) implies an overthrust (Tiahuanacu Overthrust) in the Tiahuanacu Range, where the Huayllamarca beds overlap Cretaceous rocks. On the other hand,

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[2] The Nevadian movements were generalized in the area on the side of the compartment corresponding to the actual Huayllamarca Range, as indicated by the extension of the Coniri Member, but they produced folding only within localized small compartments of block A_2 (Huari, Lagunillas).

[3] Valuation of the geologists of the « Mision geologica Alemana en Bolivia ».

a Tertiary age of these rocks would implie a more extensive (120 km of front) overthrust (Pirin Overthrust) in the Peruvian Lake Titikaka region, where Cretaceous Moho overlaps the Puno. I believe that it is more easy to admit the Tiahuanacu Overthrust that the Pirin one. The origin of the first can have been facilitated by the presence of the lubricating salt and gypsum beds of the Chuquichambi-Campana Formation, it can be regarded as a free gravity glide, and it is at least indicated by a breccia at its base. The second should have originated by an unusual very strong tangential force only, because lubricating beds do not exist at the base of the Moho Formation.

§ 18. — Concluding, the following mutual movements of indicated blocks of the Bolivian Andes seem to have occurred through the geologic time. During Silurian, block A (A_1 + A_2) was raised in ratio with blocks B, (C), D, (E?), and F.

During Devonian, block A was divided into blocks A_1 and A_2. Block A_1 (or parts of it) remained uplifted, block A_2 moved down. Block F rose.

There were no important new mutual movements during Carboniferous, or during Lower Permian. During Carboniferous a continental sedimentation of Gondwana type occurred in block B, where the sediments were accumulated from block A_1, and East-wards of block F, from this block itself. Probably a peneplanation ensued. During Lower Permian, there was a generalized marine transgression. It was accompanied by a tectonic pulsation (Permian Pulsation), which produced the synkinematic ultrametamorphic Kutikucho granite of Cordillera Real (block D), and perhaps similar rocks in place of actual Western Cordillera, and around the northern part of the Coniri Fault.

During Upper Permian or at beginning of Triassic, the Hercynian orogeny occurred. The Hercynian orogenic conditions were different from one block to another. In blocks D, G, and probably in block H, the Paleozoic rocks were strongly folded, and finally, partly transformed into granitic magmas of Huayna Potosi type. In the remaining blocks the Paleozoic rocks were only gently folded and metamorphic conditions were not attained in them. Blocks G, D, F, and h were comparatively raised, and an evaporitic environment was originated between them, especially West-wards of the Coniri Fault, where Permo-Triassic gypsiferous marles (Chuquichambi-Campana Formation) were accumulated. During Triassic and Jurassic, continental formations were then deposited : the ToroToro Formation into structural slows of block F, the Llanquera Member in a. During Nevadian tectonic movements (boundary Jurassic-Cretaceous), blocks A_2 and F moved down, but not completely. Compartment a, corresponding to the actual Huayllamarca Range, between the faults of Chacarilla and Chiriquiña, remained lowered in comparison with h (or parts of it), but raised in comparison with the remainder of block A_2, into which it constituted a cap when Cretaceous sea filled it. Nevadian movements were particularly strong in G and h, as registered in the stratigraphy of contiguous blocks B, a, and A_2, where the conglomerates of the Coniri Member (Huayllamarca Formation, Corocoro Group), of the Aranjuez and Peñas Formations (block B), and of Condo Formation (block F) were deposited. Local unconformities were also produced (Huari, Lagunillas, La Paz Valley, and Peñas).

On the other hand, the Nevadian movements produced a very important paleogeographic change, by permitting the Cretaceous sea to invade several parts of Bolivia, that is, blocks A_2 (partly), F, C, and the northern part of the country, near the Lake Titikaka (block M).

South of Poopo Line, the Hercynian Western Cordillera disappeared at this time. Marine Cretaceous rocks are different in facies and in thickness from block A_2 to block F. The former was a true trough, where clastic sediments were accumulated near the Coniri Fault ; the latter constituted a shelf. Cretaceous rocks of blocks C and M are different from those of the southern Bolivian basin. They have a Peruvian facies. This marine Peruvian basin was separated from the southern Bolivian one by blocks B, h, and A_1, where continental Cretaceous rocks were accumulated. Besides, blocks C and M were divided one from another in the southern region of the Lake Titikaka by block B.

