Vertical crustal movements of the Andes in Peru

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Although the Peruvian Andes provide no evidence of the widespread, strong deformation which might be expected in a tectonic belt widely held to overlie a zone of oceanic subduction, consideration of the tectonic and magmatic history shows that the occurrence of large scale, vertical block faulting in that region is not incompatible with a plate tectonic model.

THE important association between vertical crustal movements and magmatism during the evolution of the Andean mountain range was recognised[1,2] in the nineteenth century. Most mountain belts later became interpreted in the light of alpine tectonics[3] and comparisons with the Alps continued throughout the period during which mountain belts were viewed as expressions of the final phase of geosynclinal cycles. The concept of plate tectonics eventually emphasised the fundamental differences between many mountain belts[4], but the Andes was equated[4] with the cordilleras of western North America where it was postulated that major doming of the continental margin above underthrust oceanic lithosphere has caused overthrusts on the continent and the spread of sediments over the adjacent oceanic crust. There is little supporting evidence for this hypothesis in the Peruvian Andes[5,6], where consideration of the past 100 Myr of tectonic and magmatic history suggests a tectonic model which is different from that postulated[4] for western North America. The description is based on detailed mapping of the western Andes between latitudes 10° and 10° 30′ S (ref. 7) and published descriptions of adjacent regions[8-10], supplemented by radiometric age determinations (P. A. Wilson, unpublished).

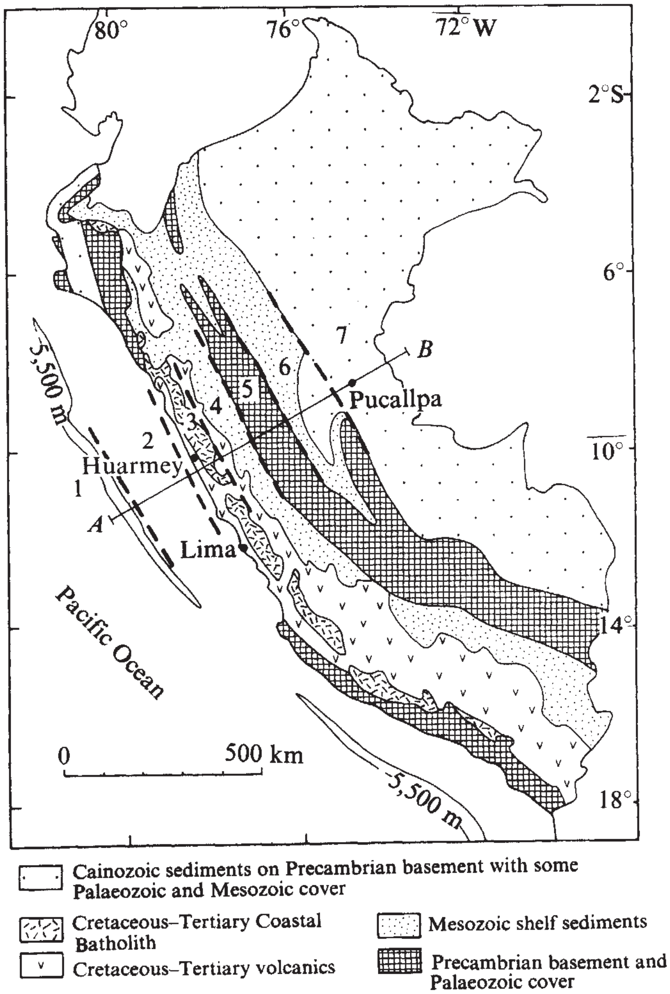

Fig. 1 Simplified geological map of Peru (after ref. 13) showing the tectonic framework of northern Peru during Cretaceous and early Tertiary time. 1, Oceanic crust; 2, Paracas Geanticline; 3 and 4, West Peruvian Trough (3, Paramonga Block; 4, Chavin Block); 5, Marañón Geanticline; 6, East Peruvian Trough; 7, Brazilian Shield. *A–B*, line of sections of Figs 2, 3 and 5.

