

THE STRUCTURE OF ECUADOR

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ABSTRACT. The territory of Ecuador can be divided into three tectonic provinces: Coastal, Eastern and Central. The study of these in the light of the writer's field observations as well as the known published data show that the Western Cordillera of Ecuador, of upper Cretaceous age, preceded the rise of the later Tertiary Cordillera Real. The former is magmatic while the latter is of geosynclinal and metamorphic constitution.

The structure of the three geological provinces is of block-faulted nature. Active volcanism and persistent seismicity of the cordilleras point to the direct effects of active tectonic forces still at work in this country.

INTRODUCTION

EXTENSIVE geological field work throughout most of Ecuador was carried out by the writer in 1938 and 1939 when in charge of field work for the Anglo-Saxon Petroleum Company. Additional investigations were also made in the writer's position as Honorary State Geologist for the government of Ecuador. The writer's notes were recently revised in the light of his later geological observations in the Andean region as well as in connection with the more recent geological data released by the oil companies operating in Ecuador. For specific geological information reference will be made to the existing publications. Particular emphasis in this study is placed on the tectonic movements in Ecuador and their relation to volcanism and the high seismicity of this part of the Andes, some of the effects of which have been witnessed by the writer.

Ecuador presents an interesting field of study of the intricate relations between tectonics, volcanism and seismicity.

TECTONIC PROVINCES OF ECUADOR

Three different tectonic regions or provinces corresponding to geographical divisions of the country can be distinguished in the structure of Ecuador:

- (1) The Coastal Province, extending between the Cordillera Occidental and the Pacific Ocean.
- (2) The Eastern Province or "Oriente," extending east of the Cordillera Real, toward the Brazilian Shield.
- (3) The Central Andean Province, embracing the high ranges of the Cordillera Real and Cordillera Occidental and the Inter-Andean Basin.

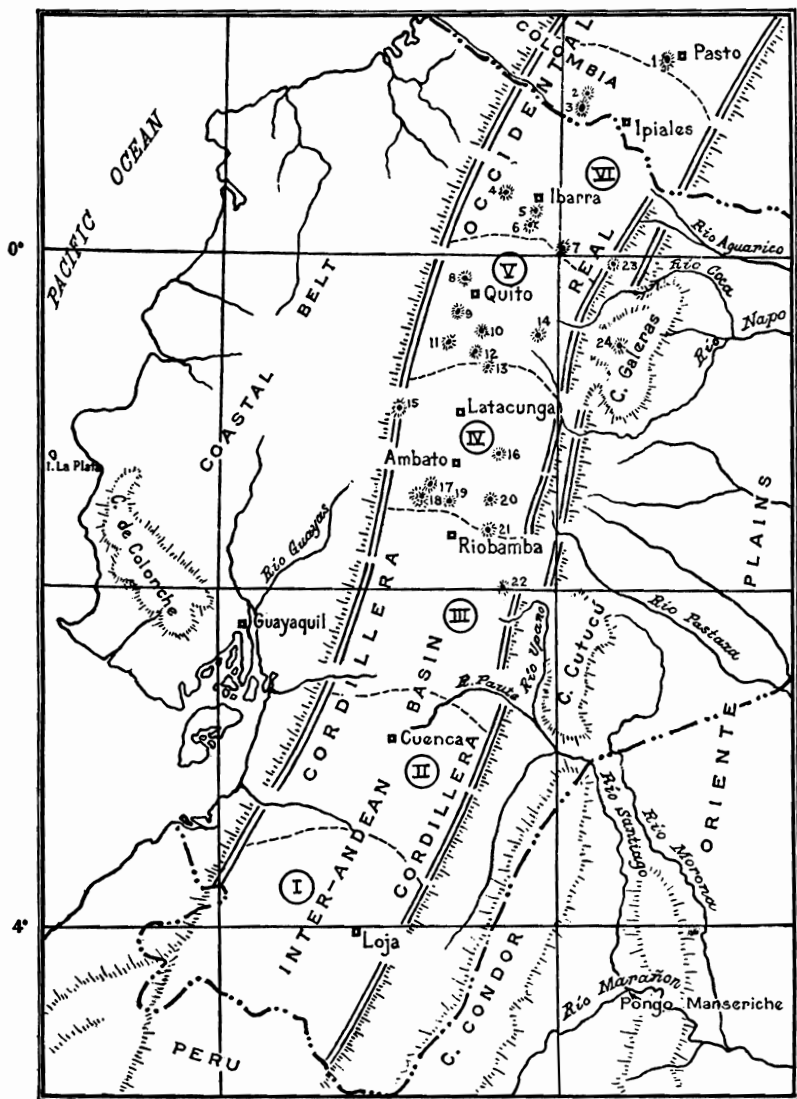
Each of these provinces shows distinct characteristics and diastrophic effects. The three are closely related, however, in

making this part of the Andes one of the very seismic and volcanic regions of the continent, tectonically still very active.

