Tectonic Framework of Basin Evolution in Peru

by

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EXECUTIVE SUMMARY

The sedimentary basins of Peru preserve a long history of Phanerozoic subsidence and accumulation of terrigenous clastic and subordinate carbonate sediments. The tectonic and structural framework is attributed to intermittent reactivation of pre-existing fabrics in the basement. Regional tectonic compilations show that two important structural trends dominated basin evolution. These trends are a system of NW-oriented shears that were most recently involved in Andean deformation, and numerous NE-oriented cross faults that compartmentalised the overall tract of basins. Depending on stress fields, the basins were at times structurally unique and at other times yoked together.

- This study recognises and maps numerous NE-striking cross faults that formed the principal basin sidewall faults and also compartmentalised some basins internally. Particularly conspicuous are the Jambeli-Naranjal-Vuana fault zone of Ecuador and the Contaya shear zone of Peru. Crustal attenuation between these two structures created a deep basin comprising the Oriente, Cutucu, Marañon, Santiago, and Huallaga depocentres. This is an important consideration regarding pre-Aptian source rock distribution.

- The pre-Mesozoic paleogeographies are little more than thumbnail sketches because the data is unreliable. However, an attempt is made to document a prominent Late Permian – Early Triassic orogeny, referred to the Juruá event.

- The Late Triassic – Middle Jurassic interval is important from a source rock perspective.

- Two time-slice reconstructions broadly define the structural architecture of basin development, the Late Jurassic – Early Cretaceous paleogeography and the Maastrichtian – Quaternary paleogeography that was dominated by Andean mountain building.

- Reactivation of the Jambeli-Naranjal-Vuana shear zone after the Aptian created a suite of strike-slip basins along the Gulf of Guayaquil, such as the Tumbes and Talara basins, and left-lateral antithetic subsidence in the Progreso basin of southwestern Ecuador.

- A tract of left-lateral strike-slip basins formed beneath the continental shelf (e.g. Trujillo) after the Aptian. Although described as fore-arc basins, the processes that controlled their formation were equally related to NE-wrenching of the Gulf of Guayaquil system.

- An intriguing aspect of Peruvian geology is the tract of rigid blocks that have been rotated about 30º from regional since the Aptian. These rotated blocks are referred to as strike-slip dominoes. The emplacement of coarse-grained granites and granodiorites of the coastal batholith complex took advantage of this tract of crustal weakening created by rigid block rotation. Along the inboard margin of these rotated blocks, extensional dilation has accommodated emplacement of higher-level trondhjemitic stocks. These trondhjemitic stocks are most spectacularly expressed in the Cordillera Blanca. The

offshore Salaverry and Pisco ‘basins’ appear to be shallow downwarps related to the seaward margin of rigid block rotation.

- Finally, a tectonic model involving substantial thin-skinned structural-shortening is presented for the Madre de Dios Andes. Northward vergence was accommodated by an arcuate strike-slip fault zone.

INTRODUCTION

Sedimentary basins are accumulations of sediments that are accommodated by subsidence of the brittle crust by tectonic and structural processes. The petroleum systems and prospectivity of any particular basin depend upon the tectonic-structural framework and the sedimentary response to the patterns of subsidence and periodic internal deformation or structural inversion. It is, thus, essential that any exploration strategy be built upon a thorough understanding of basin dynamics.

There are two important elements that control basin formation. Subsidence of a sedimentary basin depends in some way upon the interaction of regional stress fields with ancient basement fabrics. Extensional subsidence will occur if the principal extensional stress σ_3 at a particular time is at a high angle to a basement structure. Conversely, were there a change in regional stress so that a compressive stress σ_1 was applied, then it is likely that the fault would be reactivated in a reverse sense resulting in structural inversion or, on a very large scale, the fold-thrust belts that may create flexural foreland basins. This methodology permits one to reconstruct the patterns of basin evolution without recourse to basin classification schemes. For example, were it inferred from geographic considerations that a particular basin was a back-arc basin, then this interpretation would likely dictate our understanding of basin dynamics and relative prospectivity. In other words, an ideal approach to basin interpretation should not be model driven.

A dynamic basin interpretation is based on knowledge of pre-existing basement fabrics, regional stress fields and their timing. Nowadays there is broad consensus that sedimentary basins form by reactivation of pre-existing weaknesses or structure within the brittle upper crust. The timing of the various stages of basin evolution is based on the major stratigraphic sequences and their bounding unconformities. However, the Achilles heel in this type of tectonic study has always been knowledge of stress fields. In this study, stress fields for any particular time are derived from very large-scale regional reconstructions that show the way families of faults behave, as well as their angular relationships. I realise that detailed paleostress measurements reveal variations throughout a region, but in the absence of paleostress data I have taken the approach of estimating the effects of mean stress directions (Tankard et al., 1995). Interpretation is not based on comparison with a conceptual strain ellipse, although the incremental strain ellipse may be used locally as a guide *only in reference to the orientation of the principal shear zones.* It is important in any scientific endeavour that ideas are tested. The consequences of these tectonic interpretations may be tested directly by seismic, wells, outcrop, mineralization, etc., or less directly by experience. Does this approach based on estimated stress azimuths work? Throughout South America this approach has proved to be satisfactorily predictive with respect to petroleum and mineral exploration.

The purpose of the present study is to interpret the framework and dynamics of basin evolution and basin linkage in Peru, and to interpret these basins in their regional context. This report summarises a very brief two-month study, and for this reason it is based on integration and interpretation of existing reports that are themselves based on seismic, gravity, magnetic, and well data in PERUPETRO files. Other sources of data include the 1: 1 million scale geological map of Peru (Ingemmet, 1999), 1: 1 million scale topographic map, radarsat images, published literature (e.g. Mégard, 1979, 1987; Dalmayrac et al., 1980; Mathalone and Montoya, 1995; Gil et al., 2000), and personal proprietary reports

(Tankard, 1999a, 1999b, 2000). This report presents a suite of maps, the most important of which are the Late Triassic – Middle Jurassic, Late Jurassic – Early Cretaceous, and Maastrichtian – Quaternary compilations.

My interest in the Phanerozoic basins of Peru is due to my earlier work on the basins of Ecuador, Bolivia and Brazil that surround the Peruvian tectonic province, and to a more ambitious attempt to reconstruct the tectonic framework of basin development in South America. Much of this geology was the subject of my 1997 AAPG Distinguished Lecturer tour of South America, and was also addressed in a full-day seminar through the Sociedad Geológica del Perú in June 2001 at which petroleum and mineral exploration concepts were presented.

DISCLAIMER

This tectonic interpretation of basin dynamics in Peru is the result of a very brief two-month contract that was intended only to establish the framework of basin evolution upon which other exploration-prospect related work could be based. The study attempts a thorough integration of information (mostly maps which are based on seismic, wells, gravity-mag, geochemistry, etc) that was supplied by PERUPETRO. Time was insufficient to reinterpret the primary data. Nevertheless, there is an overall internal consistency *at the scale of this study* between different generations of exploration maps at different stratigraphic intervals.

REGIONAL FRAMEWORK

Peru is divided into five conspicuous physiographic provinces. (1) The *NW-striking Andean ranges*. The Andean ranges of Peru are not so much a classical fold-thrust belt as a welt of structural inversion and transpressional uplift. In northwestern Peru, the intermontane Santiago region consists of the markedly inverted Santiago basin which, before Andean deformation, was a continuation of the upper Amazon Marañon basin; (2) the jungle-covered *upper Amazon basin* or Oriente region, inland of the Andean ranges, which is a continuation of the Oriente basin of Ecuador. This Marañon – Oriente basin complex onlaps the cratonic Guyana shield along the Iquitos arch. East of the Contaya arch this jungle-covered lowland continues as the Ucayali – Madre de Dios foreland into northern Bolivia. (3) The *coastal plain* that owes much of its topography to weathering of the granite-granodiorite coastal batholith complex. (4) The *Gulf of Guayaquil and the Huancabamba deflection* where the structural grain of the Andes changes to a NNE orientation, and also encapsulates the Santiago intermontane region. This region is profusely dissected by NE-directed, post-Aptian strike-slip faults. (5) The *continental shelf* faces an active subduction zone which is characterised by modern subduction earthquakes.

The kinematics of the Nazca plate is relatively well known (Pilger, 1981, 1983; Gutscher et al., 1999). Plate convergence is broadly orthogonal to the Peruvian margin and since the late Tertiary has been characterised by flat-plate subduction, compared with Ecuador on one side and Chile on the other where convergence is markedly oblique. Oblique subduction invariably results in strike-slip deformation of the adjacent continental crust, such as characterises the Gulf of Guayaquil-Tumbes-Talara tract of basins, whereas orthogonal compression typically produces fold-thrust belt tectonics. Except for the Madre de Dios ranges which were formed by substantial structural shortening and thin-skinned tectonics, the NW-striking Andean ranges are marked by large-scale transpressional uplift driven by left-lateral strike-slip processes.

Phanerozoic basin formation was guided by pre-Mesozoic fabrics in the basement. This is clearly shown in the Oriente basin of Ecuador (Balkwill et al., 1995; Tankard, 1999a) and the Marañon basin of Peru (Figure 1) where the Mesozoic cover overlies inclined basement reflectors and planar or listric faults which have been periodically reactivated These basement discontinuities appear to be of Proterozoic origin (Balkwill et al., 1995). Regional mapping shows two conspicuous structural trends in South America, consisting of a suite of NW-oriented structures of inferred middle Proterozoic origin, and NNE-oriented structures that define the Neoproterozoic Brasiliano thermotectonic event (Cordani et al., 2000; Tankard Enterprises proprietary files). These middle Proterozoic and Neoproterozoic trends are an important control of basin formation in Peru.

There are several papers that interpret the basement in terms of allochthonous terranes (e.g. 1800 – 1180 Ma *Garzon* migmatites and granulites, *Iquitos* marbles, granulites and magmatites, *Amotape* schists and gneisses, *Arequipa* terrane…). However, the evidence supporting these terrane interpretations is generally ambiguous because of very sporadic data scattered over a vast area. The basins of Peru probably have formed above a mosaic of allochthonous terranes, however poorly they are understood, but they are not important to this investigation.

TECTONO-STRATIGRAPHIC SETTING

Figure 2 summarises the Phanerozoic stratigraphy of the northern Peru Marañon basin and compares it with the Oriente of Ecuador and Putumayo of Colombia. Overall, there was a remarkably persistent pattern of stratigraphic evolution expressed in the stacked stratigraphic sequences. Some events are diachronous, reflecting the nature of basin evolution as well as the vagaries of biostratigraphic analysis. The stratigraphic sequences and their intervening unconformities are attributed to tectonic processes and changes in stress fields (see Tankard et al., 1995) rather than relative sea-level fluctuations. It is this pattern of intermittent stratigraphic accumulation on which the time-slice tectonic maps are based.

Paleogeographic Reconstructions

Each tectonic episode is summarised in a time-slice paleogeographic reconstruction that characterises the overall tectonic setting, and by inference expresses the nature of the stress fields. Late Triassic – Middle Jurassic events were dominated by extensional processes that resulted in the fragmentation of east Gondwana and opening of the Indian Ocean. From Late Jurassic (Callovian) to Early Cretaceous (Aptian) time there was a fundamental change in the stress fields related to extensional opening of the Atlantic Ocean. Aptian opening of the Atlantic created a spreading ridge and widespread matching subduction on the Pacific margin of South America. In Ecuador this Aptian event is expressed in conspicuous arc magmatism. From the Maastrichtian to the present, tectonism was dominated by Andean compression and mountain building, expressed in strike-slip processes, large-scale structural inversion and transpressional uplift of earlier depocentres. Each episode produced a distinctive paleogeography. Regional reconstructions of this type that emphasise basin linkage offer a different perspective in basin interpretation. Events in any particular basin cannot violate stress. Nevertheless, for each time slice it is necessary to test interpretations by integrating all data bases; e.g. seismic, wells, isopachs, magmatism… *Think big but focus on the detail!*

An instructive reconstruction is the Late Jurassic – Early Cretaceous paleogeography (Figure 3) because this episode marks the disintegration of west Gondwana and opening of the Atlantic, the onset of intense subduction along the Pacific margin, and it is marked also by some very well studied tectonic trends. In southwest Gondwana, the onset of extension was accommodated by the Agulhas-Malvinas-Gastre wrench system that had a right-lateral sense of translation as the Malvinas plateau sheared westward past the Agulhas Bank and Outeniqua basin complex offshore South Africa. The geometry of this wrench defines a small circle. As extension started in the Outeniqua basin (σ_3 directed southwest), tectonic linkage via this transform ensured that the principal E-W basin-forming fault zone in the Neuquén basin of west-central Argentina became a restraining bend during the Late Jurassic, resulting in marked structural inversion of the Huincul arch. This interpretation demonstrates the importance of understanding tectonic linkage, and also suggests that the dynamics of the Neuquén basin were linked to the Gondwana interior and not the nearby subduction zone. A second important family of faults occurs in Brazil, where the NW-oriented Guapiara and Curitiba faults were reactivated along Proterozoic trends, also in a right-lateral sense. Through Bolivia these broadly merge with the ancient Chiquitanas front and other slip faults. These trends are correlated with the Baboa shear zone of Peru.

Tectonic Framework of Basin Distribution in Peru

Anticipating the various paleogeographic reconstructions, overall structural setting, and basin compartmentalisation, Figure 4 shows the way basins are distributed. This map emphasises a pre-Andean reconstruction. Basin formation was controlled by a suite of NW-oriented wrench faults (see Figure 3) and numerous NE-oriented cross faults that compartmentalised the overall tract of basins. There are several important elements controlling basin distribution:

- In Ecuador and northern Peru there are a matched pair of NE-striking shear zones, *viz.* the Jambeli-Naranjal-Vuana fault zone of Ecuador (Tankard, 1999a) and the Contaya shear zone of Peru. Between these two parallel structures, crustal attenuation from Paleozoic time created a deep basin comprising the Oriente, Cutucu, Marañon, Santiago, and Huallaga depocentres. For much of their history, these various depocentres were yoked together; only during Andean deformation did structural inversion of the principal basin-forming faults result in transpressional uplift and basin isolation. This is an important consideration regarding pre-Aptian source rock distribution.

- The focus of Late Jurassic – Early Cretaceous extensional subsidence was a suite of linked basins where distal crustal attenuation is inferred to have been most substantial. These basins are the Santiago, Cutucu, and Napo depocentres. These basins are believed to have originated as extensional basins in a strike-slip setting.

- The Contaya shear zone is reconstructed from a variety of maps, gravity-mag data, isopachs, seismic, etc. It is one of the most fundamental structures controlling basin formation in Peru. Along strike it separates and offsets the Contaya high and the Cushabatay high. In this way, the Huallaga and Ucayali basins were always distinct basins, and may only have been yoked together during the Paleozoic.

- Likewise the Ene and Madre de Dios basins are also bounded by NE-striking sidewall faults.

- In this reconstruction, the Acre basin of western Brazil is an isolated rift segment bounded by NE-trending sidewall faults.

- Reactivation of the Jambeli-Naranjal-Vuana shear zone after the Aptian created a suite of strike-slip basins along the Gulf of Guayaquil, such as the Tumbes and Talara basins, and left-lateral antithetic subsidence in the Progreso basin of southwestern Ecuador.

- A tract of left-lateral strike-slip basins (e.g. Trujillo) formed along the continental shelf after the Aptian. Although described as fore-arc basins, the processes that controlled their formation were equally related to NE-wrenching of the Gulf of Guayaquil system.

- The offshore Salaverry and Pisco 'basins' appear to be shallow downwarps related to rigid block rotation. Block rotation does not involve any widespread process that would create accommodation space, hence there appears to be little opportunity to develop prospective basins with well-defined petroleum systems.

PALEOGEOGRAPHIC RECONSTRUCTIONS OF BASIN EVOLUTION

There are two important time-slice reconstructions that broadly define the structural architecture of basin development, each of which has its own advantages but which nevertheless have to be absolutely compatible. First, the Maastrichtian – Quaternary database is the most abundant and, being the shallowest part of the cover succession, also the most reliable. The mapped structures are visible in surface geology, Landsat and Radarsat, as well as abundantly defined by seismic expression, seismic structure maps, and isopach maps. Interpretation requires a minimum of restoration because this time-slice represents the final phase of Andean deformation. Second, data is still voluminous enough to define adequately the Late Jurassic – Early Cretaceous paleogeography, and this episode is also best mapped on a continent-wide scale so that regional stress fields are well defined. Except for the late Tertiary Madre de Dios fold-thrust belt, there is very little thin-skinned deformation and pronounced structural telescoping so that for most of the Peruvian basins it is unnecessary to restore structures palinspastically at the scale of this investgation.