Until Miocene, new movements cannot be recognized. Also the transition from marine Cretaceous to continental Tertiary sedimentation of block A_2 occurred without any discordance. But Miocenic movements differentiated from one block to another are easy to recognize. In block F, there were high orogenic conditions, which produced granitic magmas through the melting of Paleozoic rocks (Kari Kari), and the Mondragon discordance. In block B, the Miocenic lacustrine La Paz Formation rests unconformably over older rocks. Granitic pebbles of the basal conglomerate of this Formation, which were deposited from the Hercynian batholiths of Cordillera Real, indicate that block D was raised at the beginning of Miocene, but granitic melting was not produced here. On the other hand, in the Huayllamarca Range, at the base of the Vetas Member (Totora Formation, Corocoro Group), which is correlative both in facies and in age with the La Paz Formation, an unconformity does not appear.

Only at the end of Miocene, and during and after Pliocene, an almost similar geologic evolution is recognizable throughout all the Bolivian Andes. Then the old rocks of blocks G and h were definitively moved down, to be successively covered by volcanic rocks, and then the Tiahuanacu Overthrust was produced, if it exists. All over the country an intensive volcanism was developed, which was stronger in blocks F (Los Frailes lavas), and G (Western Cordillera volcanics) that elsewhere, and which was preceded and followed by numerous intrusions of stocks, sills, and laccolites of hypabyssal rocks.

Finally, the Andes assumed their actual physiography by ultimate movements along the indicated old tectonic features : in addition to the general uplifting, block F was raised in comparison with A_2, block D over blocks B, and C, block a (Huayllamarca Range), between the Faults Chacarilla and Chiriquiña over neighbouring parts of the Altiplano, and the block on the left of the northern part of the Coniri Fault over block B.

§ 19. — The nature of so-called both Ichilo and Poopo Lines must be discussed. The Ichilo Fault of E. Rod (Ichilo Line in this report) has been suggested by E. Rod (1962) as a strike-slip fault in order to explain the E-W displacement of the Sub Andean Zone [4] North- and South-wards of the Ichilo Line. But along this line there is not a recognizable continuous fault, indicated by some break of the outcropping beds. In a general way, the outcropping Early Paleozoic beds are crossing out, and a field geologist would never be able to indicate the Ichilo Fault in an objective geological map. So that, the Ichilo Line cannot be a strike-slip fault along which the northern compartment would have been moved from East to West by a tangential force. On the other hand, the displacement of the Sub Andean Zone, as well as the presence of recognizable E-W faults (Tunari, Ivirizu, and Colorado Faults) along the Ichilo Line, and the Chiquitos graben indicate clearly a megatectonic value of this line.

Nearly the same remarks can be done for the Poopo Line, which on the East seems to coincide with the Ichilo Line. Along the Poopo Line, a geologically recognizable fault exists perhaps only across the Huayllamarca Range. Elsewhere, the Early Paleozoic beds cross the Poopo Line without any break. Nevertheless, as indicated above, that has a precise geologic meaning. The Hercynian orogenic metamorphic rocks and granites suddenly disappear South-wards of Poopo Line ; Cretaceous rocks are different in both sides of it, and it coincides with the northern boundary of the Devonian continental Proto-Puna.

So that we must conclude that such tectonic features represent Deep and Old Screens (D.O.S.) between primary subsurface independent blocks, which can evolute to give, locally or along all their extension, some geologically recognizable fault (Palca, Tunari, Coniri... Faults), but not necessarily. A similar character might have the transverse faults suggested by J. Debelmas and G. Trottereau (1964) in the Andes of Peru.

It is very interesting to note that the Poopo Line (Poopo D.O.S.) coincides exactly with the northern boundary of one of the four earthquake provinces indicated by Gajardo and Lomnitz (fig. 7) in Chile (in C. Lomnitz, 1962).