Regional tectonics

During Cretaceous time, northern Peru consisted of two ribbon-like belts of subsidence known as the West and East Peruvian troughs[8,11] (Fig. 1). They were separated by a belt of relative uplift, the Marañón Geanticline[8], and a second belt of relative uplift, the Paracas Geanticline[12], formed the western edge of the continent. Each belt was founded on a block of Precambrian basement with thin Phanerozoic cover[13], and was bounded by steep fractures and shear zones. Oscillatory vertical movements of these ribbon-like blocks controlled both the deposition of sediments and their near-surface deformation from at least Cretaceous to early Tertiary time.

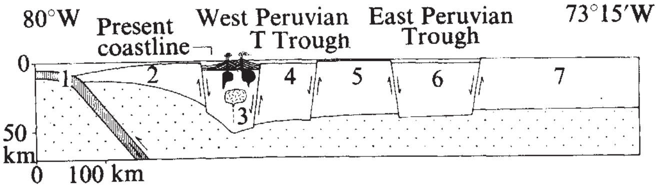

Fig. 2 Schematic section (*A–B*, Fig. 1) across Peru 100 Myr ago, showing subduction of oceanic crust (1), and the movement of major blocks of continental crust: 2, Paracas Block; 3, Paramonga Block; 4, Chavin Block; 5, Marañón Block; 6, East Peruvian Trough block; 7, Brazilian Shield. Casma Volcanics were erupted on the Paramonga Block from the rising Coastal Batholith (Patap Complex—black; tonalite—irregular dashes); continental crust—white; mantle—stippled; T, Tapacocha Axis.

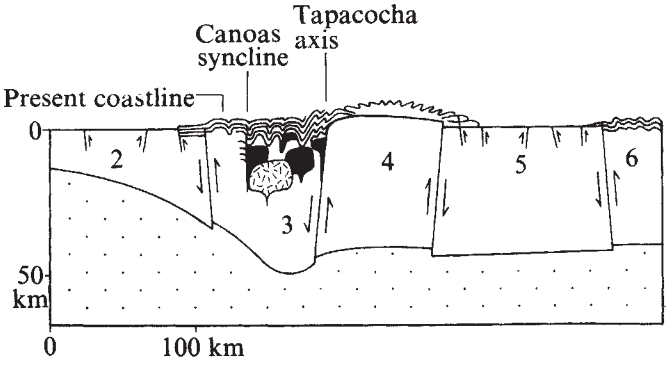

Fig. 3 Schematic section (part of *A–B*, Fig. 1) showing the different kinds of deformation of Mesozoic sedimentary and volcanic rocks which resulted from uplift of different crustal blocks (numbered as on Fig. 2) about 95 Myr ago. Ornamentation as on Fig. 2.

The West Peruvian Trough was itself divided into western and eastern belts by another steep shear zone, the Tapacocha Axis[14], which between 115 and 95 Myr ago allowed the western belt to subside about 4,000 m more than the eastern belt (Figs 1 and 2). The crustal blocks which underlie the western and eastern belts of the West Peruvian Trough are here called the Paramonga and Chavin blocks, respectively, and those which underlie the Paracas and Marañón Geanticlines are called the Paracas and Marañón blocks, respectively (Fig. 2).

Casma Volcanics and the Coastal Batholith

The Casma Group of volcanic rocks was erupted through the descending Paramonga Block from the rising Coastal Batholith below, forming a pile of andesite lavas, sills and pyroclastic rocks 3,000–6,000 m thick (Fig. 2). Meanwhile, about 3,000 m of sandstone and limestone[10] accumulated on the more slowly subsiding Chavin Block. Relative variations between the amount of volcanic material erupted and the rate of subsidence of the Paramonga Block resulted in oscillatory cycles of deeper and shallower marine and terrestrial volcanism within the Casma Group. The age ranges of ammonites interbedded with the volcanic sequence indicate that most eruptions occurred in the late Middle Albian and early Upper Albian (about 100 Myr ago)[7,14]. The occurrence of granodiorite, diorite and gabbro fragments in some pyroclastic flows suggests that the Casma Group of volcanic rocks was erupted through, and was probably associated with, plutonic rocks similar to the Coastal Batholith which was later emplaced into the Casma Group.