The Late Permian – Middle Jurassic interval is important from a source rock perspective, but the increased depth of these stratigraphic intervals reduces data reliability, and there appears to be some obvious lithostratigraphic and biostratigraphic problems of correlation. An example is the relationship between the important Ene and Mitu formations, and whether they are coeval or belonging to different tectonic episodes and styles. The seismic evidence suggests that the Ene was deposited in a post-rift epeiric basin when individual fault activity had ceased and the various depocentres were progressively yoked together during regional subsidence. In contrast, seismic shows the Mitu to have a pronounced fault-controlled extensional style of subsidence and deposition.

The pre-Mesozoic paleogeographies are little more than thumbnail sketches, the data being that unreliable. A considerable part of the isopach reconstructions are based on extrapolation of very widely spaced outcrop points with little regard for structural influence. Although tenuous, the Late Permian – Early Triassic (probably the latter) Juruá episode of deformation is examined. This late Hercynian episode of deformation was widespread in western Gondwana, and in Argentina is referred to as the San Rafael orogeny.

This investigation started with a Late Jurassic – Early Cretaceous reconstruction, followed by the Andean age deformation in the Maastrichtian – Quaternary. Notwithstanding, results will be presented to reflect stratigraphic hierarchy.

Late Carboniferous – Permian Paleogeography

Mabillard and Rigby (1997) have ascribed the onset of post-Llanganates deposition to Early Ordovician transgression which progressively overstepped the Guyana shield. This lower part of the Paleozoic is poorly documented in Peru and Ecuador. The Devonian – Lower Carboniferous consists of sandstones, mudstones, limey mudstones, and limestones that vary up to 700 m in thickness in the Cutucu uplift. This succession is extensively intruded by diabase sills. The overlying Upper Carboniferous – Permian succession is lithologically very similar, and not always easy to differentiate seismically.

Figure 5 shows a reconstruction of the structural architecture during the Late Carboniferous – Permian. There are two distinct styles of basin formation, one reflecting extensional processes and crustal thinning, the other subsidence along strike-slip faults.

The thickest parts of this Tarma – Copacabana succession is preserved in isolated rift segments. A broad tract of extensional depocentres occurs between the NE-oriented Contaya shear zone and the Shionayacu shear zone (named after the Shionayacu well near the Ecuador - Peru boundary). The principal extensional stress σ_3 was oriented approximately east – west. Regional considerations suggest that the Contaya and Shionayacu shear zones had a left-lateral sense of displacement. The thick sedimentary succession and the associated tract of rift depocentres between these shear zones implies that this area had been subjected to a long history of crustal attenuation. Elsewhere, there also appears to have been a component of extensional subsidence in the areas of the present Ucayali and Ene basins.

In a second style of basin development, right-lateral strike-slip processes produced several elongate NW-oriented basins, for example along the Baboa shear zone. Isopach distribution appears to have been confined locally by NE-oriented accommodation zones or sidewall faults. The distribution of these strike-slip depocentres match the general structural framework. However, in places the isopachs have been interpreted from some very widely spaced outcrop data points.

By Late Permian Ene time, extension had ended and rift-controlled subsidence on individual faults had largely ceased. The various depocentres were yoked together in a broad, shallow epeiric sea in which calcareous mudstones and petroliferous source rocks were deposited. However, preserved Ene cover is now apparently restricted to the area southeast of the Contaya shear zone (Gary Wine, personal communication 2001). These processes of extensional basin formation and post-rift regional subsidence would have required Ene deposition across the basin tract between the Contaya and Shionayacu shear zones. The Late Permian – Early Triassic relaxation of extensional stresses is believed to have resulted in structural inversion of the earlier extensional faults as well as widespread uplift and erosion of the Ene (see Juruá orogeny below). I anticipate that there should be local pockets of Ene preserved in the Contaya-Shionayacu depositional tract.

Juruá Orogeny: Late Permian – Early Triassic Paleogeography

The late Hercynian orogens were generally intracratonic. They formed a set of isolated segments that are commonly associated with NE-trending shear zones (Cobbold et al., 1986; Tankard et al., 1995). In Argentina, this tectonic episode is known as the San Rafael orogeny where it formed several deformed belts, such as the Sierra de la Ventana, Septentrionales, Sierra Grande, Bariloche, and the San Rafael mountain belt of Chile and Argentina. Barros and Carneiro (undated Petrobras manuscript) describe this Early Triassic event as the *Juruá orogeny* based on the seismic evidence of marked structural inversion in the Solimoes basin (e.g. gas-bearing Juruá River trend). The farfield effects of this orogeny are also recorded in the transpressional reactivation of structures in the Paraná basin.

Towards the end of the Permian, relaxation of the earlier extensional basin-forming stresses resulted in the various depocentres being yoked together to form a broad epeiric sea in which the argillaceous Ene Formation was deposited as a regional blanket (see previous section). Field relations and seismic show that the succeeding Mitu molasses were deposited in fault-controlled extensional basins (Figure 7), and that a pronounced unconformity intervenes between the Mitu and the underlying Ene. In the Solimoes basin, Milani (personal communication, 2001) describes similar stratigraphic relationships where the Upper Permian cover is succeeded by Andira molasses deposited in fault-bounded wedges. This report follows Barros and Carneiro in ascribing this tectonic episode and prominent unconformity to the Juruá orogeny.

In Peru, this Juruá orogeny is marked by regional uplift and a pronounced unconformity that marks a first-order sequence boundary after Ene accumulation, an event that is also strongly represented in the Acre and Solimoes basins of the Brazilian upper Amazon (Figure 6)(Barros and Carneiro, undated); σ_1 was directed approximately east – west. Isopach maps (PERUPETRO proprietary files) clearly show preservation of the stratigraphic cover in a suite of fault-bounded pods.

Together with the previous Late Carboniferous – Permian episode, there is a three-part cycle of basin formation and sedimentation that is repeated throughout the Phanerozoic of South America (Tankard et al., 1995). Typically each cycle consists of (1) an early phase of rift-controlled subsidence and deposition of relatively coarser-grained clastics, (2) abandonment of individual fault-controlled subsidence and yoking together of the various depocentres into a shallow epeiric basin, and deposition of a widespread cover of finer clastics and potential petroleum source rocks, and (3) a marked change in the stress fields resulting in structural inversion, uplift, and orogeny.

Late Triassic – Middle Jurassic Paleogeography

The Late Triassic – Middle Jurassic tectono-stratigraphic cover accumulated in a compartmentalised basin complex (Figure 8). The cover succession consists of Mitu red beds in isolated rift segments, accumulation of finer-grained Pucara clastics, limestones, and evaporates, and terminating in the widespread Sarayaquillo blanket (Figure 7) (Parsep, 2000a). Initiation of subsidence and deposition of the Mitu Formation is attributed to a process of orogenic collapse following the late Hercynian Juruá orogeny.

Subsidence and sedimentation was particularly pronounced between the NE-trending Contaya and Shionayacu shear zones, while the Pucalpa shear zone marks the southeastern margin of basin subsidence. This Pucalpa shear zone is believed to have relayed deformation to the Solimoes basin of western Brazil. Generally, the thicker isopach areas abut the NE-oriented accommodation zones showing that they functioned as abrupt basin sidewall faults. These NE-striking accommodation zones were essentially antithetic structures (or conjugate Riedel structures) to the NW-trending principal displacement zones such as the Baboa shear zone that had a left-lateral sense of displacement during this time.

Nevadan Orogeny: Late Jurassic – Early Cretaceous Paleogeography

The Late Jurassic, or more specifically the Callovian – Kimmeridgian, marked a reorganisation of regional stress fields and an episode of extension that culminated in Aptian opening of the Atlantic Ocean. Fragmentation and ocean opening started in the south and proceeded northwards in a zipper-like fashion. In detail, these stages of extension and ocean opening were accommodated by a series of NW-trending shears throughout South America. The most conspicuous is the Agulhas – Malvinas – Gastre fault system that ultimately accommodated translation of the Malvinas plateau past the Agulhas bank and Outeniqua basin complex offshore South Africa. The sense of displacement was obviously right lateral. Another prominent suite of NW-trending faults is the Guapiara – Curitiba – Torres family of faults that reactivated pre-existing Proterozoic lineaments in the Paraná basin (Zalan et al., 1990; Tankard et al., 1995). In the Early Cretaceous Atlantic margin basins of Brazil, these faults formed inter-basin accommodation zones. More pertinently, they provided tectonic linkage through the Chiquitanas front and Izozog arch of Bolivia to a system of NW-trending, right-lateral shear zones such as the Baboa in Peru. Overall, these right-lateral shear zones define small circles. Translation along this NW trend locally resulted in NE-oriented antithetic faults that facilitated basin compartmentalisation as well as being associated with magmatism, such as the Lower Cretaceous alkaline Velasco intrusives of Bolivia (Darbyshire and Fletcher, 1979).

The Late Jurassic – earliest Cretaceous reorganisation of stress fields and orogeny was experienced throughout South America. In Argentina, this event is referred to as the Araucanian orogeny where it resulted in substantial structural inversion in the San Jorge, Neuquén, and Cuyo basins (e.g. Tankard et al., 1995; Vergani et al., 1995, their figures 10 and 11). Mathalone and Montoya (1995) ascribe this deformational episode in Peru to the Nevadan orogeny. Marked structural inversion affected the Solimoes basin too.

Tectonic Framework: This Late Jurassic reorganisation of stress fields is represented by widespread structural inversion of earlier depocentres, uplift, magmatism, and a prominent unconformity above the Sarayaquillo cover. The Upper Jurassic Lower Cretaceous cover comprises the succession Cushabatay, Agua Caliente, Raya, Chonta, and Vivian. Typical of previous tectonic cycles, this episode also terminated in stress relaxation that resulted in the various depocentres being yoked together to form a broad, shallow subaqueous platform, and deposition of the prolific Chonta source rocks.

Figure 9 summarises the tectono-stratigraphic framework. Basin dynamics were controlled by NW-oriented, right-lateral shear zones or principal displacement zones such as the Baboa, and several prominent antithetic shear zones that were NE-oriented. Sedimentation occurred mainly in strike-slip related basins, stepover jogs such as the Ucayali basin, and at along-strike releasing bends such as the Acre basin of western Brazil. In this tectonic setting, the principal extensional stress σ_3 was E to ESE oriented. The most important cross faults that defined sidewall structures were the Contaya shear zone in central Peru and the Jambeli – Naranjal – Vuana shear zone of the central Oriente basin. Baldock (1982) has mapped the Jambeli – Naranjal fault system, and this has been extended across the Oriente basin as the Vuana fault zone by Tankard (1999a). This reconstruction implies that during the Late Jurassic – Early Cretaceous tectonic episode, subsidence between the Contaya and Jambeli-Naranjal-Vuana shear zones formed a single broad basin complex that was, nevertheless, punctuated by local depocentres. In other words, the Oriente, Marañon, Santiago, and Huallaga depocentres essentially formed a single basin complex. Left-lateral slip on the Contaya shear zone maintained the Contaya and Cushabatay highs and separation of the Huallaga and Ucayali basins.

This reconstruction does not attempt to restore the Madre de Dios range palinspastically, but it would be necessary to restore at least 150 km of structural telescoping that developed during the Andean phase of deformation.

This phase of tectonism required significant displacement on the NW-trending shear zones and, of course, concomitant space problems that needed to be resolved. The rates of slip of neighbouring shear zones was not always the same, and in several places right-lateral relay faults (Riedel structures) linked them. The deformation was ultimately accommodated by pronounced extension at the terminus of this system and formation of a linear tract of rift basins that were offset from each other across accommodation zones; these depocentres are the Santiago basin of Peru and the Cutucu and Napo basins of the western Oriente of Ecuador (Tankard, 1999a).

Extensional Santiago Basin: The detail of extension in the Santiago basin is shown in Figure 10a. The Santiago is a 100 km wide rift basin, measuring about 20,000 km^2 in area. Most of the seismic is in a relatively narrow strip along the eastern margin of the basin in the broad valley of the Santiago River. Flattening the E-W seismic on the Chonta Formation reflector provides only a glimpse of the extensional stratigraphy. The basin is compartmented by right-lateral, NW-oriented accommodation faults. The strike of the extensional basin-forming faults is N to NNE. It is inferred that the principal basin-forming faults were along the western margin of the basin because that is the area of greatest structural relief created during the subsequent Andean phase of mountain building. (Structural inversion is invariably focused on the principal basin-forming faults.) The thickness of the Santiago rift succession is unknown.

Andean Orogeny: Maastrichtian – Quaternary Paleogeography

By Aptian time, South America had separated from Africa and had developed a continuous zone of subduction the entire length of the Pacific margin. Convergence of the Pacific plate relative to Peru was orthogonal, in contrast to convergence along the margins of Chile and Ecuador that was markedly oblique. The strike-slip transpressional processes that formed the coast-parallel Andean ranges of Peru are not entirely compatible with orthogonal subduction, and are better understood in a more regional context. Mégard (1979, 1987) discusses Andean deformation in detail.

Figure 11 summarises the tectonic framework of Maastrichtian – Quaternary Peru. The Andean ranges formed by massive structural inversion and transpressional uplift (Figure 12), mainly along left-lateral, NW-striking shear zones. There is very little thin-skinned deformation present that would require palinspastic restoration, except along the Madre de Dios range. In the Huallaga and Ucayali basins, seismic shows structural inversion of the Late Jurassic – Early Cretaceous transtensional depocentres (Figures 13 and 14), and there are places where inversion appears to have culminated in flattening of shortcut faults that simulate thin-skinned processes over small distances. (Listric normal faults are very efficient at creating rift basins, but when the process is reversed during structural inversion they are very inefficient leading to shortcut faults that may even uplift basement.)

Tectonic Framework: The overall tectonic framework of the Peruvian basins is relatively simple (Figure 11). The basins are controlled by left-lateral displacement on the NW-oriented principal displacement zones, and a well-developed set of antithetic, NE-striking, right-lateral accommodation zones (with conjugate Riedel affinities) that locally form conspicuous sidewall faults, such as the Contaya and Jambeli-Naranjal-Vuana shear zones. The Vuana fault is also associated with Cretaceous magmatism. During this episode, structural inversion along some of the basin-forming faults resulted in distinct separation of the Marañon, Huallaga, and Santiago depocentres. They share a common pre-Andean stratigraphy including source rocks and reservoir horizons, but unique hydrodynamic systems imposed by compressional deformation.

The margins of the Oriente – Marañon basin are defined by the Vuana and Contaya shear zones respectively. Between these shear zones, the Oriente – Marañon basin has subsided as a foreland basin in front of the Andean ranges, accumulating a very thick sedimentary wedge. However, this is not a typical foreland basin. Foreland basins are generally attributed to flexural processes whereby thin-skinned deformation applies an overthrust load. The Andean ranges (except the Madre de Dios range) have formed by large-scale structural inversion of pre-existing extensional basins (compare Figures 9, 11 and 12). In this way, structural inversion mainly rearranged the sedimentary succession that already existed within the rift basins, and did not apply substantial new loads. In this respect, the Oriente – Marañon basin probably owes much of its subsidence to a combined overthrust-transpressional load on a crust that had been thinned over a very long period of time. Nevertheless, compression has resulted in widespread inversion of older extensional faults, creating a suite of sometimes very subtle structural traps in the northeastern Marañon basin. The inboard margin of the basin along the Paragua arch and the eastern Oriente basin is replete with subtle inversion structures that form attractive hydrocarbon traps (Figures 1b and 15).

The marginal shear zones or sidewall faults play another very important role. Between the Vuana and Contaya shear zones, the Andean ranges are not as high as elsewhere. I suspect that crustal thinning between the Contaya and Jambeli-Naranjal-Vuana shear zones explains the comparatively lower relief. In Ecuador, the highest Andean elevations are north of the Jambeli-Naranjal-Vuana shear zone, and in Peru south of the Contaya shear zone. Immediately south of the Contaya shear zone is the Cordillera Blanca, the only permanently snow covered range in Peru, and containing the second highest mountain in South America. In other words, thicker crust outside these two shear zones is considerably more buoyant.