§ 20. — The preceding pages indicate that the geologic evolution of the Bolivian Andes, including stratigraphy, depends on mutual movements of

[4] From a stratigraphic point of view, the Sub Andean Zone is constituted by Marine Devonian, chiefly continental (Gondwana) Carboniferous and Permian (and Triassic ?), mainly continental Mesozoic and Cenozoic. Unconformities are known at the base of Carboniferous, between Permian and Mesozoic, and between Upper Cretaceous and Cenozoic. From a tectonic point of view, the Sub Andean Zone is constituted by gentle synclines separated by faulted narrow anticlines. Several overthrusts occur which put West to East faulted anticlines over contiguous synclines.

the blocks limited by the D.O.S. From this fact one can come to two conclusions. The first inference is that a generalized cross-section valid for the Bolivian Andes as a whole cannot be established. Each cross-section is valid for that part of the country which is constituted by the same contiguous blocks. So that, for example, a geologic cross-section established South of the Poopo Line

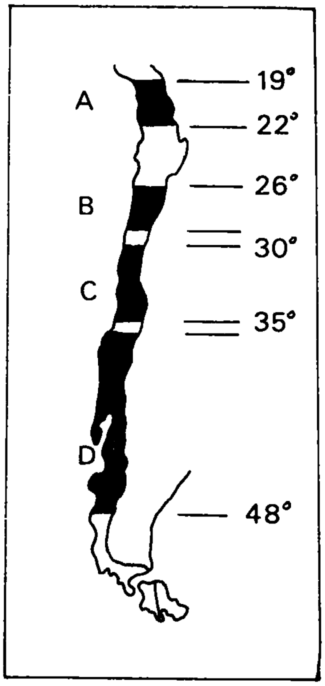

Fig. 7. — Earthquake provinces of Chile (after C. Lomnitz 1962). Northern boundary of province A coincides with the Poopo Line (compare with fig. 3).

would not have value North-wards of it. The second inference is as follows. As no mutual horizontal movements of the indicated blocks have been recognized through some slip at the intersection of the D.O.S. (see fig. 2 and 3, and discussion on Ichilo Line, § 19), one cannot think to primary tangential forces in order to explain folding. Consequently, the original width of a sedimentary basin cannot be reduced during folding.

Folding results from vertical movements of blocks, which can produce horizontal pressures in their cover blanket. Near the raising block the plastic beds of the cover are then stretched, their folds are often overturned from the raising block itself outwards, skin-deep reverse faults are originated, which disappear in schearing at depth, and gravity glides can also occur. Complexities can occur when a sedimentary basin is folded if it included several ridges and cuvettes, which moved, and move during folding, in a different way, like minor blocks. Between two main no contiguous raising blocks (which at last may be regarded as tectonic solid intrusions) opposite horizontal pressures occur, which can produce gentle folding, often complicated by movements of minor intermediate blocks. The first one is the tectonic style of the typical cordilleras, the second one of the intra-Cordilleran Zones.

§ 21. — Let us consider some examples. Apart from quaternary rocks, the Cordillera Real is constituted (P. Ljunggren and L. Radelli, 1964) by low-grade metamorphic chloritic and sericitic slates and quartzites (Milluni Formation), sericitic-muscovitic, and chloritic-biotitic slates (Condoriri Formation), muscovite, biotite, staurolite, and cordierite schists (Tikimani Formation), synkinematic ultrametamorphic metasomatic microcline Kutikucho granite, and postkinematic intrusive Huayna Potosi-type granitic bodies. From a chronologic point of view, the Milluni Formation belongs to the Silurian, the Condoriri and the Tikimani ones to the Ordovician. The granites were originated during Hercynian orogeny. The intrusive granitic bodies constitute the highest peaks of the Cordillera, from South to North : Illimani (6 480 m), Taquesi (5 550 m), Huayna Potosi (6 190 m), Chachacomani (6 140 m), and Ancohuma-Illampu (6 440 m).