The oldest intrusions of the Coastal Batholith are numerous bodies of hornblende gabbro and diorite, collectively called the Patap Complex[7], which were emplaced into the eastern side of the Paramonga Block (Fig. 2). They contain more hornblende than pyroxene and seem to have crystallised from hydrous magmas. Many bodies of hornblende gabbro show rhythmic layering which may have formed in association with volcanoes within the upper part of the Casma Group.

Regional deformation

Intermittent pulses of deformation during intrusion of the Patap Complex folded the Casma Group into folds with vertical axial surfaces and sub-horizontal fold axes parallel with the Andes. The anticlines are mostly broad and open whereas the synclines are narrow and tight (Fig. 3). The gentle north-westerly plunge of the Canoas Syncline reveals that at structurally deeper levels to the south-east, the fold becomes even tighter and passes into a 2–4 km wide belt of isoclinal folds. The grade of metamorphism also increases progressively towards structurally deeper levels, from being hardly noticeable in the north-west where the structure is an open fold, to greenschist and amphibolite facies where the folds are isoclinal. The Canoas Syncline lies near, but is slightly oblique to, the western edge of the Coastal Batholith (Fig. 4), and a similar belt of strong deformation and syntectonic metamorphism occurs at the eastern edge of the batholith along the Tapacocha Axis (Fig. 3). These belts of deformation may be the upward expression of major shear zones in the crust below, which partly controlled the edges of the rising batholith, and were channels of high heat flow from the rising plutons.

The style of deformation of the contemporary rocks on the Chavin Block was completely different (Fig. 3). There, the sequence of limestone and sandstone was folded as a single unit by décollement on the underlying Lower Cretaceous Oyon Shale in the south, and the Jurassic Chicama Shale in the north[9,10]. Upright ribbon-like folds with axes traceable for 100 km or more occur on the centre of the Chavin Block, whereas towards the margins of the block, the folds are overturned outwards, and lower fold limbs are increasingly attenuated and pass into outwardly directed thrusts.

To the east, the thin, Cretaceous sedimentary rocks and pre-Mesozoic basement of the Marañón Block were broken up by normal and reverse faults[9,10] (Fig. 3).

The distinctions between the Paramonga, Chavin and Marañón blocks which had previously been marked by different kinds and thicknesses of sediments during differential rates of block subsidence, were thus emphasised by three distinct deformation styles during uplift of the blocks. The Paramonga Block was underlain by rising magmas of the Coastal Batholith and the folds represent the high penetration of ductile deformation above steep, basement shear zones associated with the rise of the batholith through the block. The Chavin Block to the east was not infiltrated by rising magma, and it rose intact and was tilted or arched, causing folding of the Cretaceous sediments which lay on it by gravity sliding on a lubricant of shale. Further to the east on the Marañón Block, the shale lubricant