Aleman et al. (1999) have discussed the petroleum systems in the Oriente - Marañon basin. In the northeast Marañon basin, the only effective source rock is the Triassic – Lower Jurassic Pucara Formation, based on dinosterane biomarkers. This source rock entered the oil window before the Middle Eocene, thus putting constraints on the timing of prospective structures.

Structural Inversion in the Santiago Basin: The stress fields that resulted in transpressional uplift of the Andean ranges also contributed to marked structural inversion on a mountain-building scale in the Santiago basin (Figures 10b and 12). The dominant structural trends are the NW-trending, left-lateral shear zones and NNE-oriented antithetic shear zones that display a right-lateral sense of displacement. The principal displacement zone is the NW-oriented Agapa shear zone (ag in Figure 10b), aided by a suite of secondary, parallel shear zones that distribute the shortening. The principal compressional stress σ_1 is E-W, resulting in north-trending high-angle thrust faults and folds. These basement-involved reverse faults are attributed to inversion of the Late Jurassic – Early Cretaceous extensional faults.

Whereas the dominant tectonic trend is the NW-oriented family of faults, the right-lateral NE-trending antithetic shears are essentially conjugate Riedel structures whose function is to accommodate or conserve strain. The shear couple associated with these antithetic faults formed a series of N-trending marginal anticlines (Figure 10b), some of which have been drilled. In the Santiago basin, these marginal anticlines offer several drillable prospects.

An interesting aspect of this tectonic model is that the NW-oriented shear zones and their NE-trending antithetic shears compartmentalise the Santiago basin into several rigid blocks. Although tenuous, there is evidence that strike-slip rotation of these rigid blocks in a counter-clockwise sense has resulted in compressional structures in the NE and SW corners, and dilational extensional structures in the NW and SE corners. This interpretation may offer exploration opportunities to the extent that limited seismic coverage (seismic is concentrated in the Santiago River valley) and terrain permit.

Madre de Dios: Reflection seismic shows that thin-skinned deformation and substantial structural shortening is developed only in the Madre de Dios ranges of southeast Peru (MdD in Figure 11). The Madre de Dios fold-thrust belt consists of northward-verging, stacked thrust sheets (Hermoza, 2000). The western margin of the thrust belt is rotated into an arcuate string of faults against which it abuts. This arcuate string of structures is locally expressed in the northward-oriented Cordillera Vilcabamba that has a discordant relationship to the overall tectonic fabric of Peru, and continues northward to form the eastern sidewall or termination of the Acre basin, and finally appears to link the Acre and

Solimoes basins of Brazil. Like the Madre de Dios, the Solimoes basin also suffered structural inversion at this time.

Geometric relationships show that the northward-verging Madre de Dios fold-thrust belt was rotated into this Vilcabamba fault system, suggesting a left-lateral sense of displacement and lateral-ramp affinities. The Cenozoic granitoids that form the Vilcabamba Cordillera are attributed to transtensional dilation along this shear zone. This Vilcabamba shear zone accommodated structural shortening, and relayed the compressional stresses into the Solimoes basin as well. In this context, the faulted Fitzcarrald anticline (Figure 11) was formed as a lateral fold associated with transcurrent displacement along the principal Vilcabamba shear zone. The Fitzcarrald anticline owes its prominence essentially to the fact that it forms a drainage divide, and to the legendary Fitzcarrald expedition and its attempt to transport the river steamer over the divide early in the last century.

There are structures within the Madre de Dios fold-thrust belt that are rhomboid-shaped piggy-back basins. The Candamo depository (PERUPETRO proprietary reports) is interpreted as a small intermontane pull-apart basin formed by synthetic left-lateral slip along the grain of the thrust belt.

The Madre de Dios forms the northern recurved margin of the Bolivian fold-thrust belt. Since the Maastrichtian, the Andean ranges of Chile, Argentina and Bolivia have reflected the oblique, flat-plate subduction of the Pacific plate. The architecture of these ranges incorporates eastward verging, high-angle thrusts and prominent N- to NNE-oriented strike-slip faults (Tankard, 2000). Oblique subduction has driven right-lateral displacement on strike-slip faults such as the Aconquija fault of NW Argentina where transpression has resulted in many thousands of metres of structural relief. In this interpretation, terranes such as the Precordillera have been displaced northwards. The progressive northward displacement of the Precordillera and the Eastern Cordillera and Western Cordillera has been cumulative, and was ultimately accommodated by compressional shortening and northward vergence of the Madre de Dios and, on a depleted smaller scale, structural inversion of the Solimoes basin. Thus, the discordant relationships of the Vilcabamba shear zone and the Madre de Dios range with respect to the tectonic framework of Peru are intimately linked to N-NNE right-lateral displacement along the Chile-Argentina and Bolivian Andes that was driven by oblique subduction.

This reconstruction may have economic significance. Where the Madre de Dios abuts the Vilcabamba shear zone there are the giant San Martin and Cashiriari gas-condensate fields. Whether the Vilcabamba shear zone acted as a sidewall or lateral ramp to the basin-thrust complex, it undoubtedly influenced the hydrodynamic regime, high heat flows and migration pathways. Dilational emplacement of the Vilcabamba granitoids supports this interpretation. Likewise, the development of duplexing in the thrust belt probably also imposes numerous barriers to northward migration of hydrocarbons. Finally, this tectonic regime has also resulted in the development of thrust-parallel piggy-back basins, such as the Candamo depository in which the 78-53-1X/ST wildcat discovered gas and condensate in tight Permian and Cretaceous sandstone reservoirs.

Strike-Slip Rotational Block Tectonics – the Coastal Batholith Complex: The broadscale tectonic framework of basin architecture in Peru consists of NW-oriented strike-slip faults which have behaved in either a right-lateral or left-lateral sense, depending on the stress regime, and NE-oriented accommodation faults that reactivated ancient basement fabrics. However, the geology of coastal Peru is conspicuously different (Figures 11 and 16). This coastal tectonic province is bounded by an inboard, NW-striking sinistral shear zone, seaward of which there is a suite of parallel faults that are NNE-oriented (César and Noble, 1994; Quiroz, 1997; Ingemmet, 1999) and show a 30º counter-clockwise rotation from regional. Coarse-grained granites and granodiorites have been emplaced along the axis of these apparently rotated blocks, and along the landward margin emplacement of the trondhjemitic Cordillera Blanca batholith has occurred at higher crustal levels (Cobbing, 1998).

I interpret this coastal structural complex as a suite of rigid blocks that have been rotated in a counter-clockwise sense by left-lateral displacement along the Cordillera Blanca shear zone. Offshore there is a parallel tract of intermittently mapped faults from the Pisco to Trujillo basins that were also left lateral from the Maastrichtian onwards (Parsep, 2000b). In other words, these rotated blocks were sandwiched between parallel, NW-oriented, left-lateral strike-slip faults.

An elegant explanation for this geology is rotational block or strike-slip domino rotation (Nicholson et al, 1985). The rigid crustal blocks were originally formed by cross-cutting fabrics in the basement. Left-lateral wrenching resulted in counter-clockwise rotation of these rigid crustal blocks (Figure 17). However, rotation imposed obvious space problems. Each block contains two corners that rotate inwards, resulting in extensional dilation, and two other corners that attempt to rotate beyond the confines of the bounding strike-slip faults and consequently result in compression and tectonic erosion. This is an interesting model because, from an exploration perspective, the compressional corners of the rotated blocks may create structural closure and drillable prospects. However, strike-slip extensional dilation will result in porosity enhancement and lower potential pressures towards which migration is drawn. Dilation sucks! In exploring rotated-block terranes there needs to be a balance between development of compressional structures and dilational migration pathways. (See discussion above on the Santiago basin, Figure 10b.)

Quiroz (1997, his figure 1) maps one of these rigid blocks, what he calls the Chicama-Yanacocha corridor, and shows the distribution of Tertiary volcanic rocks and porphyries about the block margins, including the Yanacocha volcanic complex, that perfectly match the strike-slip domino interpretation.

Figure 18 presents a strike-slip domino model for coastal Peru. The coastal batholith is a linear tract of coarse-grained granites and granodiorites that have been emplaced along the axis of the rotated domino blocks, taking advantage of this structural weakness in the upper brittle crust. This coastal batholith complex is generally of Late Cretaceous – Paleocene age. The field characteristics of rigid block rotation and deep-seated granite emplacement imply that the mechanical boundaries of these blocks encompass the entire brittle crust, and may affect even the ductile lower crust as well. In several places, the domino boundaries offset the batholith. Cobbing (1998) interprets this and the ring complexes that developed where structures converged as evidence that this structural weakening influenced granite emplacement. The Cordillera Blanca is different, consisting of a finer-grained batholith of trondhjemitic affinity that formed as a higher-level stock (op.cit.). Emplacement of these higher-level trondhjemite stocks occurred during the Miocene – Pliocene (12 – 3 Ma; René Marocco, personal communication 2001). I suggest that the Cordillera Blanca and other trondhjemites along strike were intruded to higher crustal levels because they were accommodated by dilation along the rotated margins of the domino blocks.

Magmatic activity along the western margin of Peru is progressively influenced by the subducting Pacific plate which increases in depth in a landward direction; pressure-temperature conditions of the mantle and subducting slab change from west to east. Seismic shows that initial flexure beneath the fore-arc has resulted in brittle failure of the slab, producing small fault-bounded compartments that function as conveyor belt-like traps to transport sediment and water (Figure 19). Magmatism is broadly P-T dependent. Obviously, the P-T conditions favoured magmatism where the more deeply subducted and dehydrated slab encountered the structurally weakened zone of domino rotation. Along the inland margin of these rotated dominoes, spontaneous dilation at block corners resulted in rapid and direct ascent of trondhjemites, an interpretation supported by the low amount of plagioclase fractionation (Miguel Galliski and Florencia Marquéz-Zavalía, personnel communication 2001). In contrast, the seaward margin of this domino province is above a relatively shallow and still cold subducting slab that was not conducive to melt generation, except for rare and isolated flows in the Salaverry basin (Gary Wine, personal communication, 2001). Instead, the structurally weakened and intermittently dilated seaward margin coincides with a zone of shallow downwarping expressed in the Salaverry and Pisco basins. Seismic shows the general absence of accommodation space or substantial sediment accumulation that would result from basin-forming processes. The Salaverry and Pisco "basins" are seafloor irregularities with little petroleum potential.

In one place, right-lateral shearing has detached and transported a large olistostrome within the terrace wedge (Figure 20). Correlation with the geology of the Bayovar area suggests that this olistostrome consists of lower Paleozoic gneiss.

Finally, the coarse-grained nature of the granites and granodiorites imply very substantial amounts of uplift and erosion, probably since the Pliocene. This implies significant and relatively young depth of burial that would support maturation of Miocene age source rocks in the Talara basin (Carlos Monges, personal communication, 2001).

Talara-Tumbes Basin Complex and the Gulf of Guayaquil: The Huancabamba Andes of northwest Peru marks a major change in the trend and topography of the Andes of central Peru and Ecuador, from NW to NNE (Figure 11) (Mourier et al., 1988). This Huancabamba deflection is attributed largely to NW-directed transpressional uplift in the central Andes of Peru and structural inversion of the Santiago – Cutucu – Napo extensional basins to form the NNE-trending Cordillera Real of Ecuador (Baldock, 1982; Tankard, 1999a). However, the large-scale structural inversion that created the Cordillera Real was modified by NNE-striking, right-lateral wrench faults such as the Jambeli-Naranjal, Milagro-Guaranda, and Guayaquil-Babahoyo fault zones (Baldock, 1982, his figure 3). The Guayaquil-Babahoyo fault zone appears to track the boundary between continental and oceanic crust in Ecuador (cob in Figure 11).

The timing of these events is marked by the Aptian – Campanian magmatic arc, reflecting a plate reorganisation (Baldock, 1982; Mourier et al., 1988; Tankard, 1999a). In Ecuador, this Macuchi arc is an enormously thick accumulation, exceeding 8000 m in places, of andesitic and basaltic extrusives and volcaniclastics, volcanic sandstones, siltstones, and turbiditic tuffs. These Macuchi magmas have typical island-arc geochemical affinities. Baldock notes that the Macuchi arc has been tectonically sliced by younger NNE- to NE-striking faults. The Jambeli-Naranjal wrench resulted in 50 km offsets of the arc during the Tertiary (Tankard, 1999a). Several authors have studied the kinematics of the Nazca Plate and its relation to the Pacific margin of Peru and Ecuador (Pilger 1981, 1983; Gutscher et al., 1999). There is considerable segmentation of the Nazca Plate along strike that is attributed to heterogeneity of the subducting plate. Of particular importance are the present and inferred plate vectors with respect to the continental margin. In particular, plate convergence is more or less orthogonal to the northwestern margin of Peru, whereas along the Ecuador trench subduction is markedly oblique. Oblique subduction invariably results in strike-slip dismembering and translation of the adjacent continental crust. These characteristics distinguish the northwest Peruvian Andes from the strike-slip Costa and Sierra tectonic provinces of Ecuador.

The widespread development of NNE-trending, dextral wrench faults is thus attributed to the kinematics and oblique subduction of the Nazca Plate. The initiation of this new tectonic paleogeography and strike-slip basin formation is dated to the Aptian. This is the age of onset of magmatic arc formation (Baldock, 1982) and the Muerto Pananga and Gigantal successions in the Talara and Lancones basins (Carlos Monges, personal communication, 2001).

Strike-slip segmentation of the continental crust is expressed in an anastomosing system of NNE-striking, right-lateral strike-slip faults along which several basins formed. Notable examples are the Tumbes, Talara, and Lancones basins as well as the Gulf of Guayaquil itself. However, these strike-slip faults not only form and offset individual basins, they also compartmentalise the basins internally. Figures 21 to 23 show the seismic expression of strike-slip structural styles in the offshore parts of the Talara basin, including multiply-stacked basins and transtensionally rotated fault blocks.

The Talara basin covers 14,500 km^2 and consists of a fluvio-deltaic basin fill that is extensively compartmented by NE-trending strike-slip faults; the fill is estimated to be 5000 m (Séranne, 1987) to 8000 m (PERUPETRO files) thick. During the Middle Eocene, eastward verging transpressional thrusts locally detached the Tertiary cover (e.g. upper Lower Eocene Echinocyathus Formation). The strike-slip faults are generally reliably mapped. However, the presence and distribution of E-striking normal faults are invariably based on facies and stratigraphic variations recorded in well logs and cutting samples, suggesting that they may be fictitious in places. There have been in excess of 12,000 wells drilled in this basin. Stratigraphic correlation generally attempts to impose a tabular configuration. A characteristic of this type of strike-slip regime is that facies, stratigraphy and isopachs are highly variable, and any tabular stratigraphic reconstruction based on lithological correlation alone is likely to be suspect. The Talara basin contains an estimated 1.5 billion barrels of recoverable oil reserves, and 3 tcf of gas reserves; production has at times exceeded 40,000 BOPD. Considering the way mapping and stratigraphic correlation has been done, I suggest that there may be considerable economic benefit in attempting to resolve this geology, either by careful seismic interpretation or by detailed biostratigraphic correlation.

Reflection seismic shows that the principal strike-slip faults that form the Talara basin continue offshore where the terrace wedge has been extensively dissected and transtensionally rotated (Figure 23). Numerous unconformities interrupt this stratigraphic succession. The coastal batholith complex of coarse-grained granites and granodiorites suggests significant uplift. The youngest batholith age is 3 Ma (René Marocco, personal communication, 2001). This interpretation of significant uplift during the Late Pliocene or Quaternary suggests that potential Miocene source rocks may be mature.

Related to the overall NE-oriented strike-slip trend are several NW-striking faults that had a left-lateral sense of displacement. These are antithetic strike-slip systems, and locally control basin formation, such as the Progreso basin of southwest Ecuador (Figure 11).