The Coastal Province.—An extensive fault at the foot of the Cordillera Occidental separates this cordillera from the coastal sedimentary belt. This fault has been described by Sheppard (1937); its southern continuation in northwestern Peru has been indicated by Iddings and Olsson (1928). To the north this fault zone continues with possible interruptions along the western foot of the Cordillera Occidental of Colombia as far north as the Choco region, where it has been observed by the writer in numerous outcrops (Oppenheim, 1949). Another great fault extends along the continental shelf from northwestern Peru, in a northerly direction, possibly as far as Manta. It passes west of the Island La Plata some fifteen miles west of the mainland of Ecuador. Although the continuation of this fault northwards and along the continental shelf of Colombia is uncertain, general faulting along the shelf in this direction could be expected. The Pacific Fault of Peru and its northern continuation appears, thus, to run parallel to the fault zone of the Cordillera Occidental. The coastal sedimentary belt, bounded by these two major faults or zones of faulting, appears in itself intensely fractured and faulted.

The sediments composing the coastal belt are Cretaceous and Tertiary strata of shallow water deposition. The Tertiary alone is about 7,000 meters thick. This would indicate a continuous subsidence of the coast throughout Cenozoic times. The rise of the western Andes, which began in Mesozoic times and continued throughout the Cenozoic, has evidently accompanied the foundering of the coastal belt and the formation of the great faults. The same forces could have also caused cross-faulting of the sedimentary belt by a number of minor fractures which trend to the northwest or from east to west. The intricate pattern of these faults is not always visible by surface observations and is best revealed in the many borings made on the coast. They indicate a complex tectonic block structure. The Eocene and Oligocene beds appear to be more intensely fractured and faulted, while the Miocene beds are much less so. This points to a lesser diastrophic activity in later Tertiary times. Folding also appears prominently in the Tertiary belt. The Sierra Colonche-Chongon is the highest range on the coast; striking in a northwesterly

STRUCTURAL SKETCH OF CENTRAL ECUADOR



Dib: A. Gujuelo

VOLCANOES

- | | | |
|--------------|---------------|-----------------|
| 1 Galeras | 9 Atacazo | 17 Carihuairazo |
| 2 Cumbal | 10 Pasochoa | 18 Chimborazo |
| 3 Chiles | 11 Iliniza | 19 Iguazata |
| 4 Cotocachi | 12 Rumiñahui | 20 Tunguragua |
| 5 Imbabura | 13 Cotopaxi | 21 Alter |
| 6 El Mojanda | 14 Antisana | 22 Sangay |
| 7 Cayambe | 15 Quilotoa | 23 Reventador |
| 8 Pichincha | 16 C. Hermoso | 24 Sumaco |

BASINS

I Loja - II Cuenca - III Riobamba - IV Latacunga - V Quito - VI Ibarra-Ipiales

== - Andean fault zones

direction, it seems independent of the Western Cordillera, but its core of igneous rocks suggests the possibility of its being a spur of the Western Andean batholith.

Numerous igneous intrusions in the form of dikes and sills have greatly affected the southern part of the coastal belt and particularly its Eocene and Oligocene beds. Less is known about the occurrence of intrusive bodies in the northern part of the Ecuadorian coast. They do not seem to be frequent in the sediments of the southern coast of Colombia, although igneous rocks form the foundation of the Gorgona Island off Colombia's coast. In Colombia widespread intrusions are related to the intense diastrophic movements of late Cretaceous and early Tertiary times, age of the rise of the Western Cordillera. The intrusions, as they occur in the sedimentary belt, could have preceded or followed the process of faulting.