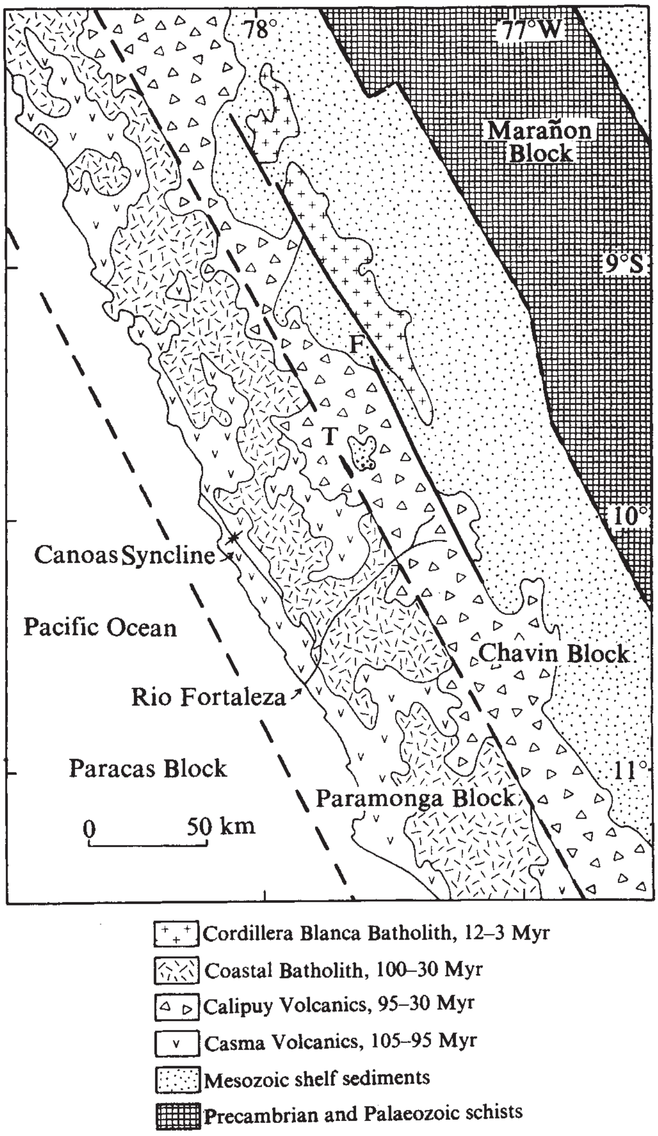

Fig. 4 Map of northern Peru showing the spatial association of the Coastal Batholith and Casma Volcanics, both restricted to the Paramonga Block, and the Calipuy Volcanics which spread on to the edge of the Chavin Block. Map simplified after ref. 15. T, Tapacocha Axis; F, fault.

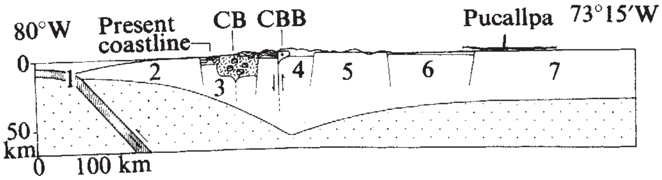

Fig. 5 Schematic section (*A–B*, Fig. 1) across Peru, showing the sum of Tertiary and Quaternary block movements, the location of the whole Coastal Batholith (CB) and Cordillera Blanca Batholith (CBB), and the present topography. Continental crust—white; mantle—stippled. Crustal blocks numbered as on Fig. 2; thickness of continental crust after ref. 16.

was absent and faults of the rigid basement penetrated the thin cover of sedimentary rocks. The overturned folds and outwardly directed thrusts at the eastern edge of the Chavin Block locally transgressed onto the Marañón Block and were dissected by the block faulting (Fig. 3). This suggests that the centre of the Chavin Block was raised higher than the Marañón Block, and that the folds flowed eastwards under the influence of gravity.

Calipuy Volcanics and the main intrusions of the Coastal Batholith

A 2,000–4,000 m thick terrestrial sequence of andesite, dacite and rhyolite, lava and pyroclastic flows, called the Calipuy Volcanics, lies unconformably on folded Casma Volcanics on the Paramonga Block, and spreads eastwards over the non-volcanic Cretaceous sediments on the western part of the Chavin Block (Fig. 4). It is intruded by many plutons of the Coastal Batholith and is probably the product of fissure and caldera eruptions from tonalite, granodiorite and granite magmas which formed much of the batholith.

