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Cretaceous Stratigraphy and Structure, Western Andes of Peru Between Latitudes 10°–10°30′[1]

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Abstract Cretaceous tectonics, sedimentation, and volcanism were dominated by oscillatory vertical movements of strips of basement bounded by major shear belts. Two main episodes of movement occurred: a Valanginian to Senonian episode of general subsidence, and a Senonian to Tertiary episode of uplift.

In the West Peruvian trough, the products of the first episode comprise a western shale-graywacke-volcanic facies and an eastern sandstone-limestone-shale facies. The facies meet along the Tapacocha axis, a major steep basement shear zone, which allowed the western side to subside faster than the eastern side.

Fracturing of the western block in its descent provided channels for volcanic eruptions, whereas, on the eastern intact block, shelf deposits were laid down. During uplift, the sediments on the eastern block were folded as a single unit by decollement on underlying shale; those on the western block were strongly deformed in narrow belts above steep basement fractures. The belt of strongest deformation is along the Tapacocha axis and was accompanied by metamorphism of greenschist facies.

The response of the Andes to lateral movement of oceanic crust beneath was to break into ribbonlike strips, parallel with the continental margin, which oscillated in vertical planes.

INTRODUCTION

The outcrop of the Cretaceous formations of the West Peruvian trough is divided geographically into a western Coastal region and an eastern Andean region by the intrusive complex of the Coastal batholith. In the Andean region of central Peru, nine distinct formations of shale, sandstone, and limestone occur whose ages are well established by stratigraphic and paleontologic evidence (Wilson, 1963). Their counterparts in the Coastal region are volcanic rocks with a less distinct stratigraphy and a scant fauna.

These volcanic rocks extend for at least 500 km along the Coastal region of northern Peru between Chancay and Trujillo (Fig. 1). They have been called the Casma Formation by Trottereau and Ortiz (1963), Cossío (1964), Cossío and Jaén (1967), Cobbing and Pitcher (1972), and Cobbing and Garayar (in press), but neither their stratigraphy nor their exact correlation with the formations of the Andean region was known.

This paper describes a section of these rocks 65 km long by 80 km wide which is present between the valleys of the Rio Huarmey and Rio Fortaleza, between lat. 10° and 10° 30′ S, west of long. 77° 30′ W (Fig. 1). The Casma Formation is raised to the status of Casma Group and is divided into six formations. The underlying Cretaceous rocks are transitional facies between the coastal volcanic rocks and the better known nonvolcanic sedimentary sequence of the Andean region. Together with the discovery of fossils in the Casma Group, they permit the first firm correlation of the coastal eugeosynclinal succession with the miogeosynclinal succession of the Andean region.

PREVIOUS WORK

The area has not been mapped previously and earlier work is scanty. The only rocks described from the area are in a 700-m section of shale and tuffaceous graywacke near Huarmey (Wilson, 1963, p. 8–9).

The regional stratigraphy and paleogeography of the Cretaceous of central Peru have been

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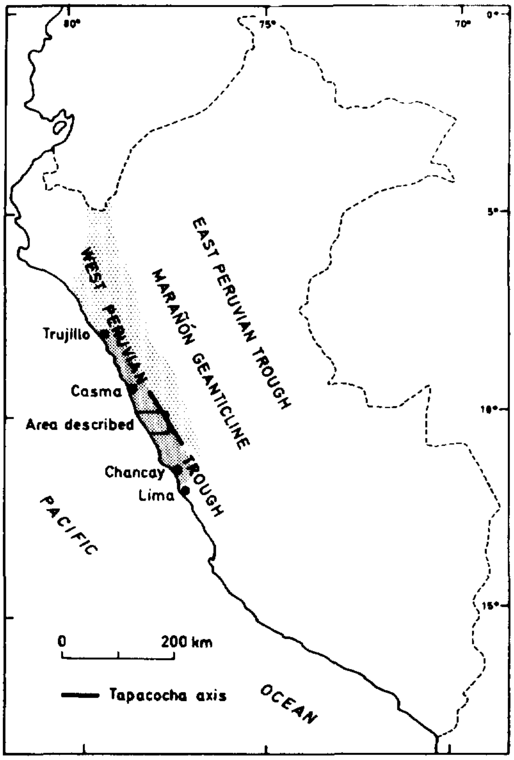


FIG. 1—Cretaceous framework of Peru, with location of East and West Peruvian troughs and Maranon geanticline after Benavides (1956) and Wilson (1963). Divisions of West Peruvian trough: eugeosynclinal facies and Casma volcanic rocks, dense stipple; miogeosynclinal facies, open stipple (after Peru, Servicio de Geologia y Mineria, 1969).

described by Wilson (1963), and of northern Peru by Benavides (1956). Benavides recognized that in Cretaceous time, the Andean belt consisted of two linear areas of subsidence, which Wilson (1963) called the West and East Peruvian troughs, separated by the Maranon geanticline (Fig. 1). The area described here is in the West Peruvian trough, which was shown by these authors to have consisted, during Early Cretaceous time, of a shallow basin, intermittently occupied by marine, brackish, and nonmarine environments. Generally marine conditions prevailed on the west, and the basin received incursions of terrigenous clastics from the east. Benavides and Wilson established that a major marine transgression took place during the Albian, submerging both the West Peruvian trough and the Maranon geanticline and that widespread emergence did not take place until the Santonian or Campanian.

Wilson (1963) discovered the lower and middle Albian ammonite *Lyelliceras* at Chancay (Fig. 1) in a volcanic and sedimentary sequence similar to that of the area described here, and tentatively correlated it with the Pariatambo Formation (McLaughlin, 1924; Benavides, 1956). At the same time, Trottereau and Ortiz (1963) proposed the name Casma Formation for similar sequences which they mapped near Casma (Fig. 1). Similar rocks were mapped northward as far as Trujillo by Cossío (1964) and by Cossío and Jaén (1967) and were referred to the Casma Formation. They recorded that it lies with marked unconformity upon the Tithonian Chicama Formation. No fossils were found, but they likened the sequence to that described by Wilson (1963) and Ortiz (1966) from Chancay, and they tentatively correlated it with the Chulec (Benavides, 1956), Pariatambo, and Jumasha Formations (McLaughlin, 1924).

The widespread predominance of such volcanic sequences in the Mesozoic eugeosynclinal successions of the Andes and the problems of their correlation have been discussed by Szekely (1966).

PHYSIOGRAPHY, ACCESS, AND FIELD METHODS

The area is 200–300 km north of Lima (Fig. 1) in the southern part of the Department of Ancash. It extends from the Pacific Ocean to within a few kilometers west of the summit of the Cordillera Negra, which forms the western range of the Andes in this part of Peru.