The subsidence of the coast ceased completely at the close of Tertiary times and in the Pleistocene a distinct emergence of the Ecuadorian coast has taken place. Three levels of raised sea beaches or "tablazos" are known to extend along the coast of northern Peru and southern Ecuador. They have been described by Iddings and Olsson (1928) as well as by Sheppard (1937). Sheppard describes three levels of "tablazos" in southern Ecuador at approximately 3 meters, 80 meters and 150 meters above sea level. Along the northern coast the "tablazos" occur at considerably higher levels; on the Isla de la Plata they are known at about 30 meters, 160 meters and 250 meters respectively. The individual thickness of these raised sea beaches is of about 5 meters and their age as identified by numerous fossils (Barker, 1933) dates from early Quaternary to Recent times. This indicates that their rise must have taken place in Recent times and points to tectonic oscillations that are still taking place on the southern Ecuadorian coast. Contrary to this, the Pacific coast of Colombia shows the effects of submergence in its southern part and emergence along the Choco coast to the north. The tectonic pattern of the Colombian coastal sedimentary belt is also quite different from the Ecuadorian coastal belt. Faulting of the sedimentary strata in the former is of minor importance and the existing faults follow the trend of folding, which is generally north-south. The rise of the coastal Choco basin to the north is determined by a recent marine fauna found by the writer west of Quibdo at about 80 meters above the present sea level.

The Eastern Province.—The eastern flank of the Cordillera Real and the vast territory east of the Andes were studied by the writer (Oppenheim, 1943a), mainly in 1938 and 1939 during several expeditions in which hundreds of miles were covered on foot and in native canoes. Many of the reconnaissance observations made at this time broadened the earlier studies of Wasson and Sinclair (1927). In a recent publication Tschopp (1948) summarizes the stratigraphic data contributed by many petroleum geologists in the service of oil companies up to 1947.

The eastern flank of the Cordillera Real consists mostly of a series of metamorphic rocks, which the writer called "Andean System"; it drops abruptly from elevations of over 4,000 meters to the plains of the "Oriente," at about 500 meters above sea level. An extensive major fault bearing evidence of a widespread zone of fracturing and tectonic crushing extends along the eastern foot of the cordillera from the southern to the northern boundary of Ecuador. It continues farther into Colombia east of the village of San Francisco. Higher up the flank of the cordillera and to the west, several other large longitudinal faults have been recorded. The largest of these begins south of the valley of Rio Pastaza and continues past Topo and Baeza to Cerro Tigre on the Colombian border. This great fault marks a belt of tectonic depression and intense crustal deformation. At the southern end of this zone of faulting, and somewhat to the west, lies the active volcano Sangay (5,323 meters), while near its northern end and on the line of the equator, is situated another recently active volcano, Reventador (1,622 meters). The presence of these active volcanoes in this zone of tectonic weakness points to its persisting structural instability. A large granodioritic batholith extends to the east of the fault zone from the Pastaza Valley to the Valley of Rio Quijos. Similar granodioritic intrusions have been noticed in the same zone north of Reventador. The lavas of Reventador as well as Sangay are, however, of an unusual alkaline, nephelinic composition of a distinctly Atlantic type (Colony and Sinclair, 1928). The great fault zone at the foot of the Cordillera Real appears exposed in many sections; however, in parts of its northern extension the contact is covered by considerable thicknesses of "mesa" formations. Where exposed, the fault seems to be of a normal type, but

with local thrusting to the east. The orogenic forces were evidently directed almost vertically but a component from the west.

Rising above the "Oriente" plains, east of the Cordillera Real and between lat. $1^{\circ} 45'$ and 3° S., extends the Cordillera de Cutucu, explored by the writer in 1938 (Oppenheim, 1943a). It is a continuation of the Cordillera del Condor and the Cordillera Oriental of Peru. It appears extremely faulted and fractured along its western flank, where it is separated from the Cordillera Real by the synclinal depression of Rio Upano. A great number of igneous intrusions of different ages have affected this sedimentary range. The southern part of the Sierra de Cutucu appears divided; its eastern branch extends east of the Santiago River and crosses the Pongo de Manseriche where it joins the Cordillera Oriental of Peru. The western branch of the Cutucu mountains, as stated, forms the Cordillera del Condor. To the north the Sierra de Cutucu plunges under the Valley of Pastaza, reappearing as the Galera Mountains north of the Napo River. The volcano, Sumaco (3,190 meters) is the highest peak of this range. To the north the Galera Mountains flatten and disappear in the valley of Rio Coca and Aguarico. The western flank of the Galera Mountains, although largely covered by the volcanic ejectamenta of Sumaco, appears to be intensely fractured and faulted. The Cordillera Oriental of Colombia has, thus, no connections with the eastern ranges of Ecuador.