The batholith is a tabular complex of plutonic rocks, 50 km wide and about 15 km thick which extends for over 1,100 km along the eastern part of the Paramonga Block (Fig. 4). It is made up of a large number of plutons of mainly tonalite, granodiorite and granite which were emplaced by repeated cauldron subsidence into the centre of the pile of Casma and Calipuy volcanic rocks to within 3 km or less of the surface[12]. Individual plutons form ring dykes and rectangular bodies parallel with the continental margin, with steep walls and flat roofs and floors.

Chronology of volcanic and plutonic history

The Casma Volcanics were erupted 100–95 Myr ago. They immediately preceded, and locally overlapped in time with, the intrusion of the earliest, Patap Complex of the Coastal Batholith, and were probably derived entirely from magmas of the rising batholith[12]. The Calipuy Volcanics which postdate uplift and erosion of the deformed Casma Volcanics and Patap Complex, were probably erupted from magmas which formed the younger complexes of the batholith 95–30 Myr ago (P. A. Wilson, unpublished). There was thus a close association between volcanic eruptions and plutonic intrusions in the eastern part of the Paramonga Block for at least 70 Myr during oscillatory vertical movements of the block.

Uplift and erosion of the modern Andes

The succession of erosion surfaces which are preserved on the western flank of the Andes indicate sporadic uplift of a gently undulating landscape formed by erosion of the Coastal Batholith and its volcanic envelope[7]. The erosion surfaces increase in altitude with increasing antiquity and distance from the western edge of the Paramonga Block. The steady increase in the slope of the erosion surfaces with age indicates that uplift occurred mainly by arching of the Chavin Block and westward tilting of the Paramonga Block. Major uplift and erosion of the modern Andes occurred between the time of emplacement of the last major plutons of the Coastal Batholith 30 Myr ago (P. A. Wilson, unpublished) and the eruption of an ignimbrite down the aggraded ancestoral Rio Fortaleza Valley 6 Myr ago (P. A. Wilson, unpublished). Later incision of the valley through this ignimbrite indicates further uplift of at least 500 m within the past 6 Myr.

In addition, the Chavin Block was split by a complex of steep major faults along the western foot of the Cordillera Blanca (Figs 4 and 5). The faults have been intermittently active from at least 6 Myr ago to the present time, and have raised the eastern part of the Chavin Block, which forms the crest of the Andes, a further 500–1,000 m. The fault complex may be the upward expression of a deep fracture–shear zone system which was active during late Tertiary time and which localised the ascending magmas that formed the Cordillera Blanca Batholith 12–3 Myr ago[17].

Andean structure and plate tectonics

The Peruvian Andes do not show any evidence of the strong deformation of the continental margin which occurred[4] in western North America during eastward movement of oceanic crust beneath the continent. In Peru the relative rigidity of the continent enabled it to float intact on the weaker oceanic crust which was deflected beneath it, and only weak tensile and compressive stresses were intermittently transmitted through the continental margin, causing oscillations of the crustal blocks. The steep fault and shear zones which bound the main crustal blocks are parallel with similar structures which were active during late Palaeozoic and early Mesozoic time, and they may all have been initiated in the same major tensile stress regime which during Precambrian time split the South American continent from continental crust to the west.

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letters to nature

Is Cir X-1 a runaway binary?

RUNAWAY stars are produced when there is a supernova explosion in a close binary system. Usually such an explosion disrupts the binary system, but Gott[1] has suggested that in a significant fraction of such supernovae the collapsed residue of the explosion may be retained in orbit around the runaway second star, the resultant system being a binary with high eccentricity and large space velocity. We suggest here that Cir X-1 is such a system.

Figure 1 shows a 408-MHz radio map of the Cir X-1 region. The map was produced from observations made with the Molonglo Cross radio telescope, and is centred on the recently