The area is divisible into two main physiographic units. The first unit is a high plateau which forms the northeast corner of the area. The plateau rises steeply 1,500–2,000 m above the adjacent southeastern topography and has a general elevation of 4,000–4,200 m. It consists of the middle-to-late Tertiary Puna erosion surface (McLaughlin, 1924), which is arched up toward the northeast. Hills rise above this erosion surface, reaching a height of 4,500 m. The second unit is a deeply dissected and very rugged landscape that forms the western flank of the Cordillera Negra. Two major episodes of deep erosion can be distinguished and resemble the Valley and Canyon stages recognized by Wilson *et al.* (1967).

The entire area is desert with almost no rainfall; minor amounts occasionally fall on the highest, northeastern corner during the winter. Settlement is confined mostly to the valleys of the Rio Fortaleza and Rio Huarmey (Figs.

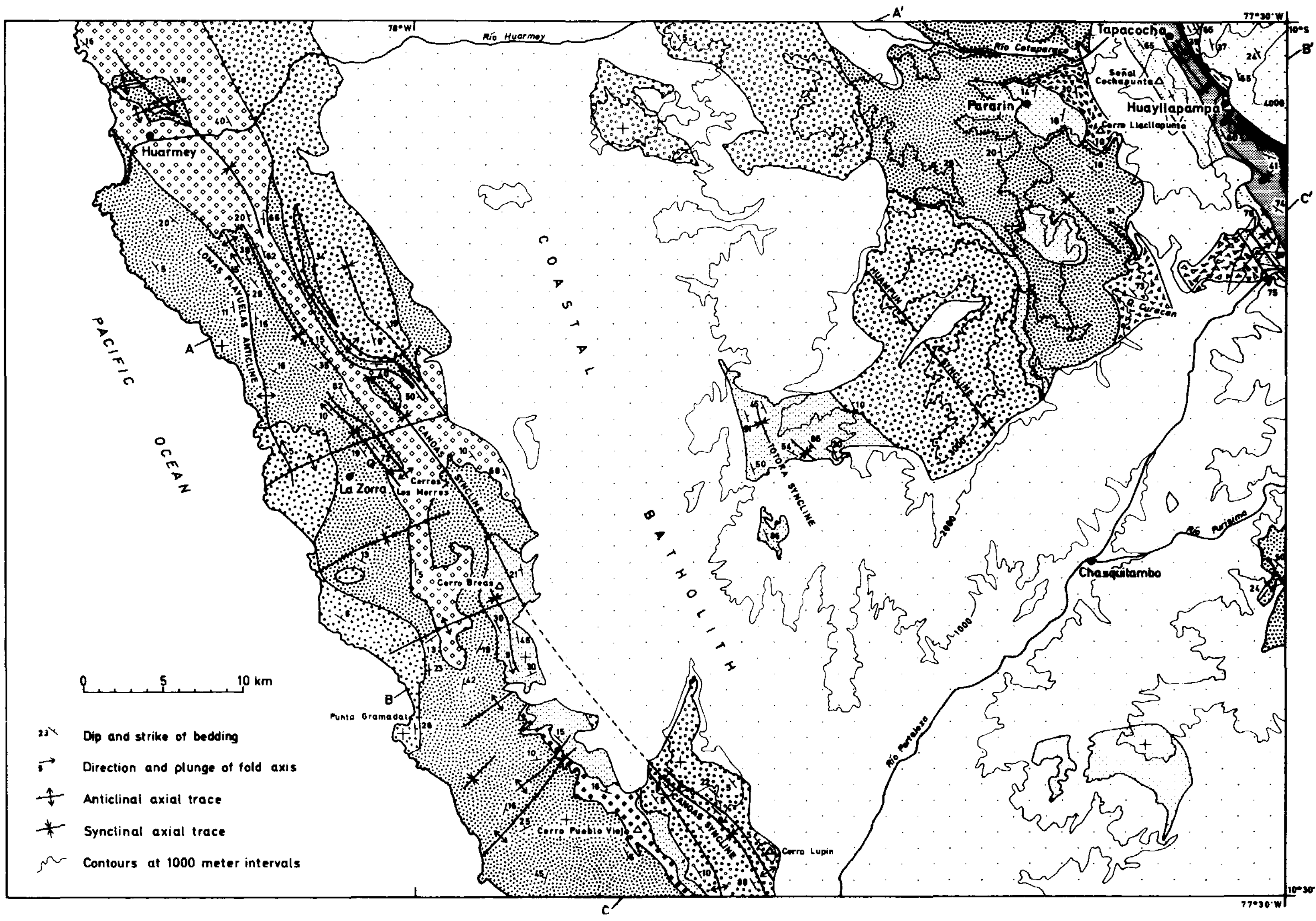


FIG. 2—Geologic map, lat. 10°-10°30'S, west of long. 77°30'W; location on Figure 1. See Figure 3 for map symbols and cross sections.