The eastern flanks of the Cordillera de Cutucu as well as the Galera Mountains expose a gentle eastern slope. The Oriente plains extending for great distances to the east towards the Brazilian shield, are folded into several large and successive anticlinal folds, striking in a north-south direction and gradually flattening to the east.

Several diastrophic phases have affected the complex tectonic history of the "Oriente" province (Tschopp, 1948). The earliest diastrophism is evident in the lower Paleozoic Gualaquiza Series of an apparently Caledonian cycle followed by volcanic activity in the later Paleozoic times. During the early Mesozoic the volcanism was accompanied by intense erosion and later continental sedimentation. The north-south trend of the tectogenesis has already been clearly outlined. During the late Mesozoic the rise of the geosyncline bordering the Cordillera

Real began to accentuate, and finally, in late Cenozoic, the last great diastrophic movement took place in the "Oriente" province, causing the final rise of the Cutucu and Galera Ranges and resulting in the folding of the young Tertiary "Oriente formation." This last cycle has brought about the intense faulting of the eastern flank of the Cordillera Real as well, probably, as the rise of the volcano Sumaco.

Tectonic activity along the eastern flanks of the Cordillera Real and at the eastern foot of the same cordillera is still in progress, as far as can be judged by the many "mesa" levels representing former river valleys that were raised several hundred meters in the process of recent tectonic uplifts.

The Central Andean Province.—As we have seen in the preceding outline, the Andean massive is bounded by great fault zones to the east and west. It rises abruptly above the Coastal and "Oriente" plains of a few hundred meters in elevation, to the great height of the Inter-Andean plateau at about 3,000 meters, above which rise the two rows of Ecuador's volcanic peaks which surmount the Cordillera Occidental and Cordillera Real. The base of the whole Andean range is in places only 100 kilometers wide, while its width in the upper part is about 60 kilometers. The highest peak of the Western Cordillera is the volcano Chimborazo (6,310 meters), while the highest peak in the Cordillera Real is the volcano Cotopaxi (5,943 meters). The comparatively narrow and elongated Inter-Andean basin separating the two cordilleras is largely filled with great masses of volcanic debris, tuffs and lavas. Thus, the contact between the two cordillera massives is completely obscured. Judging by the sharp differences in the rock composition of the two cordilleras, extensive zones of faulting and fracturing must exist along the inner base of the cordilleras facing the basin. These fault zones to the east and west of the basin outline the block structure of the Inter-Andean basin. This basin extends from south of Loja northwards and across the northern boundary of Ecuador into Colombia, where it may find its tectonic closure at the Pasto uplift. As previously stated, the great amount of pyroclastic materials and igneous flows obscure the intricate structure of this Inter-Andean basin. However, a physiographic study which has significant bearings on its structure indicates that the basin can be divided into a number of distinctly separate blocks, individually outlined by trans-

verse ranges or groups of volcanic cones. Thus, we have from south to north the Loja Basin, the Cuenca Basin, the Riobamba Basin, the Latacunga Basin, the Quito Basin and the Ibarra-Ipiales Basin. These inner basins form a block structure pattern. The Loja, Cuenca and Latacunga basins consist of Miocene or Pliocene continental sediments, several hundred meters in thickness. The sediments are intensely faulted and fractured and in the case of the Cuenca Basin also compressed into several folds. The northern basins are separated from each other by centrally located volcanoes or groups of volcanoes. The volcano Igualata (4,452 meters) separates the Riobamba and Latacunga basins; the volcanoes Pasachoa (4,255 meters) and Ruminahui (4,767 meters) limit the latter from the Quito Basin; the volcanoes Imbabura (4,382 meters) and Mojanda (4,280 meters) separate the Quito Basin from the Ibarra-Ipiales Basin. The latter is closed to the north by the volcano Galeras and the Pasto batholith of southern Colombia. The great Cauca depression between the Cordillera Occidental and Central of Colombia could be interpreted as a northern structural continuation of the Inter-Andean basin of Ecuador into Colombia. The Western Cordillera of Ecuador continues as the Cordillera Occidental of Colombia, where it is, however, considerably lower. The Cordillera Real of Ecuador continues throughout Colombia as the Cordillera Central. The Cordillera Oriental of Colombia forms a distinct branch of the Central Cordillera at about lat. 2° N. (Oppenheim, 1949). It bears no direct relation with any of the Ecuadorian ranges.