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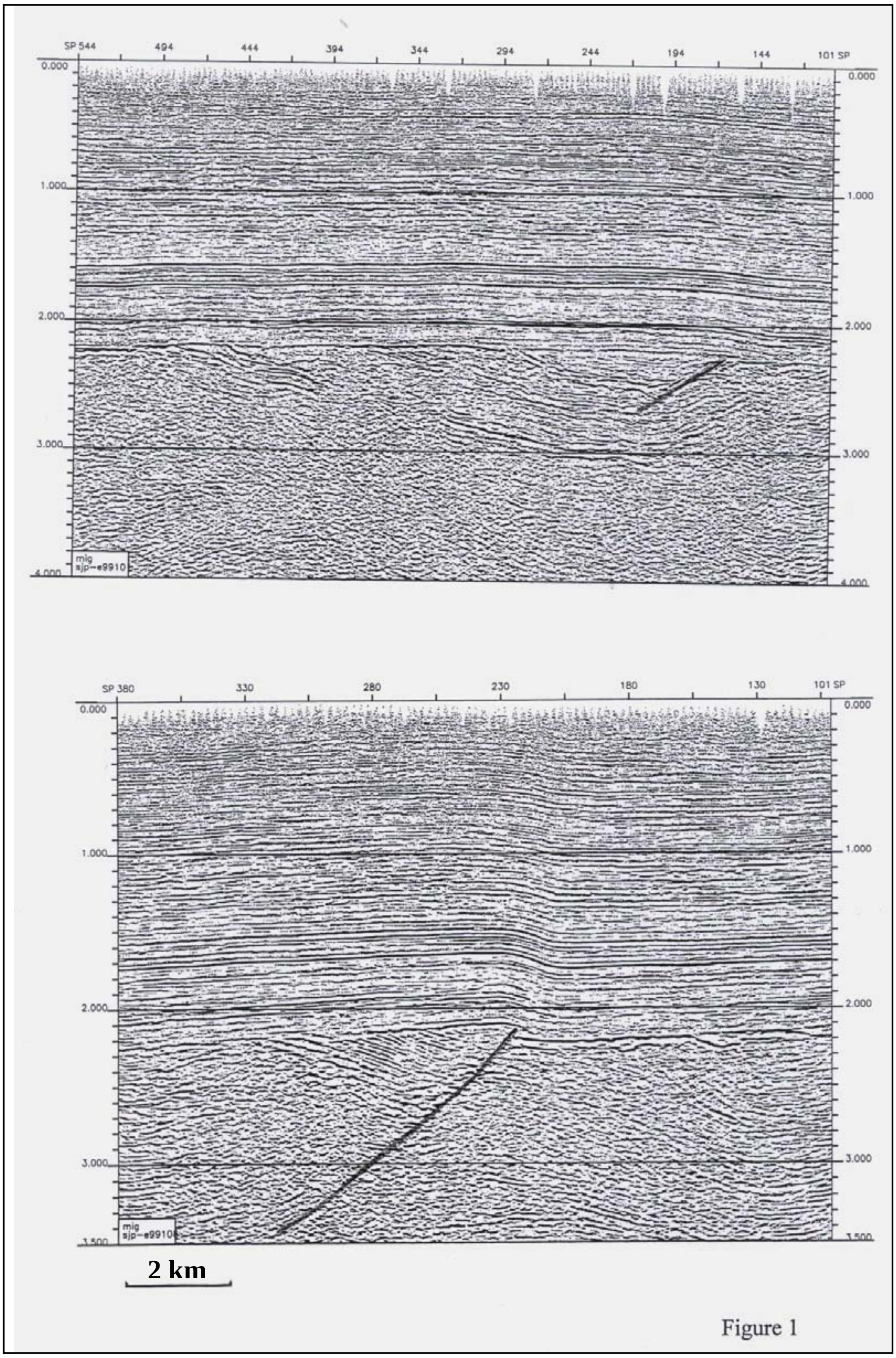


Figure 1. Seismic from the Marañon basin showing variably dipping basement reflectors, basin fill lying unconformably above basement, and basement-rooted extension faults that have been inverted during the Tertiary Andean orogeny. Scale bar 2 km.

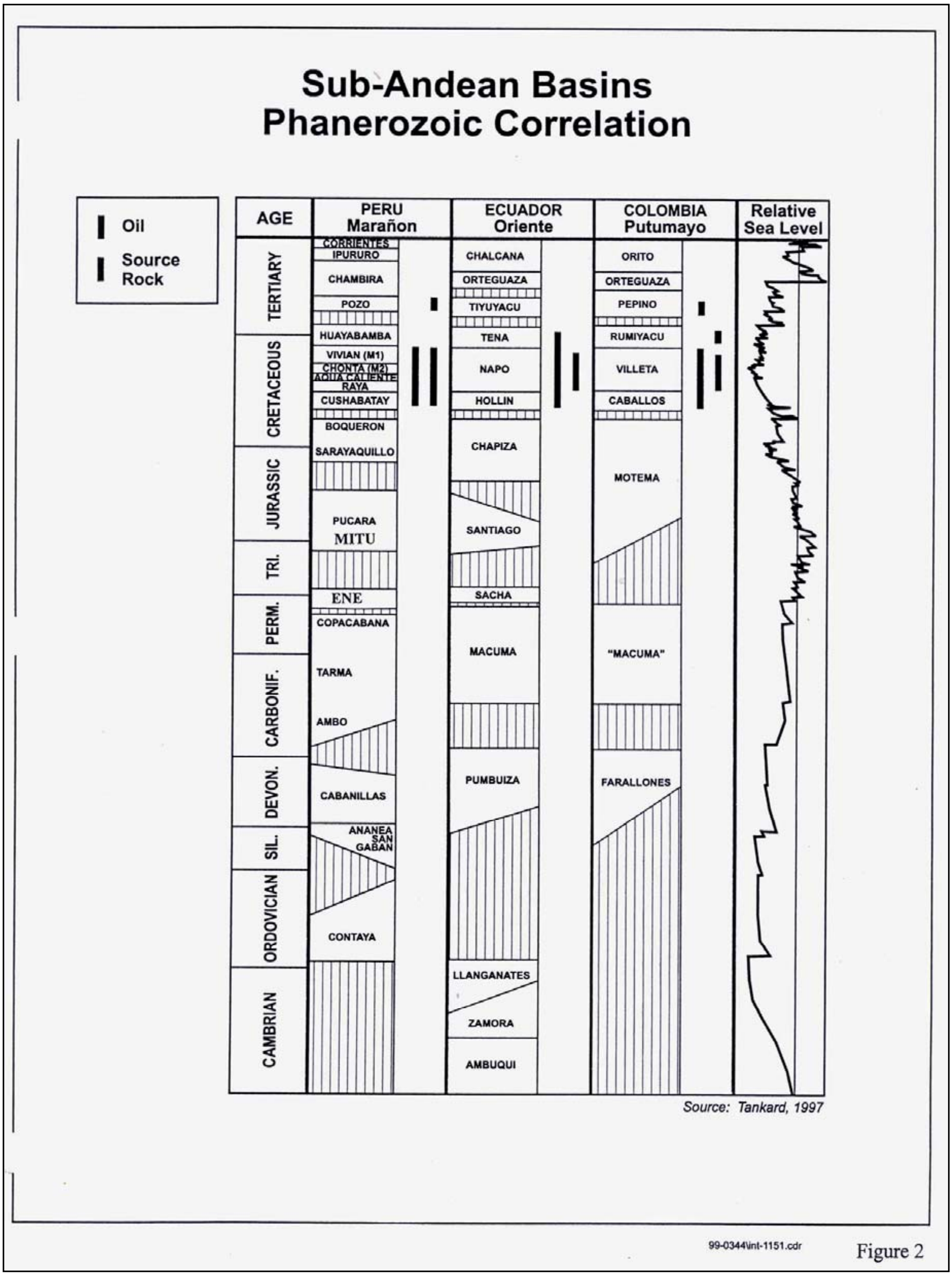


Figure 2. Phanerozoic stratigraphic columns and correlation for the Marañon, Oriente, and Putumayo basins. After Tankard, 1999a.

Figure 3. Simplified Late Jurassic – Early Cretaceous tectonic setting showing reactivation of WNW-striking lineaments related to extension and opening of the Atlantic. The sense of displacement at this time was right lateral. Displacement along the NW-trending shears in Peru are explained by this regional tectonic behaviour.

Figure 4. Structural framework of basin distribution and architecture in Peru, consisting mainly of NW- and NE-striking faults. Ac, Acre basin; Co, Contaya high; Cu, Cushabatay high; Cut, Cutucu depocentre (now Cutucu uplift); Hual, Huallaga basin; Na, Napo depocentre (now Napo uplift); P, Progreso basin; San, Santiago basin; Ta, Talara basin; Tu, Tumbes basin.

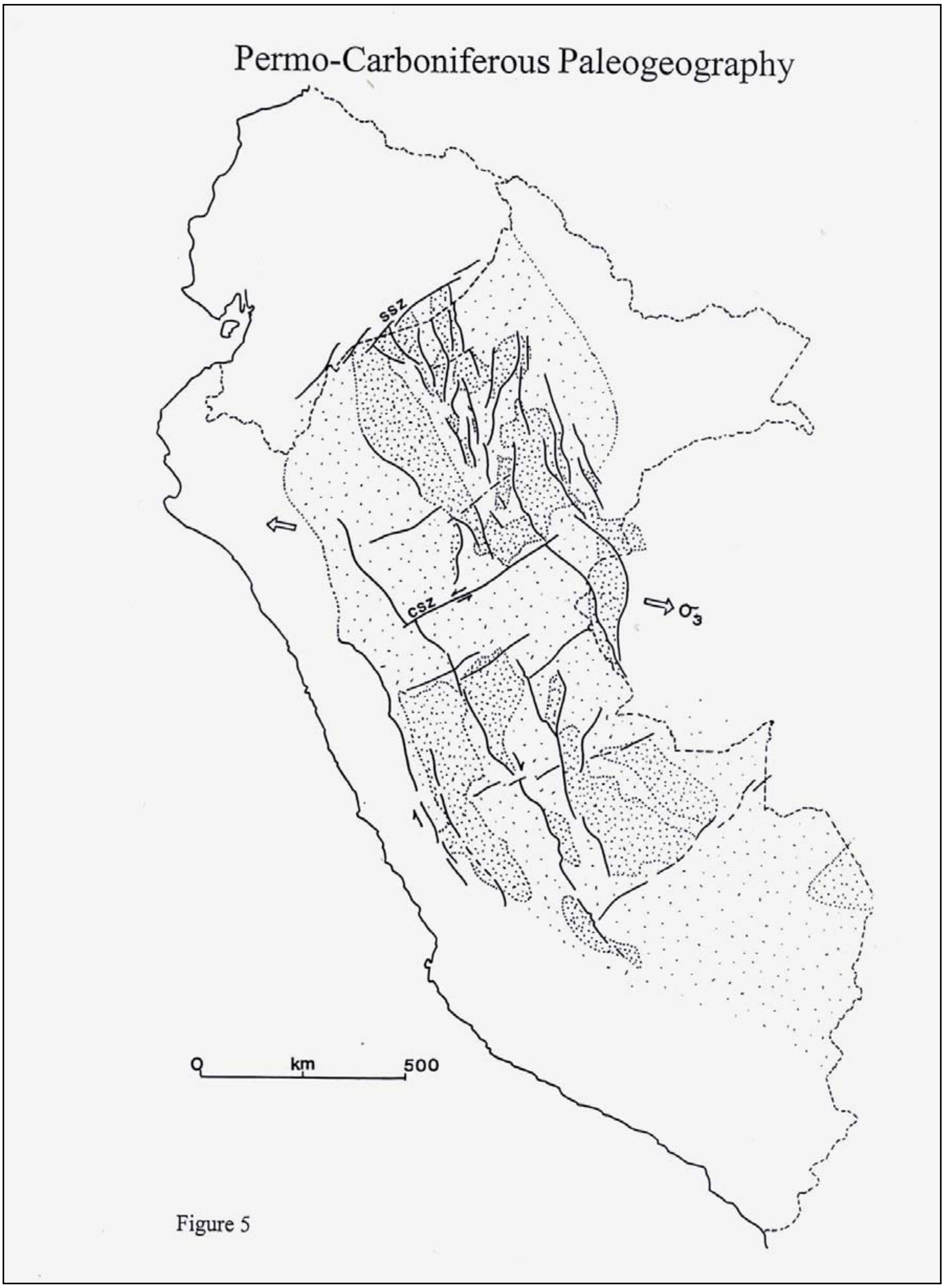


Figure 5. Permo-Carboniferous paleogeography, a thumbnail sketch based on sporadic outcrop and well data and regional seismic compilations. csz, Contaya shear zone, ssz, Shionayacu shear zone.

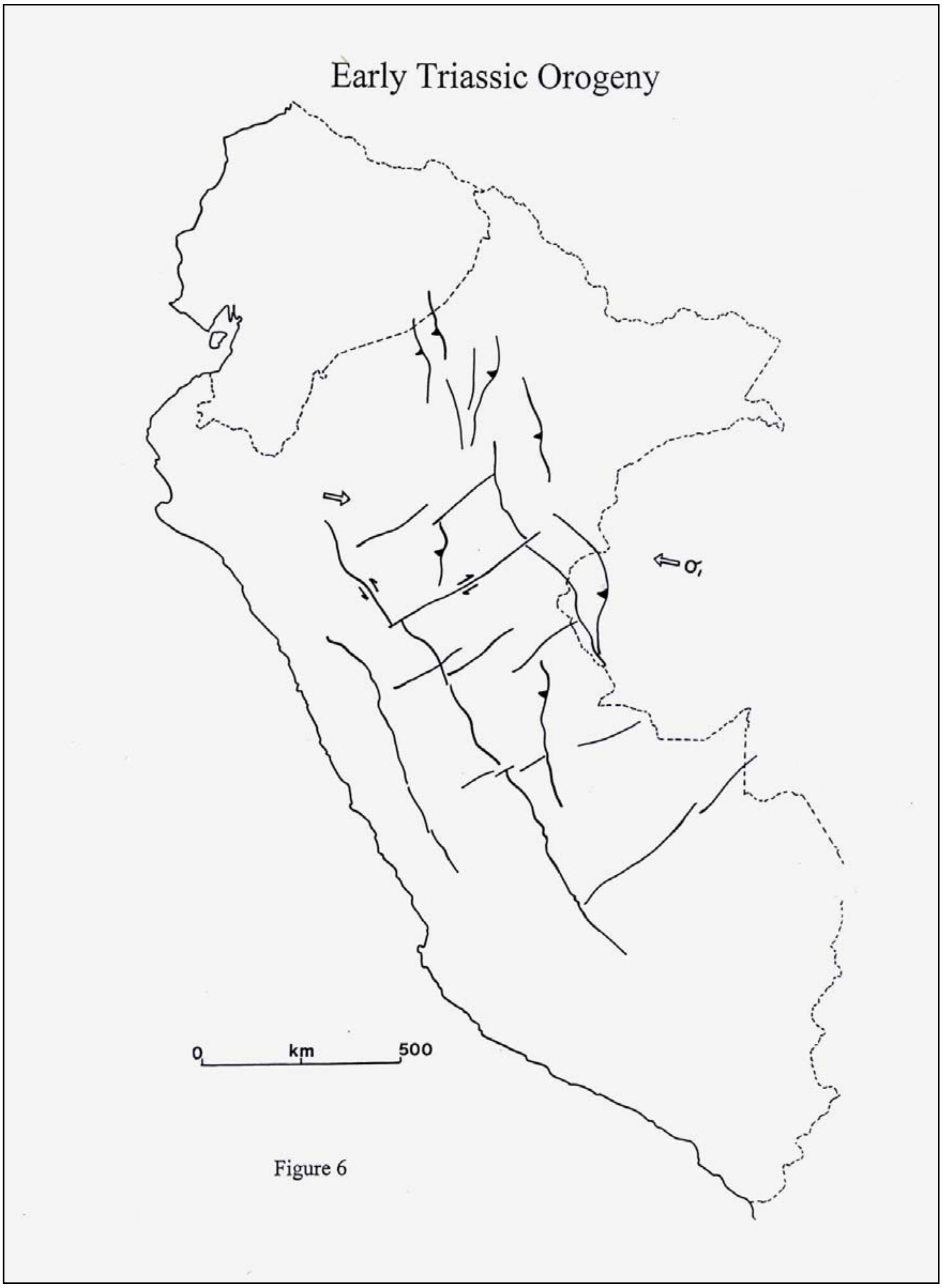


Figure 6. Juruá orgeny of Late Permian – Early Triassic age, showing inversion of earlier (Permo-Carboniferous) extensional depocentres. The Juruá event is marked regionally by a substantial hiatus that separates an Ene cover deposited in an epeiric basin, and rift-controlled accumulation of Mitu molasses attributed to orogenic collapse. Compare with Figure 7.