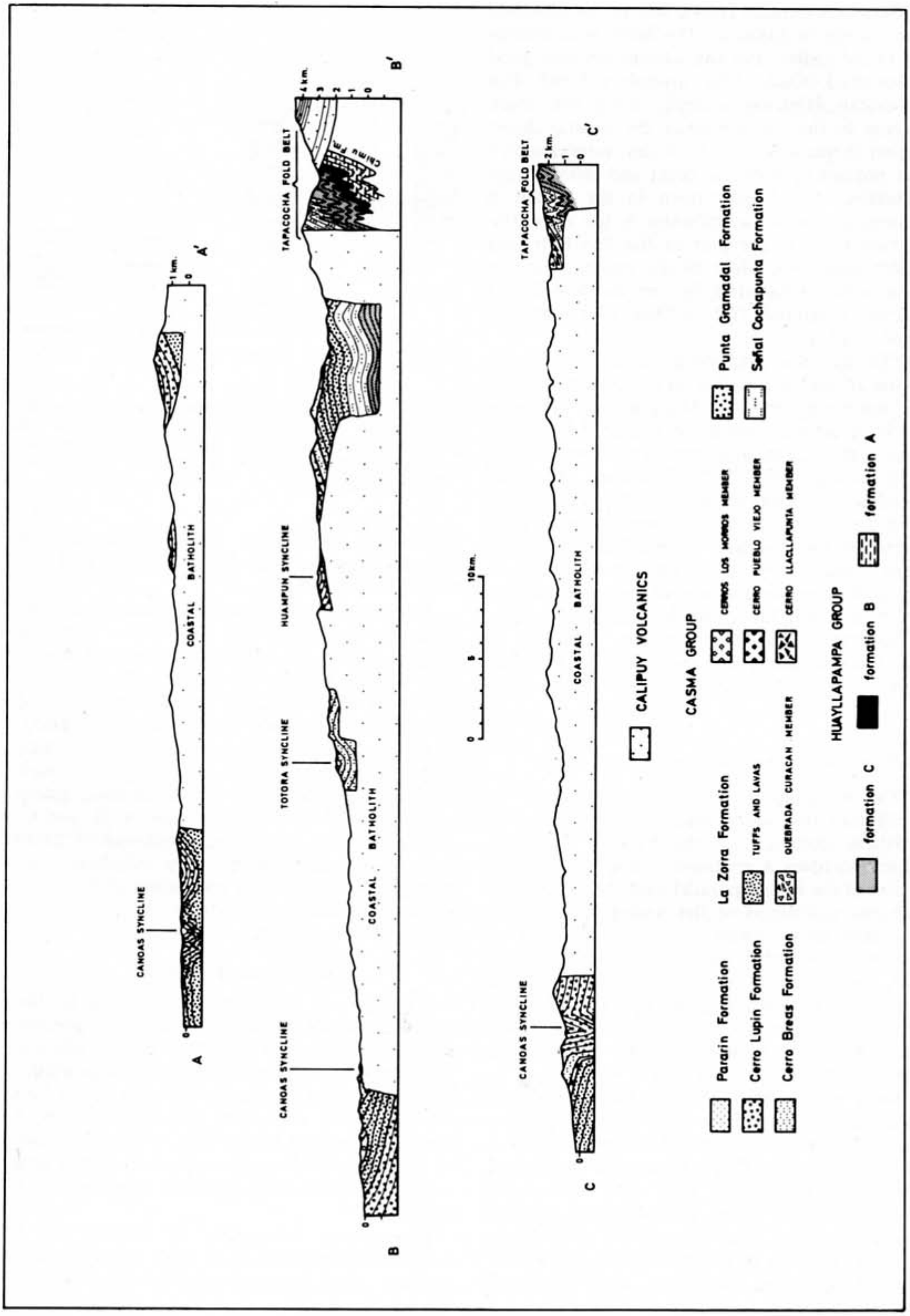


FIG. 3—Geologic cross sections (see Figure 2 for locations).

2, 3) which contain rivers, and to the dissected plateau above 3,000 m. The latter is accessible by bridle paths, and the former contain good unsurfaced roads. The asphalt-surfaced Pan American Highway extends along the coast. Access to the remainder of the coastal desert region is provided by four dry valleys which run normal to both the coast and the geologic structure. The largest town in the region is Huarmey, and Chasquitambo is the most important town in the part of the Rio Fortaleza valley described. Most of the buildings in the area were devastated by an earthquake of Richter magnitude 7.7 in May 1970 (Plafker *et al.*, 1971).

The area was mapped by covering as much of the ground as possible on foot, supplemented by photointerpretation. Mapping was done directly on air photographs at a scale of 1:50,000, during the 12 months that were spent in the field between 1968–1970. The final maps and sections have been prepared by transferring the data to 1:100,000-scale maps recently published by the Instituto Geografico Militar del Peru (sheets 21-g, 1969, and 21-h, 1971). A more detailed description of the area will be given in a bulletin of the Servicio de Geologia y Mineria, Lima, Peru, entitled "Geologia de los Cuadrangulos de Huarmey y Huayllapampa," accompanied by a map at the scale of 1:100,000.

Cretaceous Stratigraphy

The nonplutonic Cretaceous rocks are divided into two main areas of outcrop by the intrusive complex of the Coastal batholith, which occupies a continuous strip through the center of the region parallel with the local coastline and cordilleras of the Andes (Figs. 2, 3). The first area is west of and on the side of the batholith; the second is on the northeast, both on top of and at the side of the batholith. The Cretaceous rocks are chiefly sediments, pyroclastics, lavas, and sills, of which the volcanic rocks make up the greater part. Their average total thickness is 9,000 m.

West of the batholith, the Casma volcanic rocks are divided into four lithostratigraphic units which form the upward succession (Fig. 4, sec. *a*) of the (1) Punta Gramadal Formation, dominated by pillow lava and hyaloclastic breccia; (2) La Zorra Formation of andesite tuff, ignimbrite, and lava flows; (3) Cerro Breas Formation of chert, siliceous marl, fine-grained sandstone, limestone, and calcareous sandstone; (4) Cerro Lupin Formation of pillow-lava piles, hyaloclastic breccia, and waterlaid andesitic tuff.

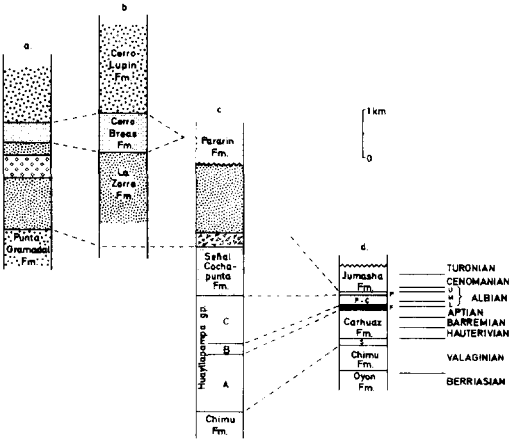


FIG. 4—Correlation of stratigraphic sections: **a,** western; **b,** central; **c,** eastern, eugeosynclinal succession of this report (symbols as on Figure 3); **d,** miogeosynclinal succession after Wilson (1963). *S.* Santa; *F.* Farrat; *P-C.* Pariahuanca-Chulec; *P.* Pariatambo Formations.

The upper three of these formations are also extensive on the eastern side of the batholith (Fig. 4, section *b*). In the eastern part of this region (Fig. 4, sec. *c*), the La Zorra Formation is underlain by a sequence of siliceous ash and chert called the Senal Cochapunta Formation. It passes gradationally downward into a thick group of shale, sandstone, and limestone which informally is called the Huayllapampa group and is divided into 3 formations, A, B, and C. This group has a minimum thickness of 2,400 m, and its components have lithologic and stratigraphic similarities with some of the widespread Cretaceous formations of the Andean region (Fig. 4, sec. *d*).

Huayllapampa Group

The base of the group is exposed in the northeast corner of the area where it overlies a sequence of bedded sandstone (Fig. 5, sec. *a*). The sandstone is predominantly orthoquartzite, forming layers individually between 1 and 500 cm thick, and is part of the miogeosynclinal Chimu Formation (Benavides, 1956). The base of the Huayllapampa group is transitional and is placed where shale becomes dominant over quartzite.