From a tectonic point of view, the Cordillera Real can be divided into two parts (fig. 8). From the Huayna Potosi peak to the North, the tectonic trends coincide with the geographic one of the Cordillera, but South of the Huayna Potosi peak there is an angularity between tectonic and geographic trends. That is, an angularity exists between the tectonic features of the northern and of the southern part of the Cordillera Real. Consequently, one cannot suppose a generalized external compressive force in order to explain the uplifting of this block. A most interesting part of the Cordillera Real is that between the peaks of Huayna Potosi and Chachacomani (fig. 9). The structure of this part of Cordillera Real is dominated by two faults (Condoriri Fault on the W, and Chachacomani Fault on the E) striking parallel to the trend of the Cordillera Real itself, and arranged to separate two main counters. Each counter has a general structure of anticline, but because a

Fig. 8. — Tectonic trends in Cordillera Real.

a, Ancohuma-Illampu; b, Chachacomani; c, Huayna Potosi; d, Taquesi; e, Mururata; f, Illimani. Achacachi Fault trace is shown.

syncline does not exist between them it would be unright to apply such nomenclature to them. They can be better called wedges (composite wedges), as C. MIGLIORINI (1948 *a,* and *b*) did for similar structures of the Apennines. The question to resolve is whether such structure was produced by compression, distension, or by compression and distension. The study of the indicated two faults is very interesting for this purpose. Both Condoriri and Chachacomani Faults begin on the SE as vertical, normal faults. Towards the NW they become reverse, East plunging, faults and over-