The Inter-Andean Basin of Ecuador suggests a similarity with the central Inter-Andean plateau of Bolivia. Both are wedged between high Andean massives situated along the edges of the main continental curvatures. However, while the Ecuadorian Inter-Andean block is placed on the outward bend to the northeast, the Bolivian Inter-Andean Basin (Oppenheim, 1947), the Puna block, is situated on an inward N.W. bend of the Andes. This position may partly account for the intense and complex tectonism of these two distant regions of the Andes. However, in Bolivia volcanism has ceased, while the orogenesis as shown by the rising "mesas" still continues (Oppenheim, 1943b). In Ecuador both factors are present and continue in an active stage.

The Cordillera Real consists mainly of metamorphic rocks such as gneiss, micaschists, and phyllites, with acid intrusives. The age of these rocks is uncertain and it may range from Pre-Cambrian to Paleozoic. It is evidently of a geosynclinal origin; hence the intense metamorphism of its composing elements.

The Western Cordillera is built mainly of great masses of pyroclastic materials and lavas of porphyritic nature. Diabase and granodioritic batholiths also appear in this cordillera. The extensive occurrence of recently described (Thalman, 1943) Upper Cretaceous sediments along the western flank of the cordillera indicates the age of this cordillera as uppermost Cretaceous. Its complex inner structure is little known. The absence, however, of crystalline formations (Tschopp, 1948) so typical in the Cordillera Real, clearly shows a different origin. The Western Cordillera rose in the late Cretaceous times, whereas the Cordillera Real reached its maximum growth at the close of Tertiary times (Oppenheim, 1947). The younger age of the Cordillera Real is indicated by the several historically active volcanoes, some of which continue to be active or to have been active recently (Cotopaxi, Tungurahua, Sangay, Sumaco and Reventador). Evidence of the continuous rise in Pleistocene times of the Cordillera Real can also be found, as stated, in the many "mesa" levels along the eastern flank of the cordillera.

Geophysical Data.—The results of gravity observations carried out by the oil companies operating in Ecuador have not been made public; however, judging from the data given by Tschopp (1948) as well as by O. F. Sundt (personal communication in 1945), it is evident that the eastern Andean range corresponds to a zone of typical geosynclinal conditions, showing minimum gravity. Thus, the gravity anomalies have a minimum near Latacunga of -201 mgl. Bouguer and -148 mgl. to the east, still in the Andean region at the confluence of the rivers Patate and Chambo, indicating a rise of gravity to the east. At the foot of the Cordillera Real at Mera the gravity rises to -143 mgl. Farther to the east across the "Oriente," the rise of the gravity anomalies is persistent and reaches at Tarqui, on the border with Peru, a maximum of $+14$ mgl. Bouguer. The rise of the gravity from the Andes eastwards reflects a mass deficiency under the Andes, and is

also due to the increasing nearness of the basement shield-rocks that underlie the sedimentary formations and culminate with the Brazilian Shield proper, east of the "Oriente." The rise of the anomalies east of the Andes is not uniform, and the many maxima observed in the reading correspond to geological structures, particularly anticlinal folds, in the sedimentary cover. Some of the maxima, however, reflect the presence of heavy masses in the deepseated basement underlying the sedimentary cover.

VOLCANISM AND SEISMICITY

The tectonic outline of Ecuador as one of the intensely fractured and faulted regions of the Andes finds its expected confirmation in the still-persistent seismicity marked by its many destructive earthquakes throughout historical times, as well as by the great number of active or latent volcanoes, one of which, namely Sangay, is one of the most active in the world. Although the relation of the deepseated causes of the continuous earthquakes and the past and present volcanic activity will necessarily remain obscure due to the impossibility of direct observations, it is evident that tectogenesis may cause seismicity and under certain conditions of crustal weakness may result in volcanic outbreaks.