The lowest formation A consists of a 1,200-m sequence of gray shale which locally contains plant fragments and gastropods. It is

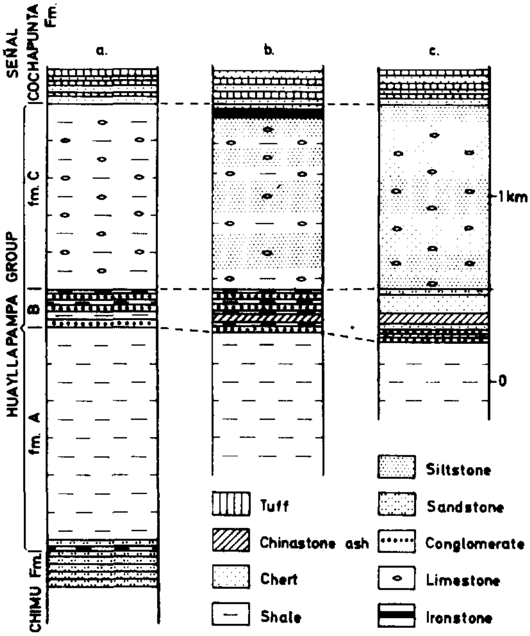


FIG. 5—Stratigraphic sections of Huayllapampa group along Tapacocha axis: **a**, through Tapacocha; **b**, through Huayllapampa; **c**, at long. 77°30′W (locations on Figure 2).

overlain by several thin beds of conglomerate (formation B) consisting of rounded orthoquartzite cobbles set in a friable matrix of white sandstone. The conglomerate beds locally are enclosed by red shale and together form a sequence 200 m thick. Southward the conglomerates pass into thick-bedded orthoquartzite. They are overlain by a 1,000-m succession of gray shale and slate (formation C), which contains thin bands and nodules of shelly limestone with large numbers of *Exogyra* sp. The shale and slate contain variably deformed ammonites (including *Parahoplites*?), lamellibranchs, and gastropods. The fauna includes *Ludbrookia, Carditidae,* a genus most commonly seen only in Lower Cretaceous rocks (Howarth, personal commun.).

Southeastward from Tapacocha, the gray shale and slate of formation C are replaced in increasing amounts by red-brown siltstone, but the shelly limestone nodules persist (Fig. 5, sec. *b*). Beds of siderite ironstone, individually up to 10 m thick, are present within the uppermost siltstone and tuff of the formation. Farther southeast the siltstone contains increasing amounts of cherty material (Figs. 5, sec. *c*).

The Huayllapampa group is strongly deformed and therefore its present minimum thickness of 2,400 m is not its primary thickness. Its correlation with the Cretaceous miogeosynclinal formations of the high Andean region is summarized in Figure 4. The shale of formation A is devoid of limestone and appears to represent a thicker, eugeosynclinal facies of the combined Santa-Carhuaz Formations of limestone, shale and siltstone (Benavides, 1956). They are capped by red shale and siltstone similar to that at the top of the Carhuaz Formation. The presence of plant fragments suggests that the formation represents a more rapidly subsiding and deeper water extension of the coastal-swamp environment envisaged by Wilson (1963) for the Carhuaz Formation.

The overlying orthoquartzite and orthoquartzite conglomerate of formation B are similar to those of the Farrat Formation (Wilson, 1963) and suggest a temporary westward advance of this miogeosynclinal facies. The thick overlying shale and siltstone of formation C contain thin discontinuous bands of shelly limestone and probably represent a eugeosynclinal facies of the miogeosynclinal Pariahuanca and Chulec Formations of shelly limestone, marl, and calcareous sandstone (Benavides, 1956).

Senal Cochapunta Formation

The name Senal Cochapunta Formation is proposed formally for a 1,000-m sequence of green and gray chert and tuff in the northeast corner of the area (Figs. 2, 3). The type section extends westward from Tapacocha over the northern flank of Senal Cochapunta. The formation is conformable on the uppermost formation C of the Huayllapampa group, at the top of which chert and tuff are interbedded locally with shale. The base of the Senal Cochapunta Formation is placed where chert and tuff become dominant over shale and siltstone. Throughout this section the chert and tuff are generally uniform and finely bedded. They contain small-scale crossbedding and washout structures in a few places. They pass gradationally upward into tuff and pyroclastic flows of the La Zorra Formation, and the top of the Senal Cochapunta Formation is placed where chert ceases to be dominant. Sections of the formation also are well exposed between Huayllapampa and the valley of the Rio Fortaleza (Figs. 2, 3).

Throughout its outcrop the formation has been deformed strongly in the Tapacocha fold belt, and the rocks generally possess a slaty cleavage and are metamorphosed to greenschist facies. No fossils were found in the Senal Cochapunta Formation but, because it grades upward into the La Zorra Formation which on the west passes gradationally downward into the Punta Gramadal Formation, it is considered to be an eastern equivalent of the Punta Gramadal Formation.

Punta Gramadal Formation

The name Punta Gramadal Formation is proposed for a 600-m sequence of pillow lava interbedded with tuff, tuffaceous graywacke, and both tuffaceous and bituminous limestone. The type section is exposed in the seacliffs south and west of Punta Gramadal (Figs. 2, 3), but the base of the formation was not seen. The lower parts of the formation consist of massive pillow lava. Where least altered, the lava consists of interlocking andesine laths with interstitial green hornblende, accessory ilmenite, and sparse quartz. Typically it is nonvesicular and is altered, plagioclase being replaced partly by sericite, hornblende by chlorite, and ilmenite is rimmed by sphene. In the uppermost part of the formation (Fig. 6) the pillow lava is interbedded with tuff and contains penecontemporaneous dikes and sills. Small pockets densely packed with ammonites are present in thin beds of calcareous tuff. The ammonites are preserved as internal casts of external molds and include *Hysteroceras orbignyi* (Spath), *Oxytropodiceras carbonarium* (Gabb), *Oxytropodiceras peruvianum* (von Buch), *Venezoliceras* sp., *Brancoceras* sp., and *Hamitidae*. A few genera of lamellibranchs and a variety of fish scales and aptychi accompany the ammonites.

The presence of *Oxytropodiceras carbonarium,* which in Peru is a zone fossil of the upper middle Albian (Benavides, 1956), indicates that part of the Punta Gramadal Formation is equivalent in age to the Pariatambo Formation of the central and northern Andes of Peru (McLaughlin, 1924; Benavides, 1956), part of the Muerto Formation of northwestern Peru (Fischer, 1956), and part of the Chonta Formation of eastern Peru (Kummel 1948).

La Zorra Formation

The name La Zorra Formation is proposed formally for a 1,800-m sequence of andesite lava flows, both andesite and dacite ignimbrite, tuff, lapilli tuff, agglomerate, and submarine pyroclastic flows. The type section extends southeastward from west of La Zorra to Cerro Breas (Figs. 2, 3). A similar section more easily can be traversed northeastward from Punta Gramadal to Cerro Breas. Its base is conformable with the Punta Gramadal Formation and is placed above the highest pillow-lava unit.