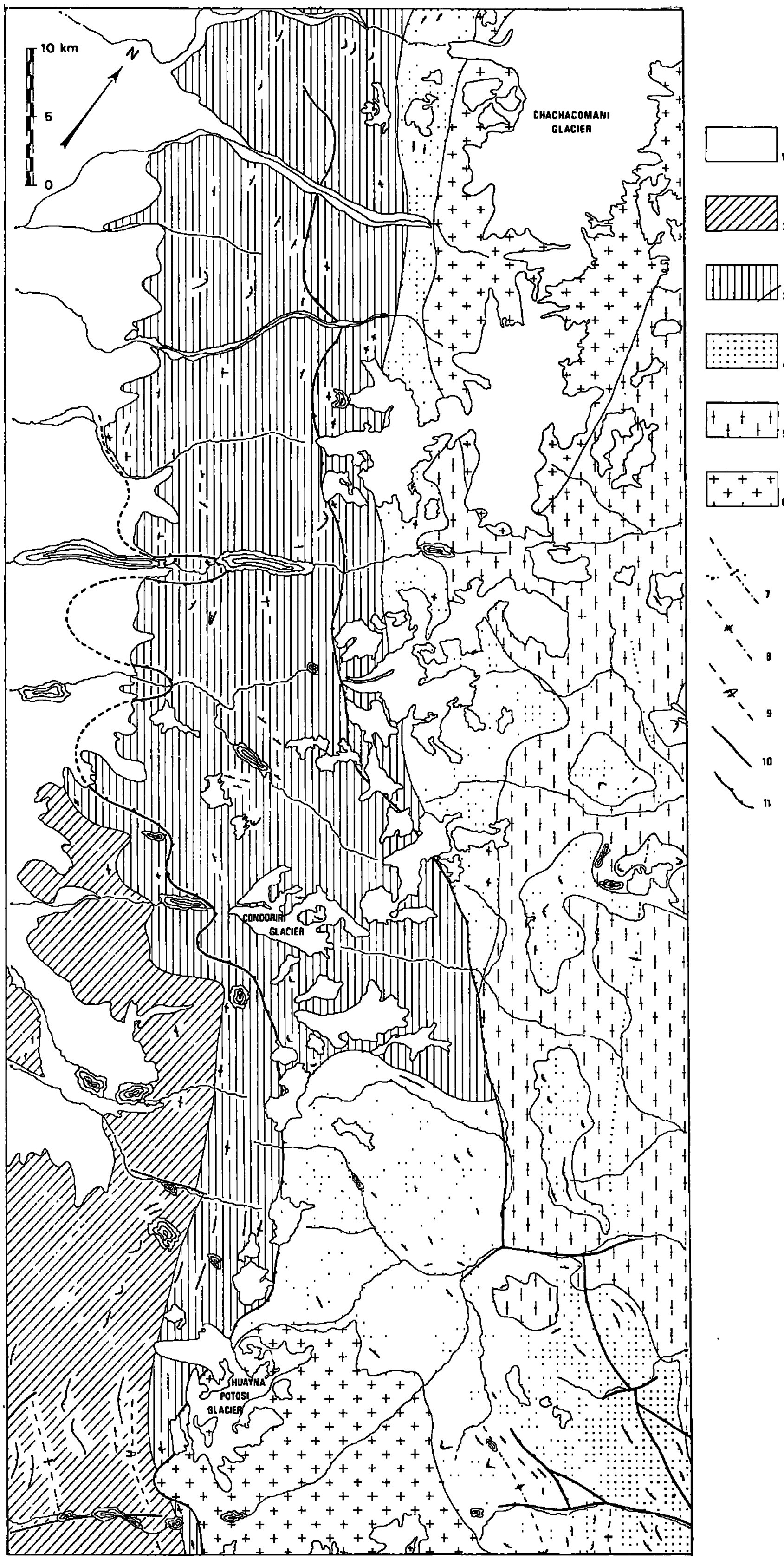

Fig. 9. — Simplified geological map of Cordillera Real between Huayna Potosi and Chachacomani peaks.

1, Glaciers and moraines (on the left); 2, Milluni Formation (chloritic and sericitic slates and quartzites); 3, Condoriri Formation (sericitic-muscovitic, and chloritic-biotitic slates); 4, Tikimani Formation (muscovite, biotite, staurolite, and cordierite schists); 5, Kutikucho synkinematic granite; 6, Huayna Potosi-type intrusive granites; 7, Anticline; 8, Syncline; 9, Reverse syncline; 10, Faults; 11, Reverse faults and overthrusts.

thrusts, and then they terminate as normal faults again (fig. 10 and 11). Vertical, distensional movements of the wedges is clearly recognizable where the faults are normal, and it appears that such movement originated the uplifts of the wedges and finally the actual cordillera. If that is true, as it seems, the actual tectonic structure can be regarded as originated through the bending of these normal faults, in places of their maximal throw, towards the W, where the falling of the contiguous block B produced an out of balance down-draught. So that, I agree with Migliorini in holding wedges responsible for the structure of a Cordillera, and on their geometric shape. But I reverse the Migliorini's hypothesis that wedges are originated by compression. I think that a wedge is primitively originated by distension through normal vertical faults, and that successively these normal faults evolve as reverse faults and/or overthrusts near the surface, by bending towards sagging contiguous blocks. The entire suggested movement results in an expansion. In this condition, the Migliorini's idea that a composite wedges structure consists « of a series of uplifted wedges, limited by faults that tend to converge in depth » can be admitted only for the structure of the cover blanket, where a main wedge can be split into a number of minor wedges (composite wedges or cunei composti). This suggested tectonic interpretation can be applied also South of the Huayna Potosi peak. Here each, generally granitized, main anticline is separated

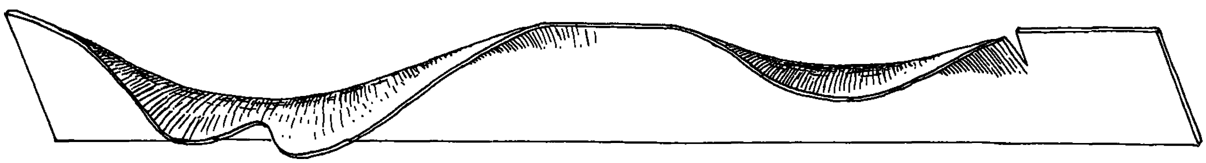

Fig. 10. — Attitude of Condoriri Fault.