Analyzing the volcanic activity in the Ecuadorian Andes, we find that within a narrow belt between lat. 2° S. and lat. 1° N. there are twenty-five volcanoes that show clearly preserved craters with comparatively recent lava flows; six of the volcanoes have been repeatedly active within the memory of man since the 16th century (Wolf, 1892). Of the twelve volcanoes of the Western Cordillera only the volcano Pichincha (4,777 meters) has been active in historical times (Sauer, 1943). Outstanding eruptions of Pichincha have been recorded in 1566, 1575 and 1582. The volcano was then quiet for seventy-eight years, until 1660 when a very strong eruption took place. The later, smaller eruptions of Pichincha were recorded in 1830 and 1881. The volcano has not been active since; however, judging by its past long intervals between eruptions, it cannot be considered as extinguished. The frequent minor local earthquakes in the area of Quito, which lies at the foot of Pichincha, undoubtedly bear relation to the inner activity of this volcano.

Reviewing briefly the volcanoes in the area of the Cordillera Real, we find that of thirteen outstanding volcanic cones, five have been active in historical times. The volcano Antisana (5,756 meters) had eruptions recorded in 1590, 1728, and 1801. Fresh lava flows have been observed at the western foot, probably of an eruption in 1871. The volcano Cotopaxi (5,943 meters) was first recorded in eruption in 1534; then it was very active from 1742 to 1768, after which it was quiet for thirty-five years until 1803. It was further intermittently active between 1845 and 1880. The volcano Tungurahua (5,087 meters) had its activity recorded during the following years: 1641, and intermittent eruptions between 1773 and 1781; a very strong and last eruption took place in 1886. The volcano Sangay (5,323 meters), the southernmost volcano of the Cordillera Real, has been in constant eruption, with undiminishing lava flows, during all historical times. It is one of the most active volcanoes known. Much less has been recorded about the two volcanoes east of the Cordillera Real; Sumaco was apparently active between 1865 and 1925 and Reventador was active in 1926. It is noteworthy to mention that the volcano Puracé (Oppenheim, 1950), in the Central Cordillera of Colombia, lies on the northern extension of the Ecuadorian volcanic range and is still active, although much less so than Sangay at the southernmost end of the range.

The above outline of the historic activity of the Ecuadorian volcanoes indicates that while volcanic activity in the Western Cordillera has almost ceased, it is still in an active stage in the eastern cordilleras of Ecuador.

Wolf (1892) describes twenty-four recorded earthquakes between 1541 and 1868, many of which repeatedly destroyed the largest cities of Ecuador, such as Quito, Ibarra, Ambato and Riobamba, causing many thousands of casualties in each locality.

The three large and destructive recent earthquakes that took place in 1939, 1942 and 1949, evidently reflect the same causes of crustal instability that are expressed in the complex tectonic pattern and volcanism in the Andes of Ecuador.

CONCLUSIONS

The three main tectonic provinces into which Ecuador can be divided indicate large-scale block faulting as their

structural pattern. Only slight thrusting exists at the eastern foot of the Cordillera Real.

The Cordillera Occidental of predominantly volcanic and pyroclastic composition is of Upper Cretaceous age, while the eastern Cordillera Real is composed of crystalline metamorphic, probably early Paleozoic, rocks and is evidently of late Tertiary to Pleistocene age of uplift. Hence the rise of the Cordillera Occidental preceded the uplift of the typically geosynclinal ranges of the Cordillera Real and the Sierra de Cutucu.

The Central Inter-Andean basin is a block-faulted intermediary depression zone forming a link between the old Western and the more recent Eastern cordilleras. It was probably brought to its much lower elevation along with the rise of the western edge of the great eastern geosyncline, and was later covered by a considerable thickness of more recent volcanic materials. Besides the extensive fault zones that limit this inner basin to the east and west, it is also divided into large blocks by transverse fracture zones.

The volcanic activity of the Cordillera Real, very active in historic times, coupled with the persistent magmatic activity of the volcano Sangay, indicate that the tectogenic processes in the Cordillera Real are still at work. The general rise of the Ecuadorian Andes is also evident in the different levels of raised sea beaches or "tablazos" along the coast as well as in the different levels of old river valleys, "mesas," on the eastern flank of the Cordillera Real.

Thus the recurrent earthquakes, some of which have been of recent destructive effects, as well as the existing active or latent volcanism, are reflections of the forces in the process of mountain-building which is actually taking place in this part of the Andes.

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BOGOTÁ

COLOMBIA