The most widespread rocks are andesite lava flows which are typically less than 10 m thick and exhibit well-developed columnar jointing. They form the bulk of the type section. Many flows possess rubbly, brecciated bases and their upper parts are vesicular. Vesicles typically are infilled by quartz, calcite, chlorite, and epidote. In many places pipe vesicles are common and

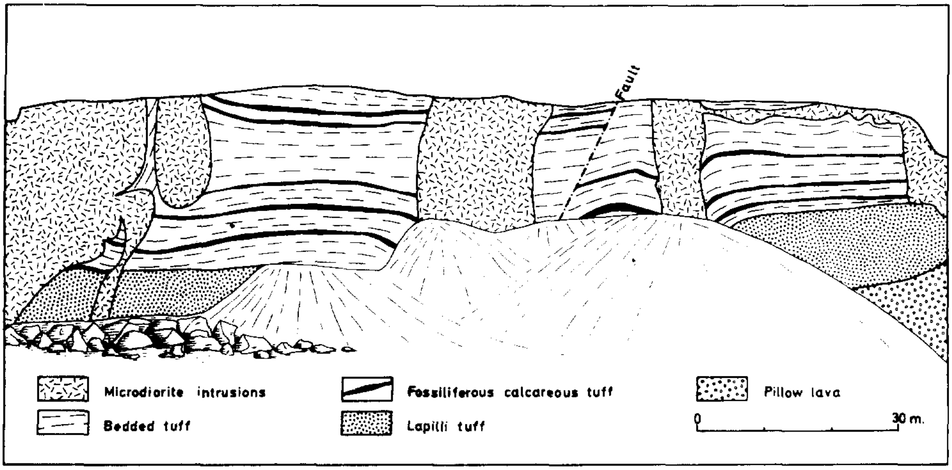


FIG. 6—Sea cliff of Punta Gramadal, section of top of Punta Gramadal Formation (location on Fig. 2).

are flow oriented. The vesicularity of the lava flows varies regionally.

Typically the lava flows are porphyritic and hyalopilitic, with phenocrysts of unzoned andesine up to 0.25 cm long and smaller amounts of pale-green twinned clinopyroxene. The phenocrysts are set in a holocrystalline, trachytic-textured matrix of andesine laths, pale-green twinned clinopyroxene, green hornblende, and ilmenite with minor amounts of interstitial quartz. Many flows are palagonitized, and the groundmass is altered to chlorite and clinozoisite with patchy secondary growth of calcite and some epidote. Some of the lavas are glassy and flow banded, and in many cases the flow banding is irregularly contorted. Many penecontemporaneous microdiorite sills are interbedded with the lavas.

Second in total volume to the andesite lava flows and sills are massive pyroclastic flows of both andesitic and dacitic composition. They are in units up to 500 m thick, interbedded with the lavas which they, in many cases, overlie unconformably. The pyroclastic flows are more variable in thickness and have a more irregular distribution than the lava flows. They display a wide range in both size and shape of fragments and show no vertical grading. Most of the fragments are of porphyritic lava similar to that interbedded with the pyroclastic flows, but a few fragments are of medium-grained granodiorite.

The four thickest pyroclastic flow members are shown on Figure 2; they are named but not defined formally. Two main types of pyroclastic flow are present. One type is characterized by many flattened shards, absence of amygdules, lack of stratification and welded base. In the second type, well preserved shards are uncommon, both matrix and fragments are rich in amygdules, fragments include both lava and tuff, and the units are stratified crudely by the presence of thin, discontinuous beds of graded tuff. The first type chiefly is present in the eastern part of the area (Quebrada Curacan and Cerro Llacllapunta members) and is the most abundant type, whereas the second type has been seen only in the western part of the area (Cerro Los Morros and Cerro Pueblo Viejo members). The first type is considered to be terrestrial ignimbrite, whereas the second type may represent pyroclastic mudflows produced by submarine eruptions.

The third major group of rocks, interbedded with the lava and pyroclastic flows, includes waterlaid pyroclastic breccia, tuff, and lapilli tuff. These rocks generally are sorted better than the pyroclastic-flow deposits, many are finely bedded, and size grading and crossbedding occasionally are present. Rock fragments typically consist of andesite lava, and dacite and andesite ignimbrite; crystal fragments are of plagioclase and clinopyroxene.

The fourth major group of rocks consists of fine-grained and fine-bedded waterlaid clastic sediments. They are restricted to the western outcrops of the La Zorra Formation and in most places appear to be derived from primary tuffaceous or eroded volcanic material. Thin beds of bituminous and tuffaceous limestone contain the external casts of evolute ammonites including *Hamitidae* and *Leymeriella* sp., shells and molds of lamellibranchs including *Inoceramus* sp. and *Cardita* sp., gastropods and aptyci.

The presence of *Leymeriella* sp., which is restricted to the lower and middle Albian, and of the late middle Albian species *Oxytropodiceras carbonarium* (Gabb) in the underlying Punta Gramadal Formation, indicates a late middle Albian age for the La Zorra Formation and its equivalence with part of the Pariatambo Formation of the miogeosynclinal facies of the West Peruvian trough.

Cerro Breas Formation

The name Cerro Breas Formation is proposed formally for a lenticular unit of chert and fine-grained sediment up to 800 m thick in the central and southern part of the area (Figs. 2, 3). The type section extends from southwest of Cerro Breas northeast across the Totora syncline. It is conformable upon the La Zorra Formation, from which it is distinguished by its finer grain size and absence of lava and volcanoclastic material. The lowest part of the formation consists of dark chert and thin-bedded quartzite which contain large amounts of organic material. They pass upward into thin-bedded pale-green chert and white impure quartzite and calcareous rocks which are, in turn, overlain by more massive white chert and siliceous rocks. Sedimentary structures other than fine banding are uncommon but include small-scale washouts and crossbedding.

The rocks are deformed and locally have a slaty cleavage which is associated with syntectonic greenschist-facies metamorphism in the Totora syncline. Most of the outcrop of the formation is within the metamorphic aureole of the Coastal batholith which overprints the syntectonic fabrics. Within the aureole the rocks are typically either garnetiferous quartzites or skarns with metamorphic assemblages including calcite, wollastonite, brucite, monticellite, idocrase, scapolite, epidote, green hornblende, tremolite-actinolite, garnet, quartz, and sphene.

Cerro Lupin Formation

The name Cerro Lupin Formation is proposed formally for a 1,800-m sequence of pillow lava and pillow-lava breccia with subordinate amounts of tuff. The type section extends northeastward across the southern part of the Canoas syncline to Cerro Lupin (Figs. 2, 3). Its contact with the underlying Cerro Breas Formation is gradational and its base is placed where pillow lava becomes dominant over chert. The succession consists of thick massive units of pillow lava and equal amounts of pillow-lava breccia interbedded with thinner units of waterlaid tuff. The latter is cross-laminated and shows graded bedding. The thickest unit of tuff, in the core of the Canoas syncline west of Cerro Lupin, contains small amounts of gray shale. The development of the Canoas syncline was associated with regional metamorphism which converted the shale into slate and quartz-plagioclase-hornblende-biotite schist. This metamorphism was overprinted by contact metamorphism of the Coastal batholith; consequently many of the pelitic rocks are now cordierite-sillimanite-quartz-plagioclase-biotite hornfels.