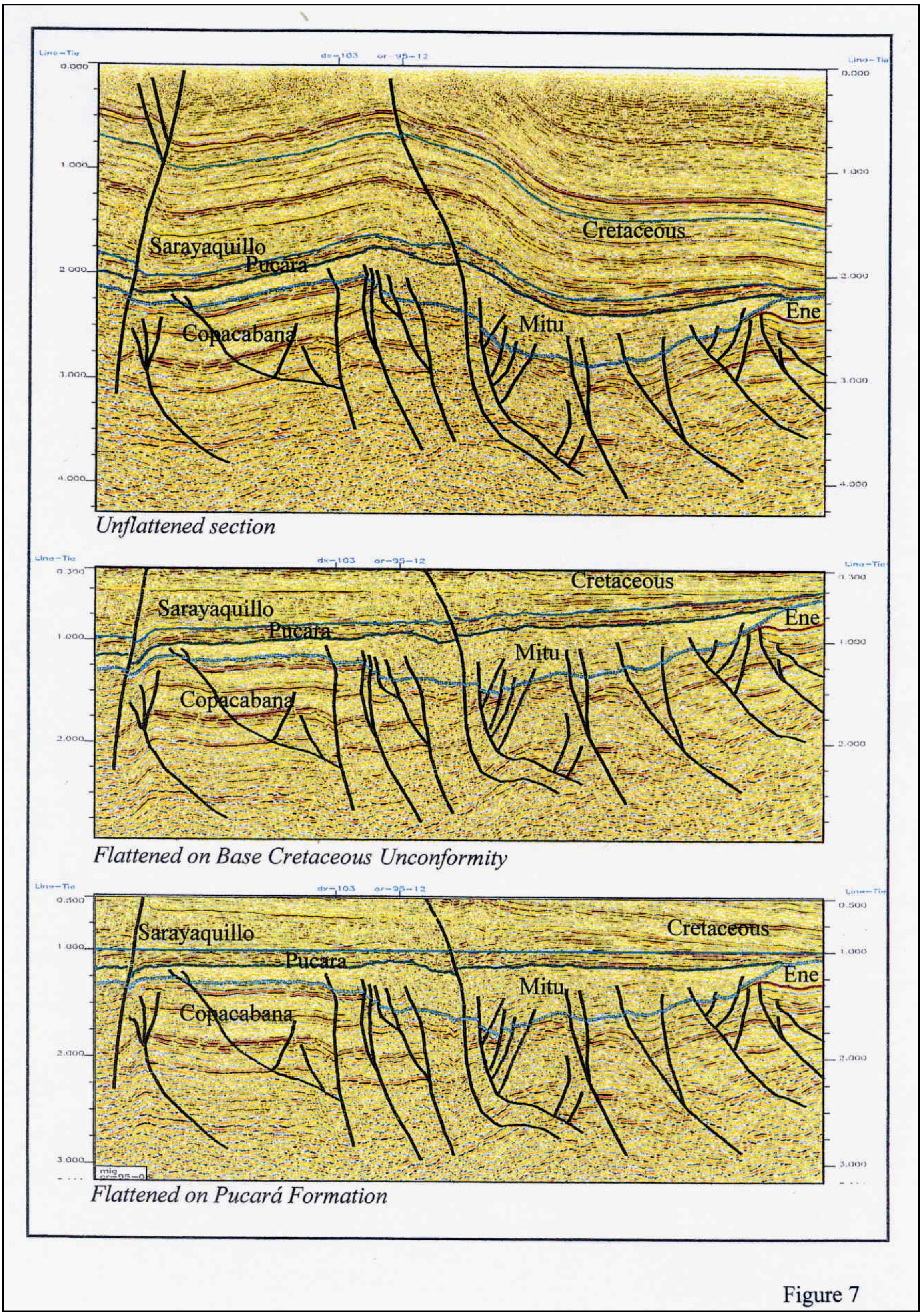


Figure 7. Flattening of Huallaga seismic showing irregular, extensional Mitu Formation above persistent Permo-Carboniferous sediments. After Parsep 2000a.

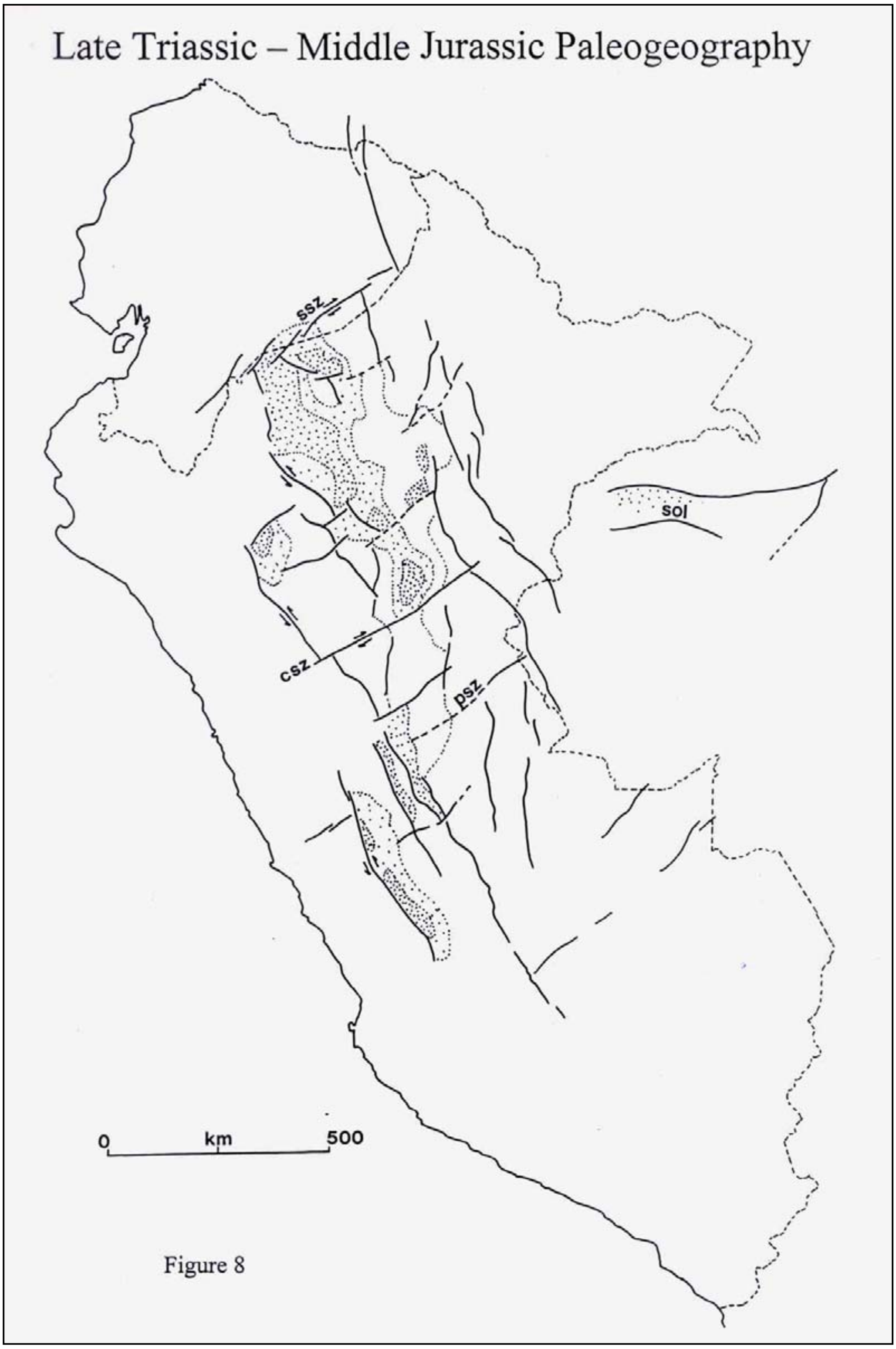


Figure 8. Late Triassic – Middle Jurassic paleogeography. The locus of sedimentation was the extensional tract between the Contaya (csz) and Shionayacu (ssz) shear zones. Isopachs show that the stratigraphy terminated abruptly against NE-striking faults, and for this reason they are described as basin sidewall faults. psz, Pucalpa shear zone; sol, Solimoes basin.

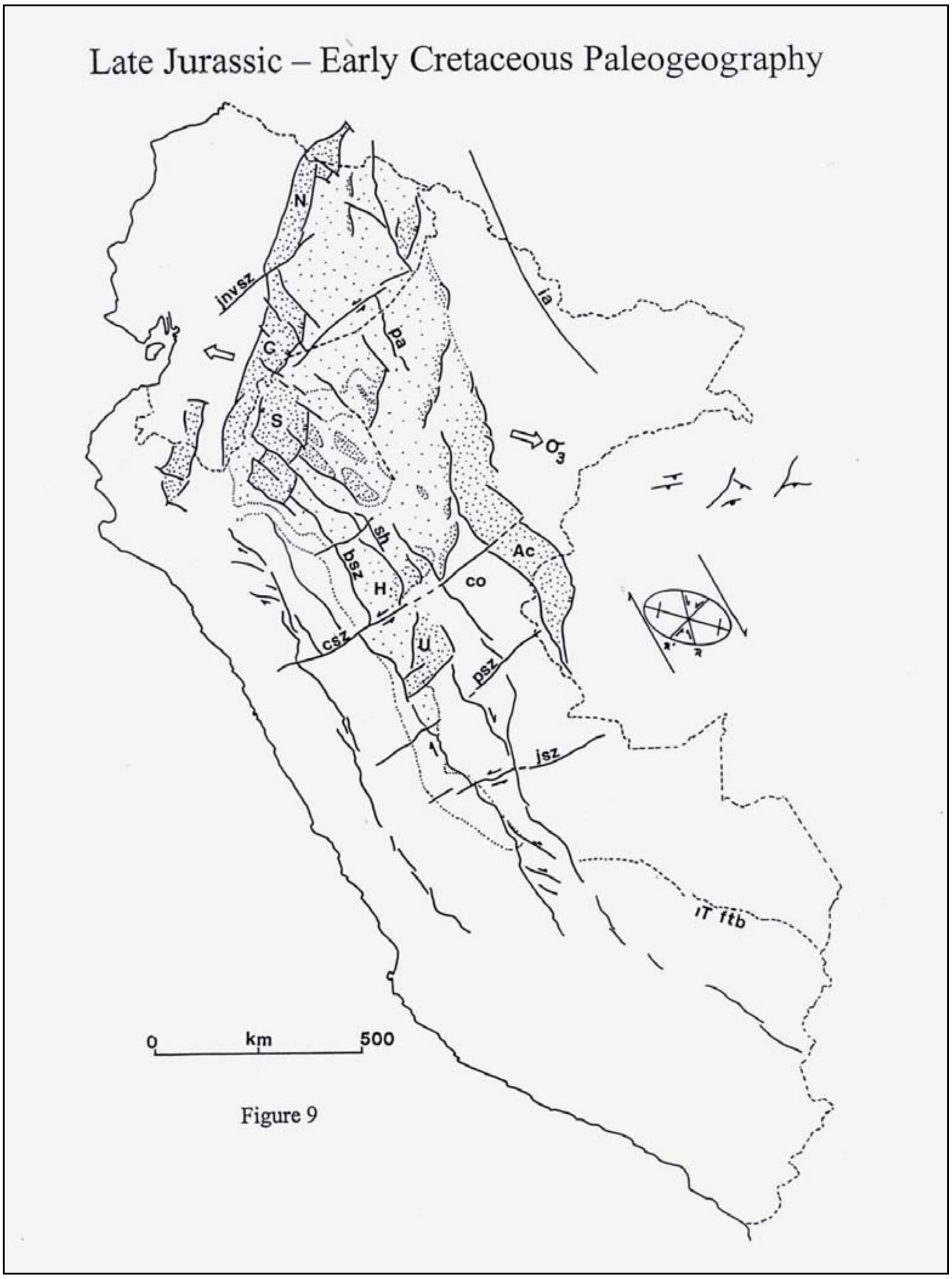


Figure 9. Late Jurassic – Early Cretaceous paleogeography, showing two principal styles of basin formation, *viz.* strike-slip associated extensional basins in which the extensional normal faults are approximately northward oriented, and NW-oriented strike-slip basins. The locus of extensional subsidence was between the Contaya and Jambeli-Naranjal-Vuana shear zones. Ac, Acre basin; bsz, Baboa shear zone; C, Cutucu depocentre; co, Contaya high; csz, Contaya shear zone; H, Huallaga basin; ia, Iquitos arch; jnvsz, Jambeli-Naranjal-Vuana shear zone; jsz, Juruá shear zone; lT ftb, late Tertiary fold thrust belt of the Madre de Dios range; N, Napo depocentre; pa, Paragua shear zone; psz, Pucalpa shear zone; S, Santiago basin; sh, Shanusi fault; U, Ucayali basin.