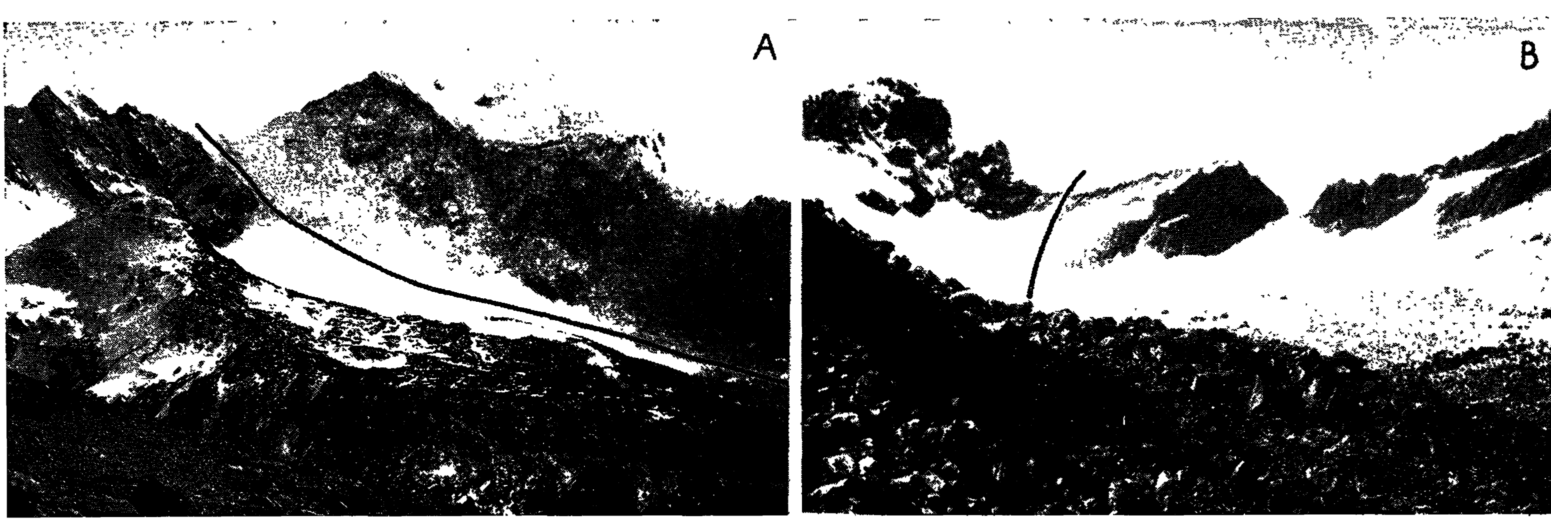

Fig. 11. — The Condoriri Fault in the neighbourhood of Huayna Potosi. Two views of Condoriri Fault show that in distance of less than 2 km, the attitude of fault changes from a nearly horizontal overthrust to a nearly vertical reverse fault, which becomes a normal fault in following SE mountain (compare with fig. 9 and 10).

A. View of Huayna Potosi looking NW. The Condoriri Fault trace is shown in photograph (granite is on the right, Milluni Formation on the left).

B. View of mountains SE of Huayna Potosi, looking SE. This photograph was taken from the same valley as photograph A. The Condoriri Fault trace is shown (granite on the left, Milluni Formation on the right).

from the contiguous main syncline by a fault zone, or by a strong flexure accompanied by drag folds.

An interesting example is that of the wedges of Illimani (anticline) and of Mururata (syncline). These two wedges are separated by a normal fault, the Achacachi-Ichilo Fault, and the trend of their axis is parallel to this main fault (fig. 12). So that, the wedges of Cordillera Real are

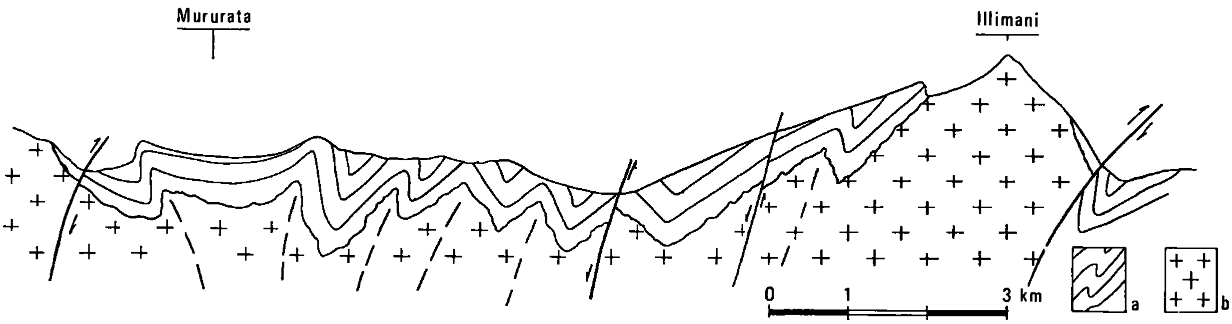

Fig. 12. — Diagrammatic geologic cross-section between Mururata and Illimani.
a, Metamorphic rocks; b, Intrusive granite (scale very approximate).