In the remainder of the area, southeast of Huarmey and in the Huampun syncline (Figs. 2, 3), the major units of the formation are coalescing ridges of pillow lava up to 1,000 m wide, 400 m high, and over 1,000 m long, which are flanked by interbedded pillow-lava breccia and tuff. The pillow-lava ridges are parallel with the present coastline and cordilleras of the Andes. The symmetric geometry of the piles suggests that they were erupted from Andean-trending fissures onto a fairly level sea floor. The pillow lava is brecciated increasingly toward the northwest, suggesting a steeper sea-floor gradient in that region at the time of eruption.

The pillow lava is similar in petrography to that of the Punta Gramadal Formation.

Pararin Formation

The name Pararin Formation is proposed for a 600-m sequence of lava and pyroclastic flows in the northeastern part of the area (Figs. 2, 3). The type section is in the mountain southeast of Pararin. The formation is unconformable upon the La Zorra Formation and its lowest part consists of altered and vesicular purple tuff. This dips moderately and is in turn overlain unconformably by a flat-lying sequence of green and purple dacite and andesite lava flows, ignimbrite, and tuff.

The formation is included in the Casma Group because it is spatially contiguous, of similar lithology, and in a state of alteration similar to the formations of the Casma Group. Its rocks are more altered than those of the nearby Calipuy Formation, which overlies the Huayllapampa group with marked unconformity (Figs. 2, 3), but the Pararin and Calipuy Formations are not seen in contact and no fossils were found in either formation.

CRETACEOUS STRUCTURE

Folds of the Cretaceous eugeosynclinal rocks trend in two directions; one is subparallel with the coastline and cordilleras of the Andes (Andean), whereas the other is at a high angle to the Andes (Andean-normal).

The Andean folds are present throughout the area (Figs. 2, 3). Their axial surfaces are subvertical and trend subparallel with the Andes, and their fold axes are subhorizontal (Fig. 7a). Generally antiforms are open and have broad hinge zones, whereas synclines are tighter, and the folds are of low amplitude and long wavelength. An exception is the Tapacocha fold belt, which is the most pronounced structure of the region and is anticlinal. This is described, together with the Canoas syncline and Lomas Playuelas anticline, which are typical representatives of the more widespread major folds. The Cretaceous miogeosynclinal deposits east of this area were folded as a single unit by decollement on a basement of the Berriasian–Upper Jurassic Oyon Formation (Harrison, 1960; Wilson *et al.*, 1967; Coney, 1971; Cobbing and Garayar, in press). Ribbonlike upright folds with subhorizontal fold axes traceable over 100 km developed in the center of the miogeosyncline. Toward the margins the folds were overturned outwards and at the margins, fold limbs were sheared and pass into outward-directed thrusts. Cobbing and Garayar (in press) described the eugeosynclinal rocks on the west as lying in a "province of structural tranquility." They inferred that there, the Cretaceous rocks form a relatively thin, flat-lying cover over the western foreland of the miogeosyncline. The structures described below are in this "province of structural tranquility" where general folding was not recognized previously.

Tapacocha Fold Belt

This belt lies in the northeastern corner of the area and includes rocks of both the Huayllapampa group and the Senal Cochapunta Formation (Figs. 2, 3). It is made up of many isoclinal and tight folds of low amplitude and short wavelength (Fig. 8). The axial surfaces of the folds are subvertical and the fold axes undulate between subhorizontal and gently plunging either southeast or northwest (Fig. 7b). Small-scale folds are present only in the hinge regions of major folds but are not developed commonly. The shale, siltstone, and other fine-grained rocks of the Huayllapampa group and Senal Cochapunta Formation have a strongly marked slaty cleavage which is subparallel with the axial surfaces of the folds. Both large- and small-scale boudinage of competent layers is widespread. Sedimentary structures indicate that the folds are upward facing. The formation of the fold belt was associated with greenschist-facies metamorphism.

The belt of isoclinal and tight folds is at least 6 km wide but its eastern limit is hidden beneath the younger Calipuy volcanic rocks. The belt extends at least as far as Aija, 25 km

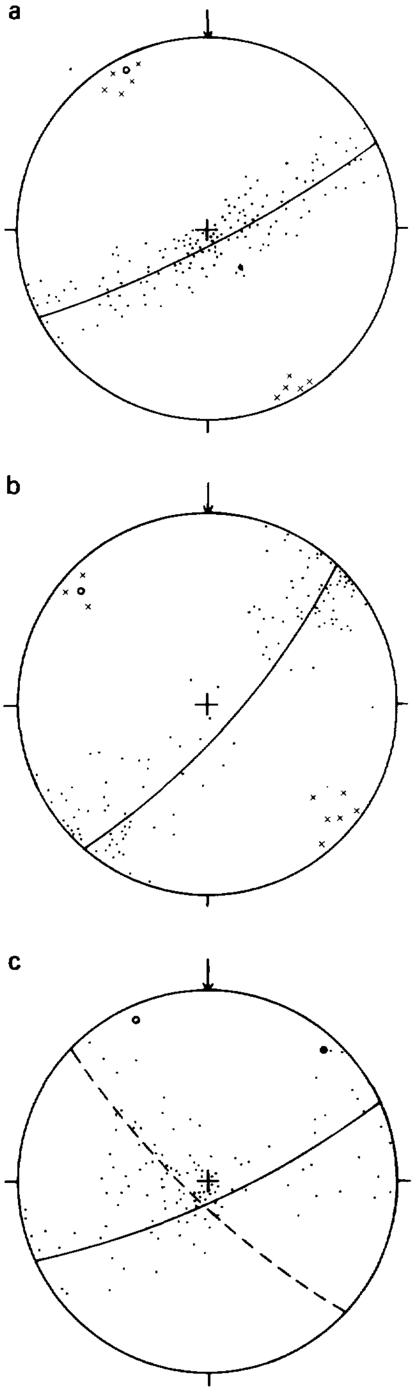


FIG. 7—Stereograms showing orientations of bedding surfaces; equal-area, lower hemisphere projections. Poles to bedding surfaces are dots; π circle of Andean folds is continuous line; π circle of Andean-normal folds is discontinuous line; measured fold axes are crosses; computed fold axes (π axes) of Andean folds are open circles, of Andean-normal folds are solid circles. **a,** Andean folds excluding Tapacocha fold belt. **b,** Tapacocha fold belt. **c,** Influence of Andean-normal folds in coastal area south of La Zorra.