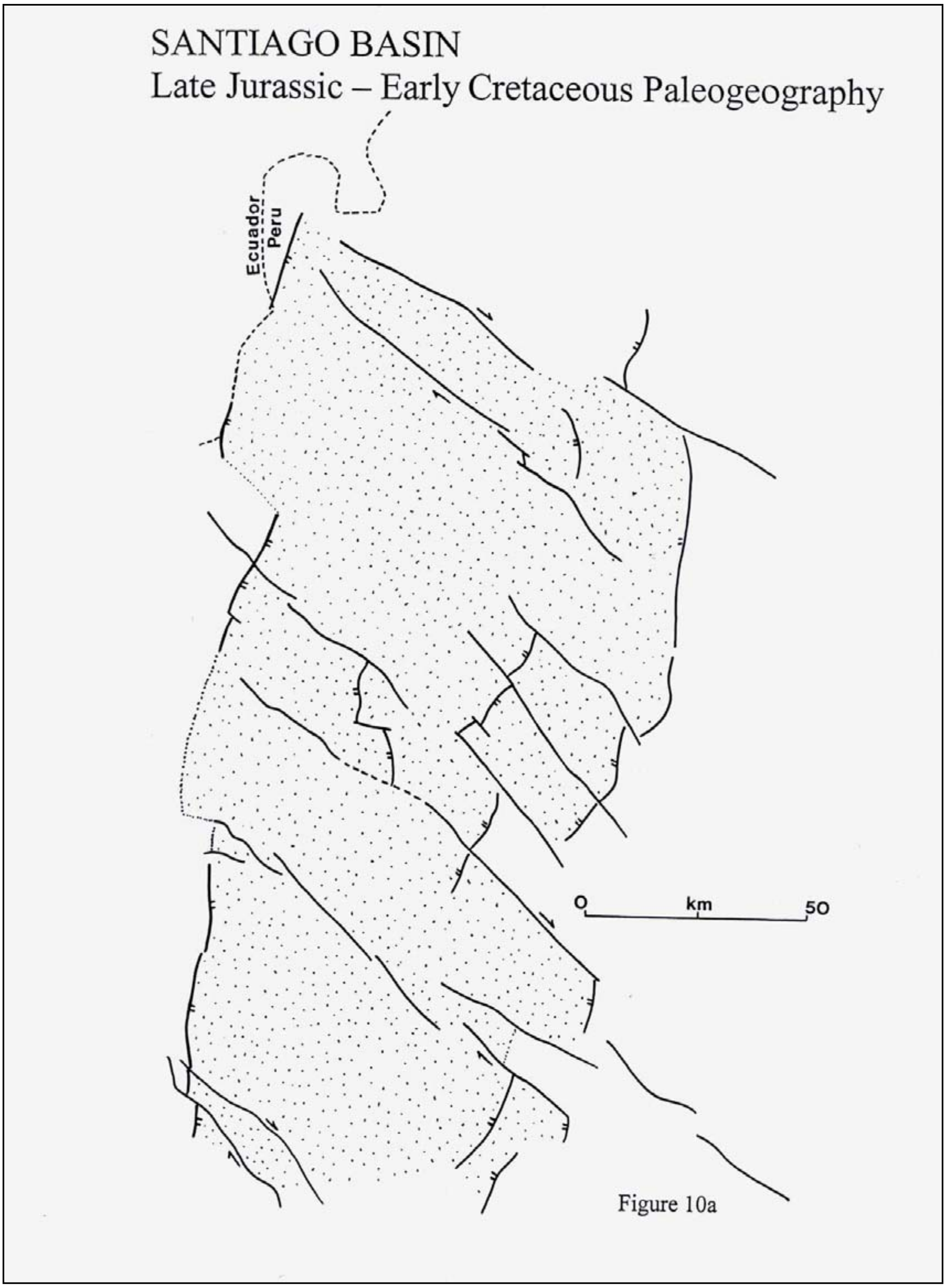
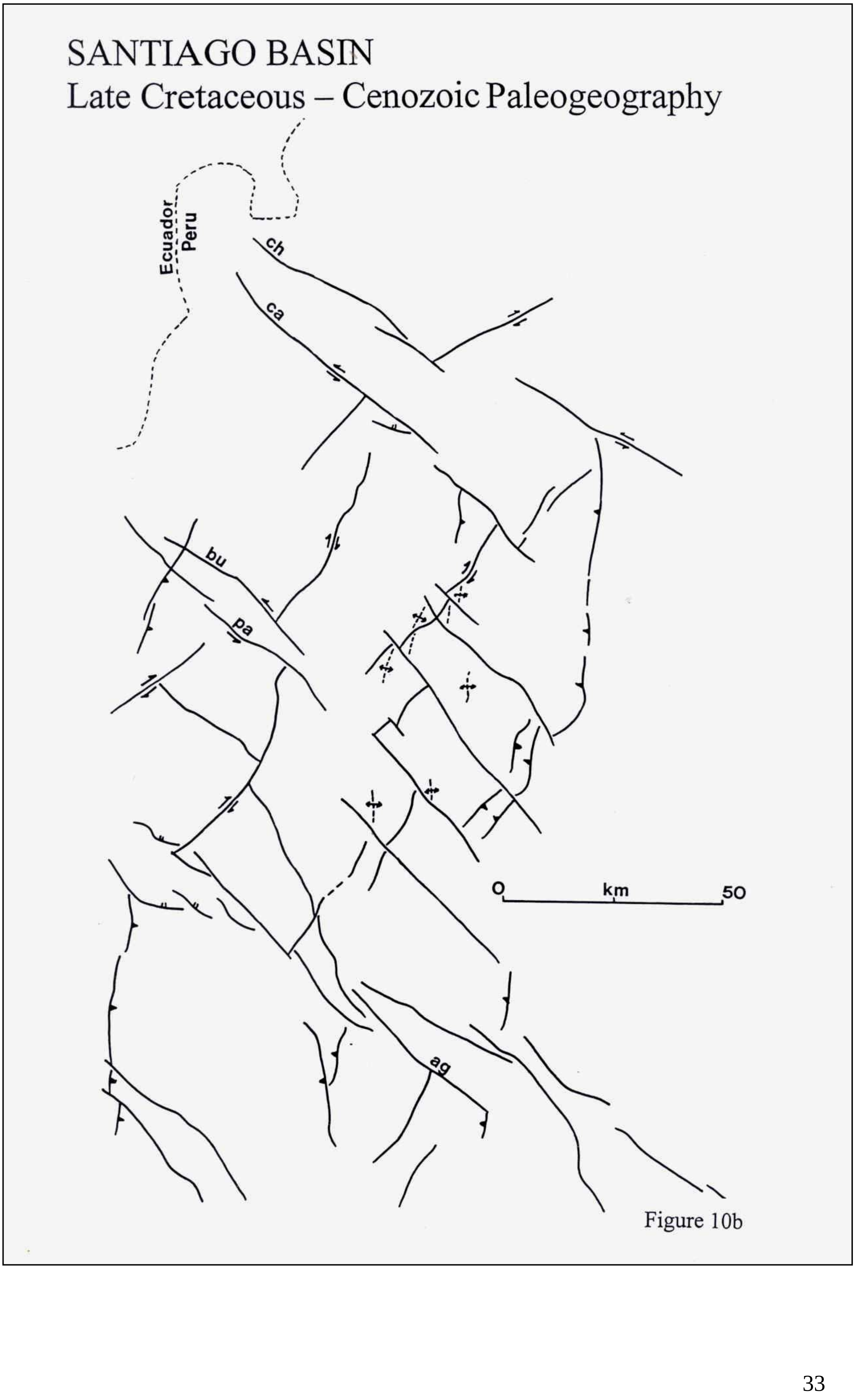


Figure 10. Santiago basin: (a) Late Jurassic – Early Cretaceous extension, (b) Late Cretaceous (Maastrichtian) – Cenozoic paleogeography. The principal displacment zone is the left-lateral Agapa fault, while translation and deformation was dispersed across a suite of sub-parallel, NW-trending slip faults or accommodation zones. ag, Agapa shear zone; ca, Cashpa shear zone; ch, Chinganaza shear zone; bu, Buchigkin shear zone; pa, Paiza shear zone.


SANTIAGO BASIN
Late Cretaceous – Cenozoic Paleogeography
Ecuador
Peru
ch
ca
bu
pa
ag
0
km
50
Figure 10b

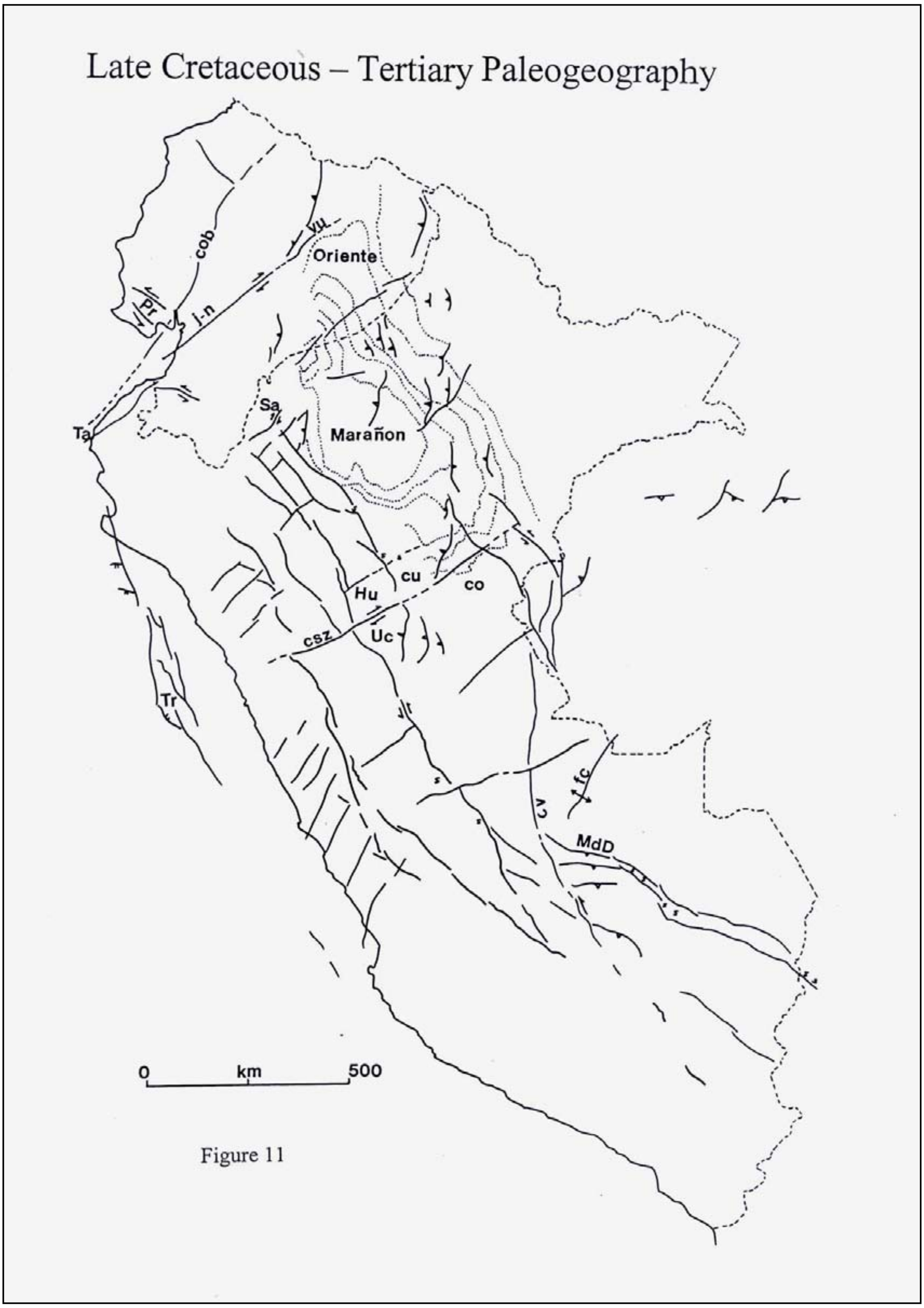


Figure 11. Late Cretaceous – Tertiary paleogeography in which the locus of subsidence and deposition was the Marañon – Oriente basin area. co, Contaya high; cob, boundary between continental and oceanic crust; csz, Contaya shear zone; cu, Cushabatay high; Cv, Cordillera Vilcabamba range and shear zone; fc, Fitzcarrald anticline; Hu, Huallaga basin; j-n, Jambeli-Naranjal shear zone; MdD, Madre de Dios range; Pr, Progreso basin; s, oil seeps; Sa, Santiago basin; Ta, Talara basin; Tr, Trujillo basin; Uc, Ucayali basin; vu, Vuana fault.

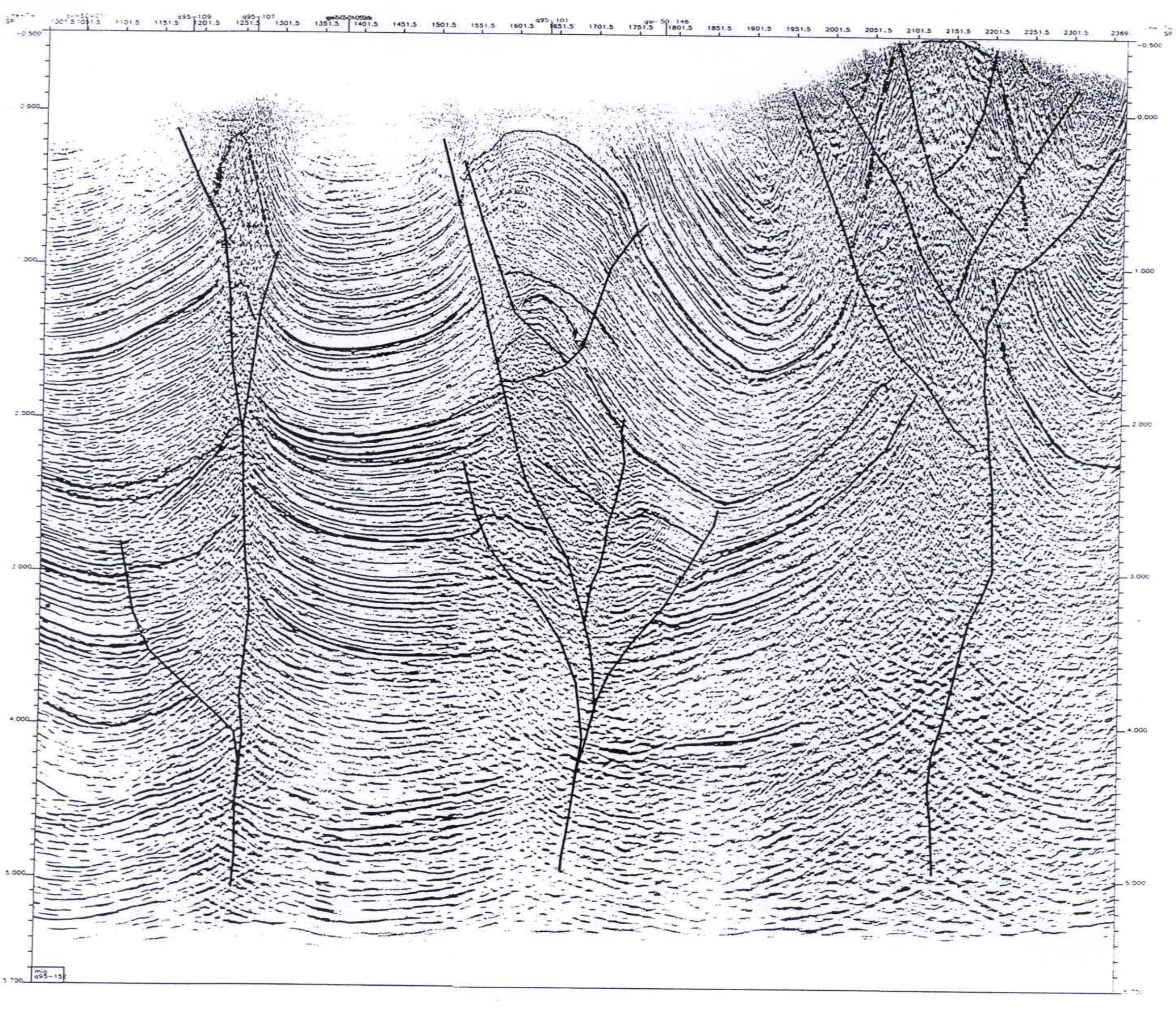


Figure 12

Figure 12. E-W seismic in Santiago basin showing characteristic transpressional deformation and massive uplift. Interpretation by Joe Arcuri., PARSEP Project, Lima

Figure 13.   Huallaga basin seismic
 showinghigh-angle reverse faulting
and structural inversion. Thin-skinned
deformation is rare. Scale bar 2 km.