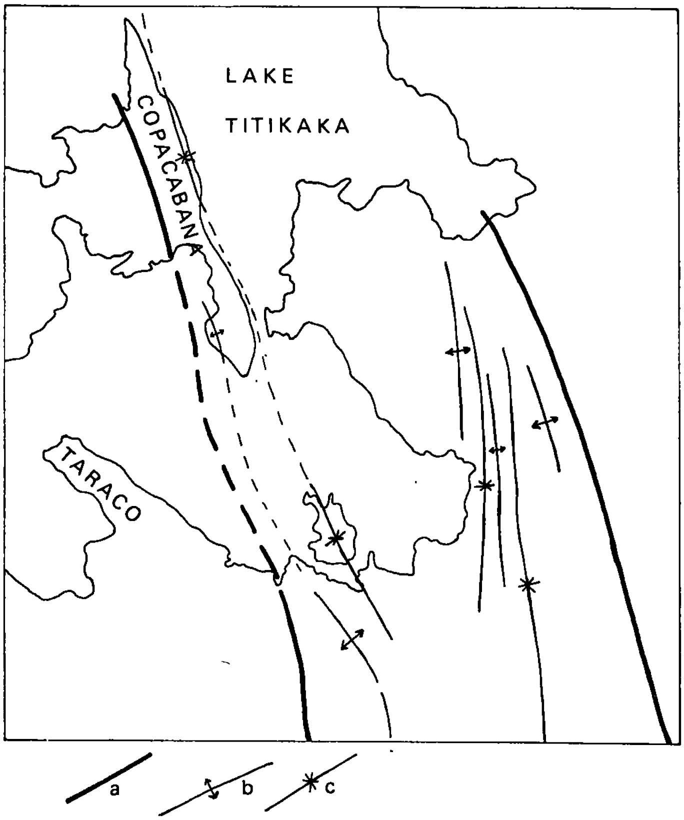

Fig. 13. — Tectonic trends between Coniri (left) and Achacachi (right) Faults. (Tectonics after field work. Topography gently simplified after NASA view. For scale compare with fig. 3.)
a, Fault; b, Anticline; c, Syncline.

always parallel to the Achacachi-Ichilo Fault. They trend NW-SE North of Huayna Potosi peak, where this main fault is directed NW-SE ; they become WNW-ESE on the South, where this fault takes such direction. That indicates clearly that the actual tectonic structure of Cordillera Real rather depends on the basic Bolivian tectonic features pointed out above. The fact that stratigraphic studies seem to prove that along these basic tectonic features (Deep Old Screens) movements occurred chiefly in a vertical way, is according to the suggested hypothesis that main wedges raised along normal distensional chiefly vertical faults, which can have been successively bended back near the surface, over sagging contiguous blocks.

Such parallelism between main faults (Old Deep Screens) and actual tectonic axis is recognizable also in block B (fig. 13). Near the Coniri Fault the axes of folds trend in a parallel direction with this turning fault (and with the Tiquina Fault). Approaching Achacachi Fault the axis of folds become parallel to this fault itself.

A composite wedges tectonic style is recognizable also in block F, where (C. CHERRONI, 1963) Paleozoic anticlines are limited in both sides by reverse faults which raised them over Cretaceous synclines (fig. 14), and in the Sub Andean Zone, as indicated above.