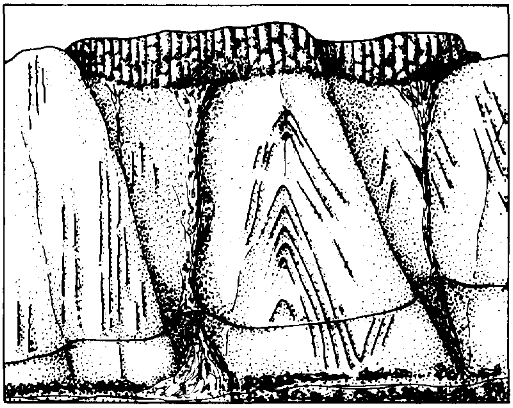


FIG. 8—Profile section of tight folds, Senal Cochapunta Formation, Tapacocha fold belt, unconformably overlain by late Tertiary ignimbrite with columnar jointing. View looking northwest; height of valley section 500 m (locality *P*, Fig. 2).

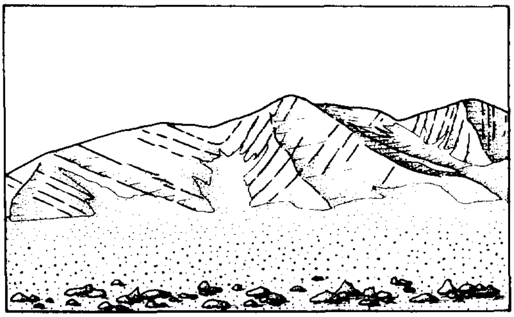


Fig. 9—Profile section of open asymmetric fold, La Zorra Formation, Canoas syncline. View looking northwest; height of valley section 100 m (locality Q, Fig. 2).

northwest (Bodenlos and Straczek, 1957). Southeast of the area, a combination of a moderate southeasterly plunge and downfaulting abruptly terminates the outcrop of tight folds and the Huayllapampa group. Only open folds of the Senal Cochapunta Formation are exposed and represent a higher structural level of the fold belt.

Canoas Syncline

This structure lies west of the batholith (Figs 2, 3). In the south it is 2–4 km wide and comprises a major isoclinal syncline and many smaller parasitic isoclinal folds. The folds have steeply dipping axial surfaces and are of low amplitude and short wavelength, similar to those of the Tapacocha fold belt. The fine-grained rocks have a strongly marked slaty cleavage, parallel with the axial surfaces of the folds. Crossbedding indicates that in some places the beds are overturned but that the folds are upward facing. Deformation was accompanied by metamorphism; acicular hornblende crystals are strongly aligned parallel with the axial direction of the folds, and a parallel lineation was produced by crinkling of biotite crystals which form an earlier foliation. These tectonic fabrics are overprinted by plagioclase, cordierite, and sillimanite porphyroblasts in the metamorphic aureole of the Coastal batholith.

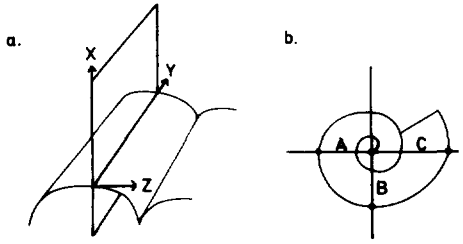
Traced northward, the fold opens and becomes an open syncline, unaffected by obvious metamorphism. The neighboring smaller folds are typically asymmetric with either subvertical or steep southwesterly dipping axial surfaces. Their northeastern limbs are shorter and dip more steeply than their southwestern limbs (Fig. 9).

Lomas Playuelas Anticline

This structure is near the coast (Figs. 2, 3) and is typical of the broad anticlines west of the Tapacocha fold belt. It has a subvertical axial surface, a subhorizontal fold axis, and a broad hinge zone. Its formation was not associated with obvious metamorphism.

Previously (Cobbing and Pitcher, 1972; Cobbing and Garayar, in press) it was considered that similar gently dipping Casma volcanic rocks just south of this area are little deformed. However in the area described here, the broad expanses of flat-lying beds represent the hinge zones of major anticlines. The presence of deformed ammonites in these localities allow calculations of the strain ratio which show that, although flat lying, the rocks are strongly deformed.

Deformed ammonites are present in five beds in the sea cliffs of Punta Gramadal (Fig. 6) near the center of the broad hinge zone of the Lomas Playuelas anticline. Complete specimens of *Hysteroceras orbignyi* (Spath) from the lowest of these fossiliferous beds were measured and the strain ratio determined by Blake's method (Blake, 1878). This method requires that the ammonites be well preserved, that they



c.

Fossil	A	B	C	Strain ratio	% Shortening
1	9	9	14.5	1.28	23
2	8	7.5	10.5	1.2	17
3	10	9	13	1.28	23
4	10	11	16.5	1.18	17
5	15	13	18	1.27	23
6	14	12	16	1.25	20

Fig. 10—Strain measurements of deformed ammonites *Hysteroceras orbignyi* (Spath): **a,** Lomas Playuelas anticline with orientation of strain ellipsoid axes X, Y, Z; **b,** ammonite showing measured lengths A, B, C; **c,** table of measurements A, B, C in millimeters, computed strain ratios and percentages of shortening.

be strained homogeneously with their matrix, and that the direction of the principal axis of the strain ellipse in the surface of the ammonite be known. All these factors are satisfied; the ammonites are preserved as casts of internal molds and are composed of the same material as their host; they lie in the plane of the bedding near the center of the broad hinge zone of an upright open anticline where the stratification is subhorizontal. The axial surface of the fold is vertical and its fold axis plunges at less than 5°. The bedding is therefore the YZ plane of the strain ellipsoid $X > Y > Z$ (Fig. 10a).

From the method of Blake (1878), the strain ratio Y/Z is $\sqrt{AC/B}$ (Fig. 10b). If it is assumed that there was no extension in the X direction, then the strain ratio also gives the percentage shortening, and these figures are given in Figure 10.

Andean-Normal Folds

Andean-normal folds are present west of the batholith (Figs. 2, 3). They are open folds with vertical axial surfaces and their fold axes plunge gently northeastward. The effect of their superposition on the Andean folds can be seen by comparing Figure 7c with Figure 7a.

In the southern part of the Canoas syncline, the phyllite and slate have a cleavage which trends east-west and dips moderately northward. This cleavage cuts across the Andean folds and fabrics and may be related to the Andean-normal folds. The latter may therefore have developed just after or during a late stage of the formation of the Andean folds while that part of the Canoas syncline was still the site of higher temperatures than the surrounding rocks.