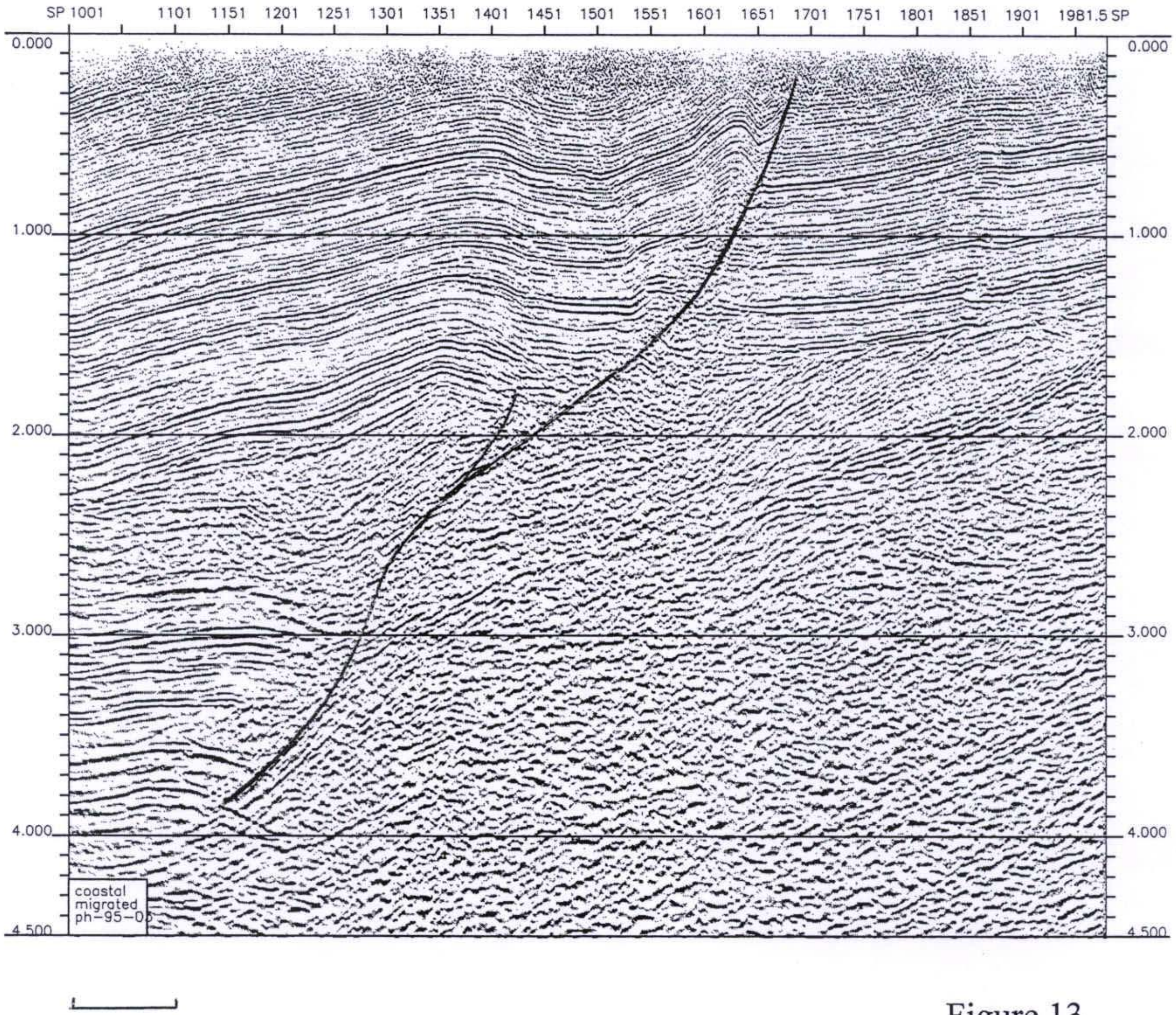


Figure 13

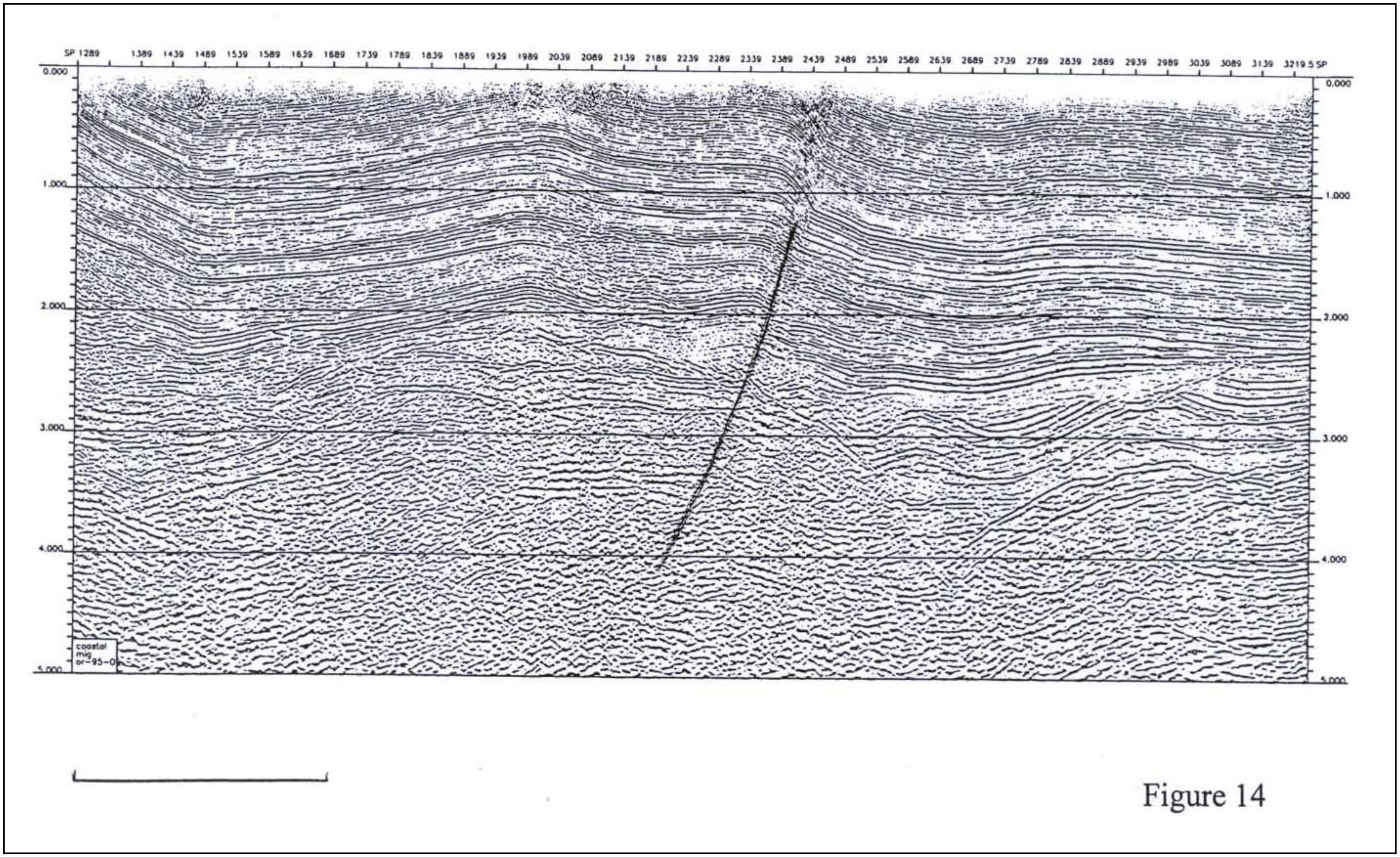


Figure 14. Huallaga basin seismic showing typical structural inversion. Scale bar 8 km.

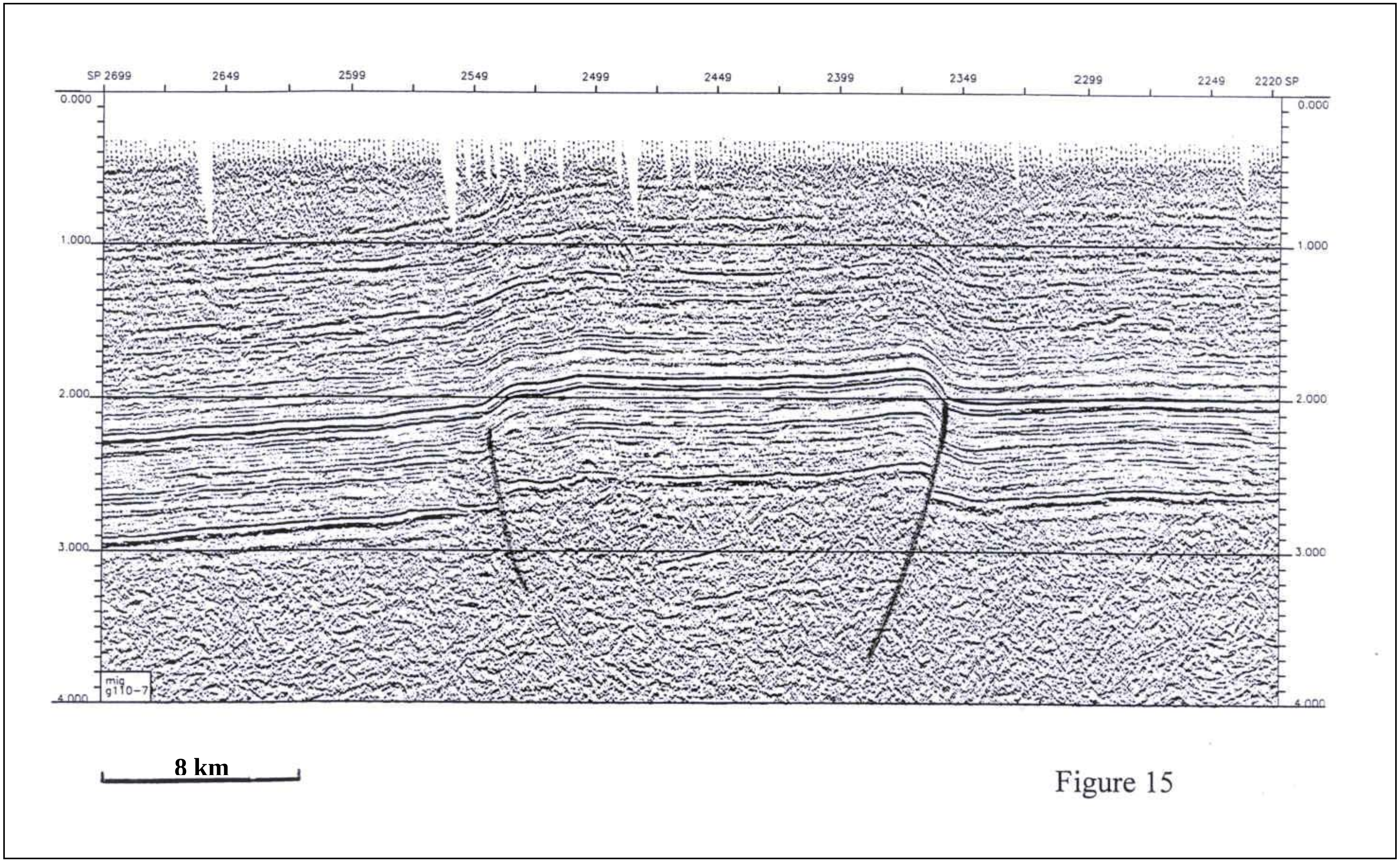


Figure 15. Marañon basin seismic showing reactivation of basement-rooted faults and subtle inversion structures with good petroleum trapping characteristics. Compare with Figure 1. Scale bar 8 km.

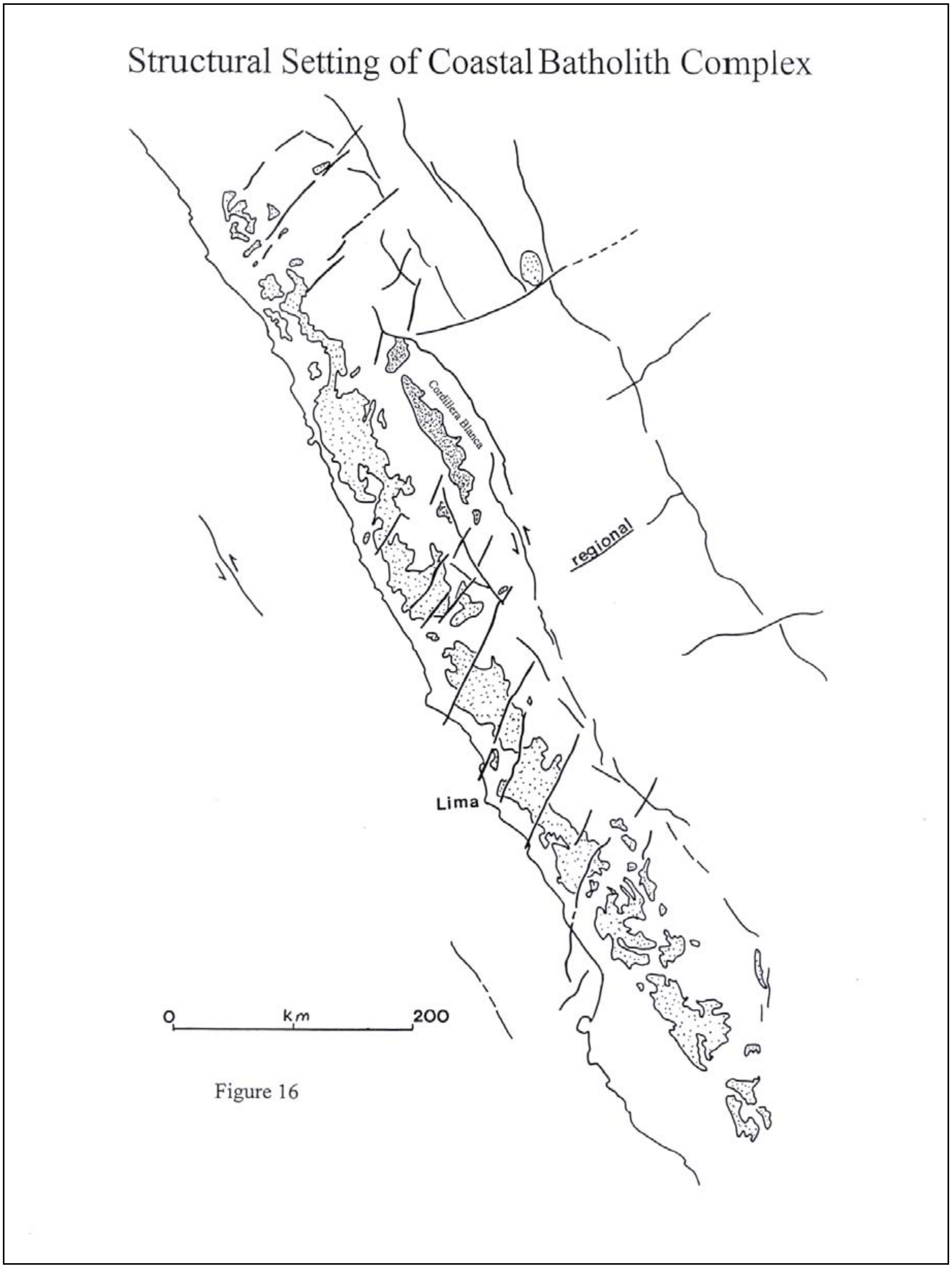


Figure 16. Structural setting of Late Cretaceous – Tertiary coastal batholith complex (light stipple) and Cordillera Blanca trondhjemites (dense stipple). Note 30º counter-clockwise rotation from regional.

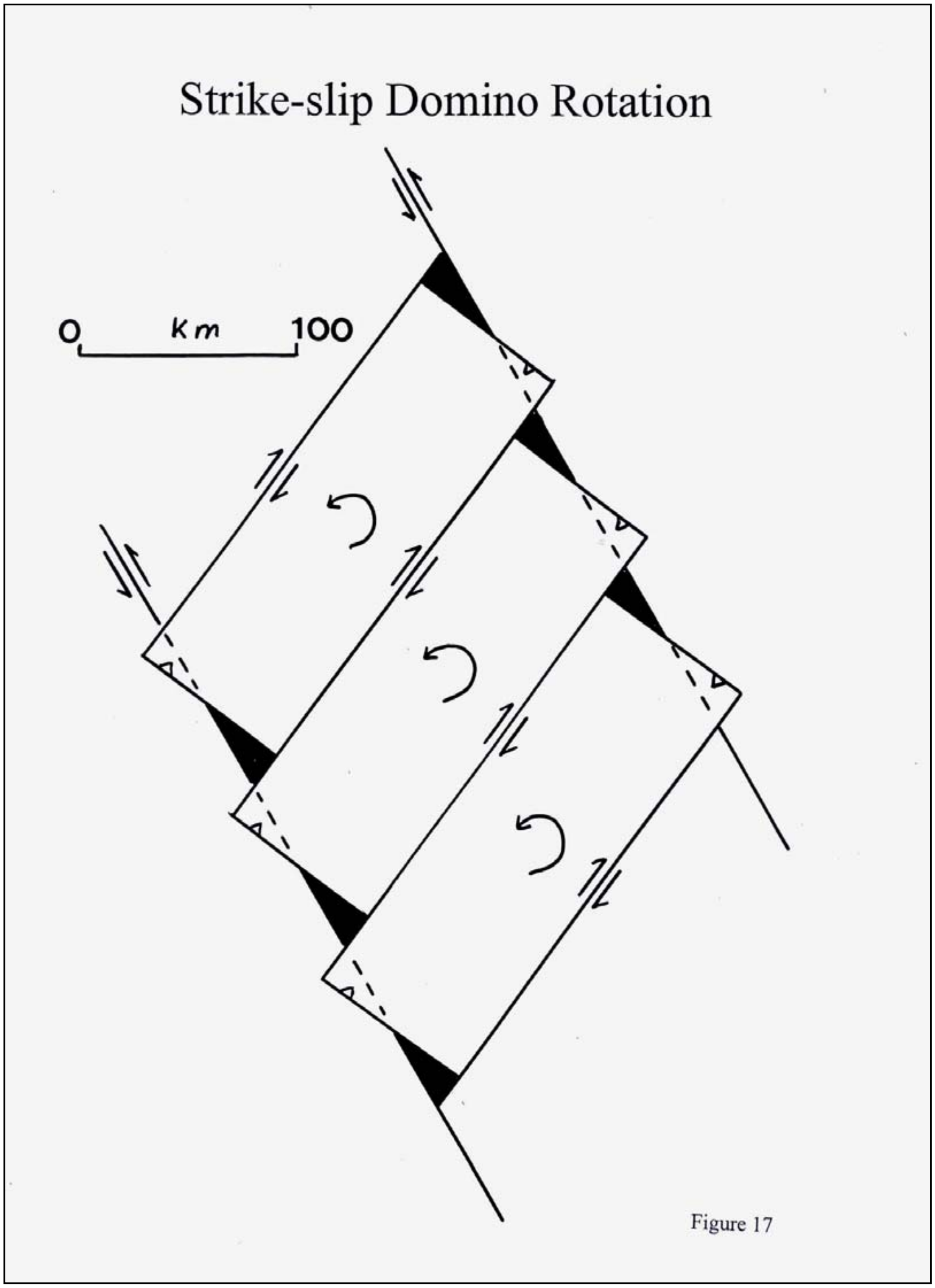


Figure 17. Model for rigid block or strike-slip domino rotation. Left-lateral strike-slip shear couples result in counter-clockwise rotation of rigid crustal blocks. Rotation creates space problems. Two corners are rotated inwards and result in extensional dilation, while the other two corners attempt to rotate outside the confining shear zones and result in compression and tectonic erosion. Modified after Nicholson et al., 1985.