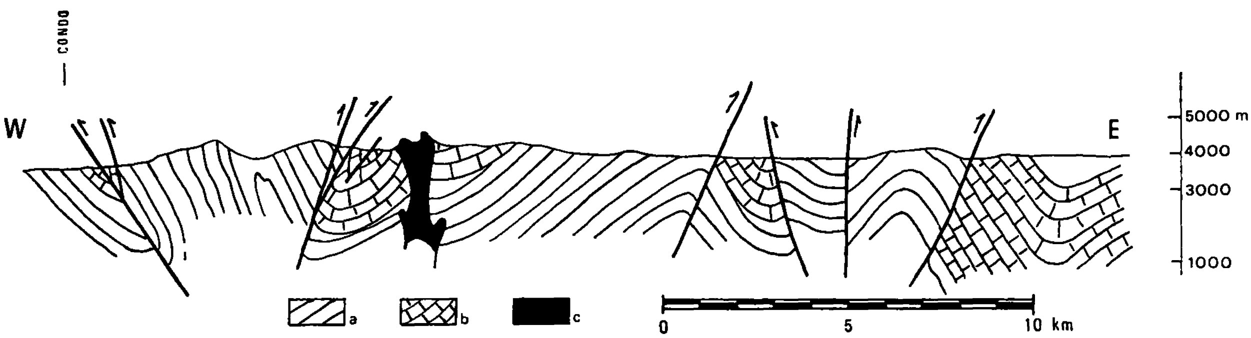

Fig. 14. — Geologic cross-section W of Lake Poopo (after C. Cherroni, simplified). a, Paleozoic; b, Cretaceous (+ ToroToro); c, Tertiary igneous rocks.

Finally a tectonic socle control is very easy to recognize in the eastern border of the marine Cretaceous basin. In fact, round about ToroToro Village, the tectonic axes of Cretaceous (+ ToroToro) folds do not coincide with which of the underlaying Paleozoic ones, but with faults which moved Paleozoic beds, as indicated in fig. 15.

§ 22. — In resume, this study permits some general conclusion about the geologic evolution of the Bolivian Andes. This evolution depends chiefly on vertical movements of some main blocks, which are separated one from another at depth by Old Deep Screens. From time to time, such features are revealed also on surface by recognizable actual faults (Achacachi, Coniri), but for the most part that does not occur. In this second case, the existence of such features can be revealed through study, as the case may be, of changing tectonic style and stratigraphy from one block to another,

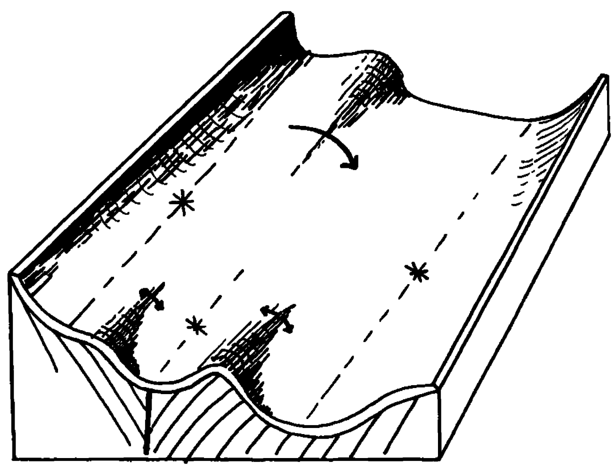

Fig. 15. — Diagrammatic attitude of Cretaceous (+ ToroToro) and Paleozoic beds near ToroToro Village (Cochabamba).

of seismographic province, and, as it seems, through study of photographs like that of fig. 1 and 2, where the Poopo Line and the Achacachi Fault are well recognizable. The effect of these basic tectonic features on the actual tectonic patterns of each part of the Bolivian Andes has been discussed.

Actual tectonic features are in many places parallel to the neighbouring Old Deep Screen. It seems allowable that actual structures were originated in the cordilleras through vertical movements of wedges along normal, distensional faults, followed by bending of these faults towards the contiguous structural lows, and/or gravitational gliding of beds in them when a lubricating blanket exists at their base. Horizontal pressures are believed to be originated in these lows during the raising of the wedges, which can produce true folding. The strong bend of the folds South and North of the Ichilo Line is regarded as depending on primary paleogeographic features, rather than on successive external compressions.

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