Age

The Andean folds are overlain with marked unconformity by the terrestrial volcanic rocks of the Calipuy Formation in the northeast corner of the area (Figs. 2, 3). Elsewhere (Wilson *et al.*, 1967; Cobbing and Garayar, in press), the Calipuy Formation unconformably overlies the Casapalca Formation which is also folded into Andean folds. The age of the Casapalca Formation is post-Santonian (Wilson, 1963; Wilson *et al.*, 1967) and is thought to be Campanian. The age of the Andean folds is therefore either very Late Cretaceous or early Tertiary, as it is post-Campanian and preceded uplift, erosion, and the accumulation of the early Tertiary Calipuy Formation.

Both Andean and Andean-normal folds are cut by the Coastal batholith and their tectonic fabrics are overprinted in its metamorphic aureole. The same batholith also extensively intrudes the Calipuy Formation (Cossío and Jaén, 1967).

East of this area, the Calipuy Formation is folded by a younger generation of Andean folds which are open and upright, and predate the middle-to-late Tertiary Puna erosion surface. In the area of this report, the gentle eastward dip of the Calipuy Formation may be the result of this younger deformation and, if so, then the Andean folds may have been reactivated mildly by a younger coaxial deformation. However no direct evidence of such refolding has been seen; probably the post-Calipuy Formation deformation died out toward the northeast, as Cobbing and Garayar (in press) noted that the intensity of this deformation increases eastward in the region southeast of the study area.

CONCLUSIONS

The Tapacocha axis was a movement line which created the major facies division of the West Peruvian trough (Figs. 1, 11, 12). It is overlain by the Huayllapampa group, which represents the interleaving of Neocomian, Aptian, and Albian miogeosynclinal and eugeosynclinal facies (Fig. 12).

The uppermost shale of the Huayllapampa group is interbedded with chert and bituminous limestone which pass upward into thicker bedded chert, siliceous limestone, and tuff of the Senal Cochapunta Formation. The latter is overlain conformably on the west by lava and pyroclastic flows and tuff of the La Zorra Formation which, farther west, pass downward into pillow lava of the Punta Gramadal Formation. The presence of *Oxytropodiceras carbonarium* and *Hysteroceras orbignyi* in the upper part of the Punta Gramadal Formation indicates that at least this part of it is the same age as part of the Pariatambo Formation. The Senal Cochapunta Formation is contemporaneous with the upper part of the Punta Gramadal Formation and thus, together, they represent eugeosynclinal facies of part of the miogeosynclinal Pariatambo Formation. They show that lava eruption was confined to the west at that time and was replaced eastward by the accumulation of progressively finer grained pyroclastic deposits, which were followed by cherts. These thin abruptly over the

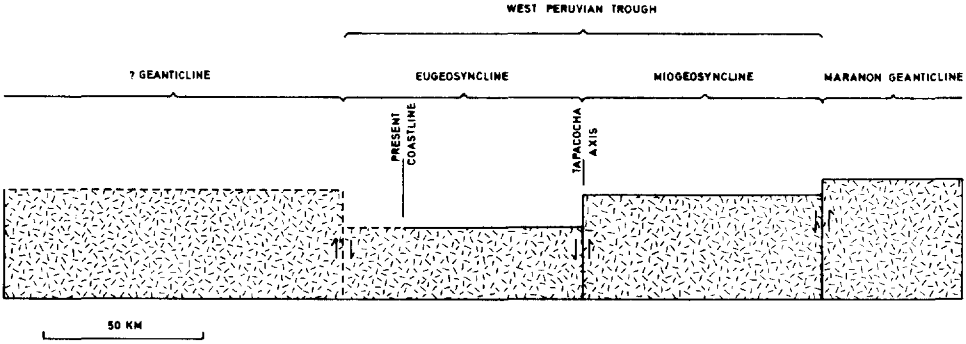


FIG. 11—Diagrammatic section across western Andes at lat. 10°S showing sum of Valanginian to Senonian upper crustal movements and location of Tapacocha axis. (Vertical scale twice horizontal scale; pre-Valanginian rocks patterned).

Tapacocha axis and pass eastward into thinner and more calcareous shelf deposits.

The La Zorra Formation indicates the spreading of volcanic activity with submarine deposition of pyroclastic material over the entire eugeosynclinal area. In the lower part of the formation, submarine lava and pyroclastic flows are abundant in the west and are replaced eastward by dominantly air- or water-transported pyroclastic material, indicating that the center of volcanic activity remained in the west. The increasing abundance of subaerial ignimbrites in the upper, eastern parts of the formation indicate emergence of the latter area and migration of subaerial eruptions eastward, whereas in the west volcanism remained submarine. The presence of *Leymeriella* sp. in the western part of the La Zorra Formation indicates that it too is equivalent in age to part of the miogeosynclinal Pariatambo Formation.

The overlying sediments of the Cerro Breas Formation are free of volcanic debris and reflect a temporary northward shift of volcanism. The widespread pillow lavas of the Cerro Lupin Formation record the subsequent spread of submarine volcanism over the entire area. This was followed by regional uplift, tilting, and the accumulation of the subaerial volcanics of the Pararin Formation.

Folding, uplift, and erosion followed between the Campanian and early Tertiary. The eugeosynclinal Casma Group of volcanic rocks was folded into both Andean-parallel and Andean-normal open, upright folds. The major Andean-parallel synclines appear to pass downward into narrow belts of more intense deformation and greenschist to almandine-amphibolite-facies metamorphism. These belts may be the upward reflection of Andean-parallel shear zones in the basement which were formerly the conduits up which the Casma volcanic rocks were erupted and which later fractured to form the steep walls of plutons of the Coastal batholith.

The strongest deformation occurred along the Tapacocha axis, forming an anticlinal fold belt of upright isoclinal folds, associated with greenschist-facies metamorphism. This axis

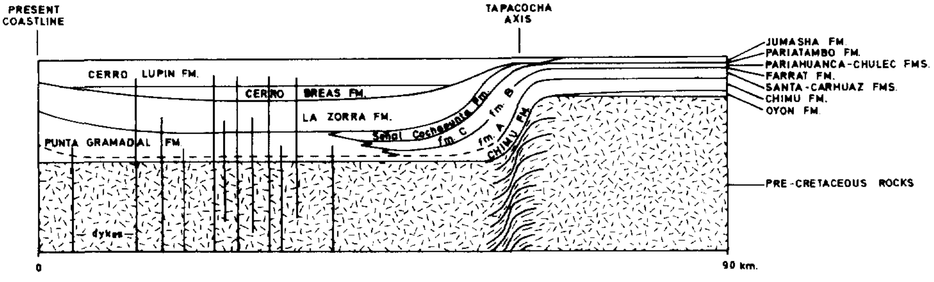


FIG. 12—Stratigraphic relations of Casma Group and Huayllapampa group with Cretaceous miogeosynclinal formations (after Wilson, 1963). Vertical scale twice horizontal scale.

continued as a major line of weakness to form the eastern edge of the Coastal batholith, emplaced by stoping into the eugeosynclinal rocks and their already fractured basement.

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