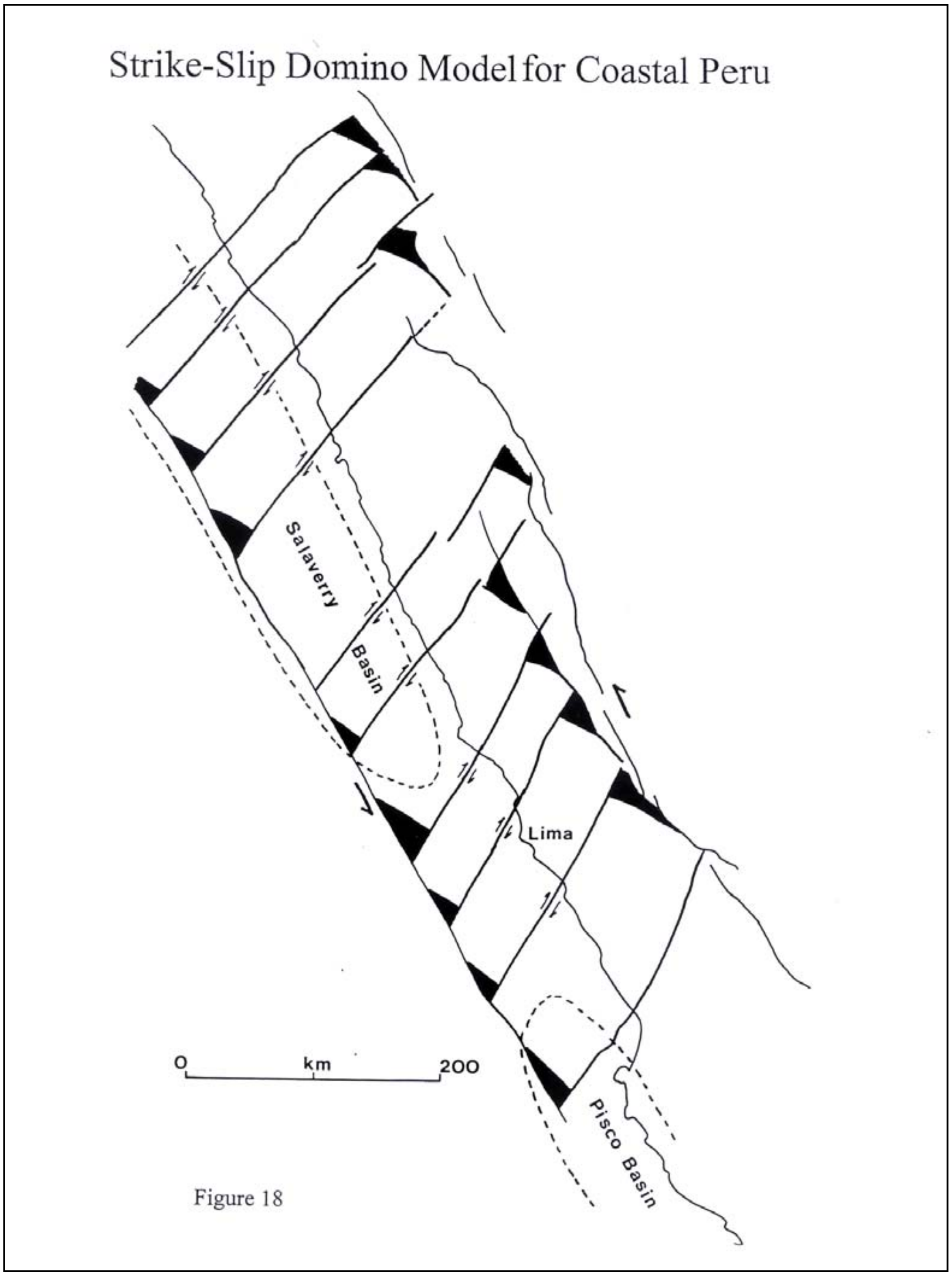


Figure 18. Strike-slip domino interpretation of the coastal batholith province. Coarse-grained granites and granodiorites were emplaced along the axis of the structural weakened rotated block zone, while higher-level trondhjemite stocks were marked by rapid ascent accommodated by the dilated inboard margin above a deep subducting slab (elevated P-T conditions). The seaward margin is above an area of shallow, cold subduction where P-T conditions were insufficient to generate melts. The Salaverry and Pisco basins are shallow downwarps above the seaward edge of the rotated block province.

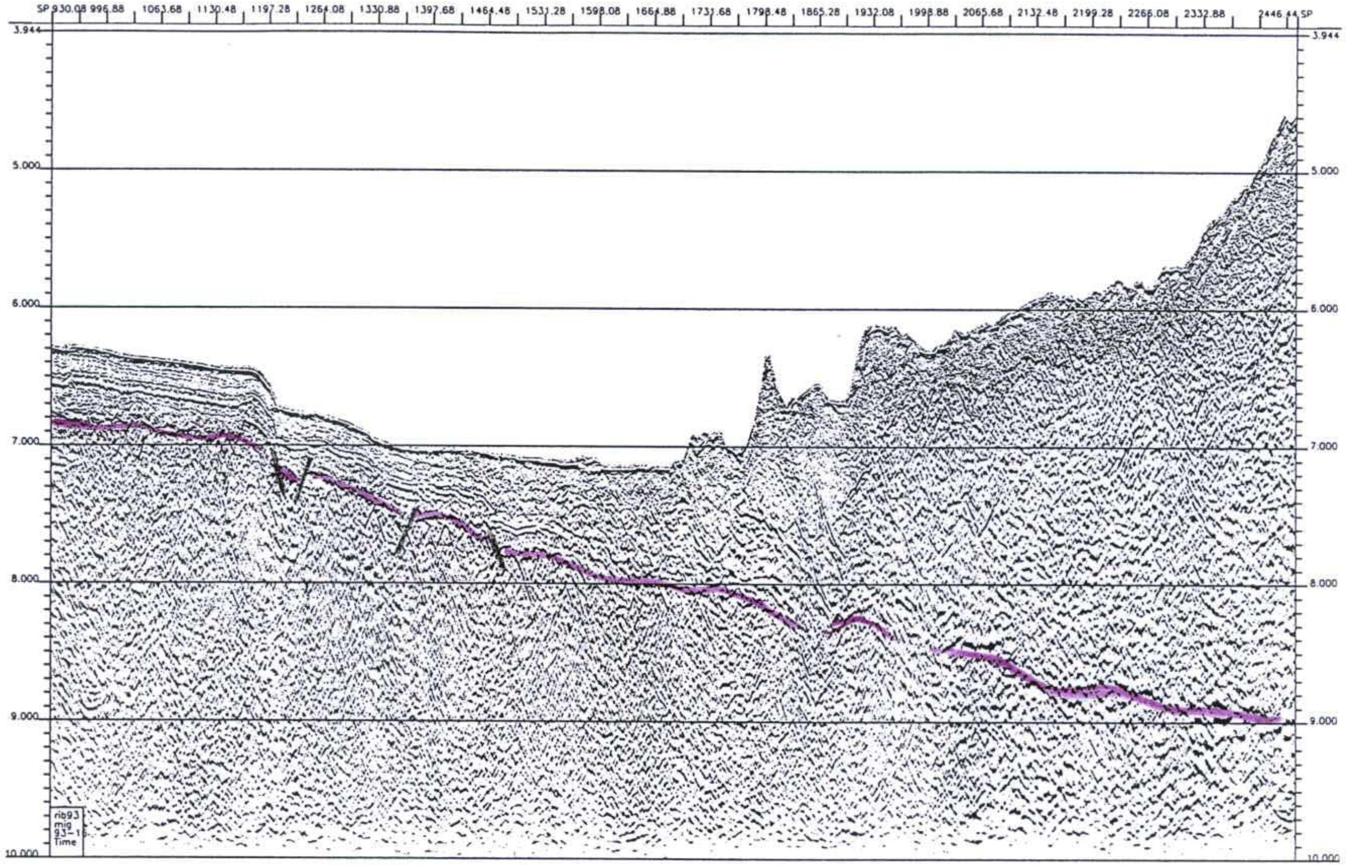


Figure 19. Seismic expression of Pacific plate subducting beneath the fore-arc terrace wedge. Note brittle failure and faulting of plate, facilitating sediment and water entrapment.

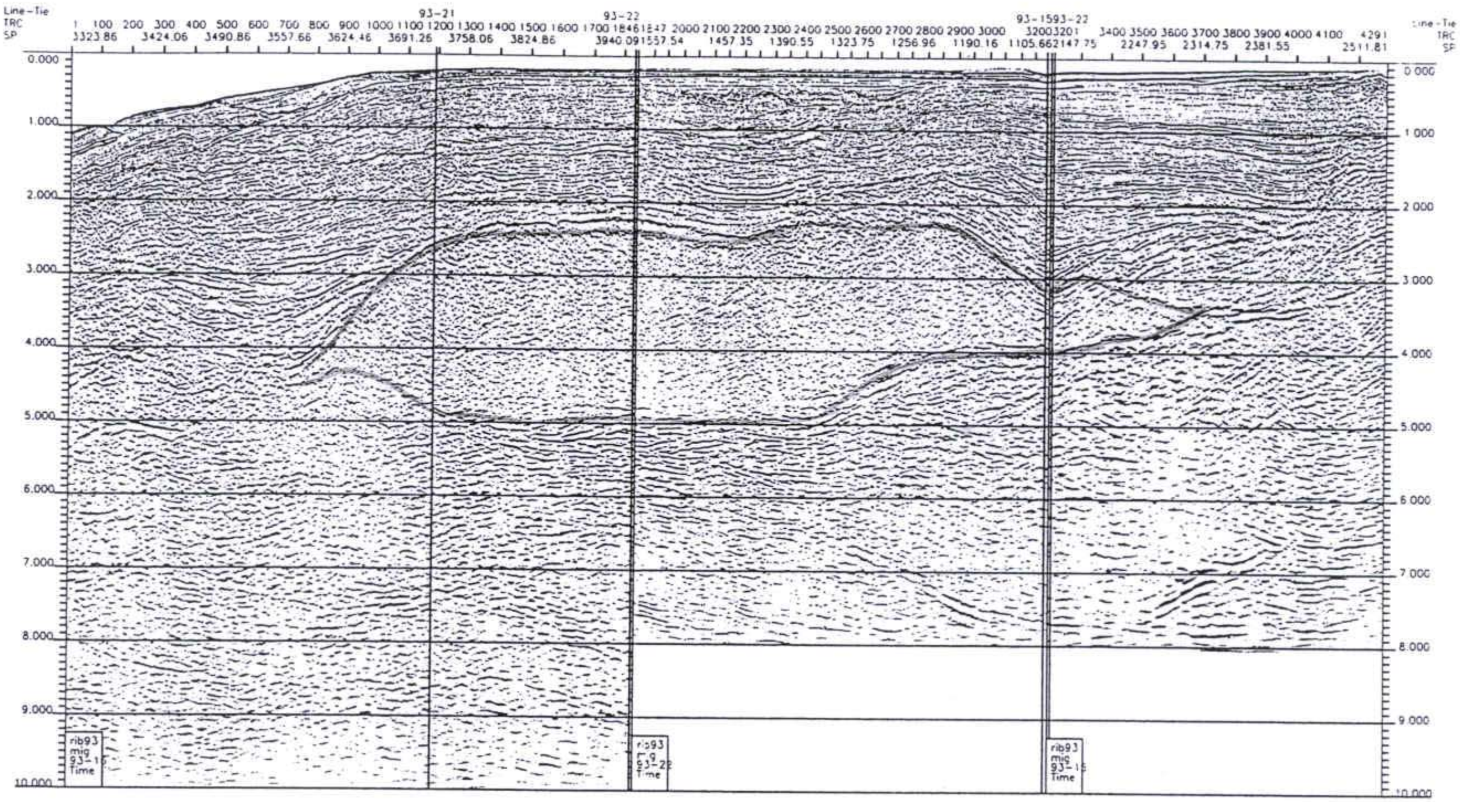


Figure 20

Figure 20. Seismic showing olistostrome of lower Paleozoic gneiss within fore-arc terrace wedge. Transportation is towards the south.

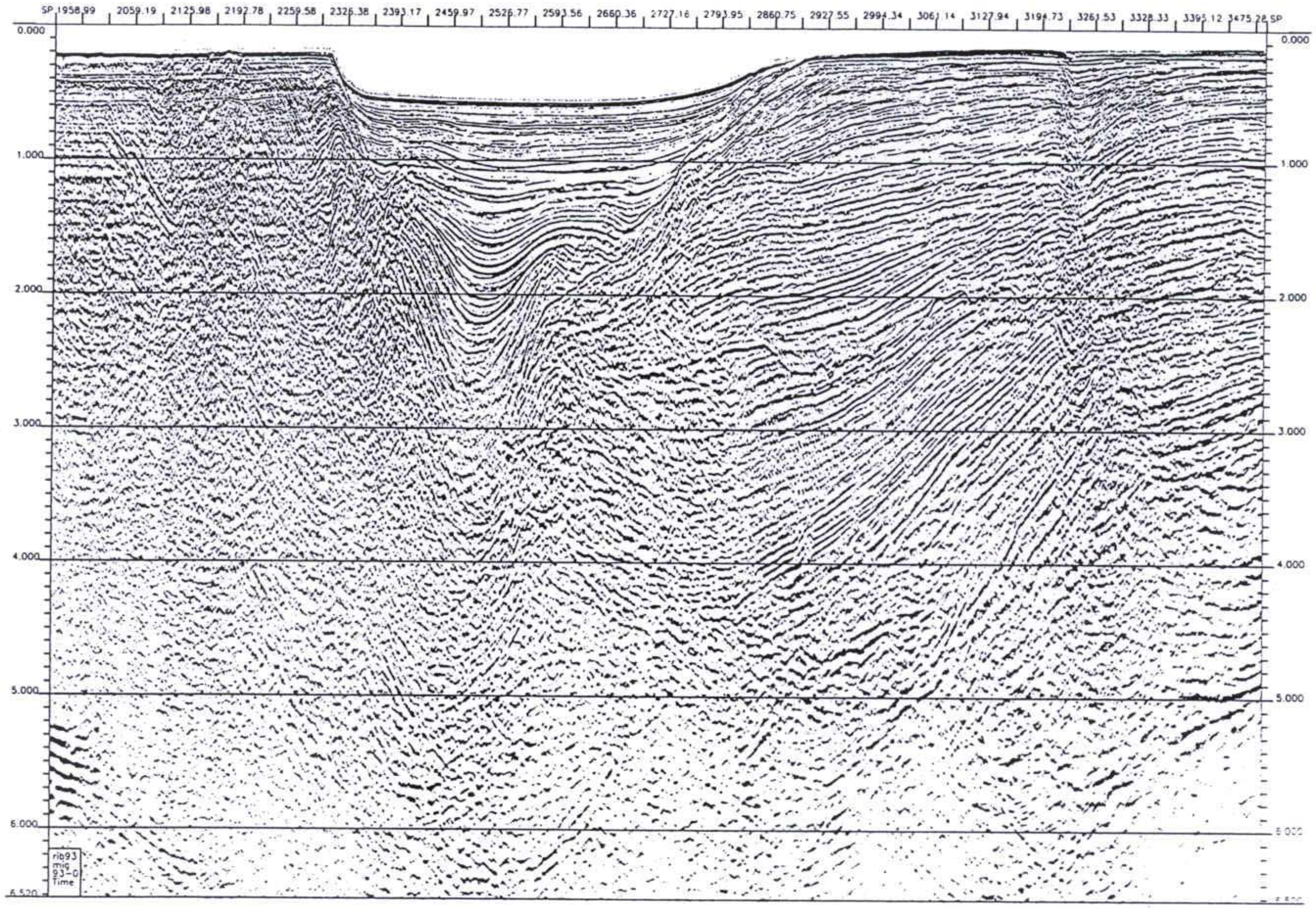


Figure 21

Figure 21. Offshore Talara basin, seismic showing strike-slip basin.

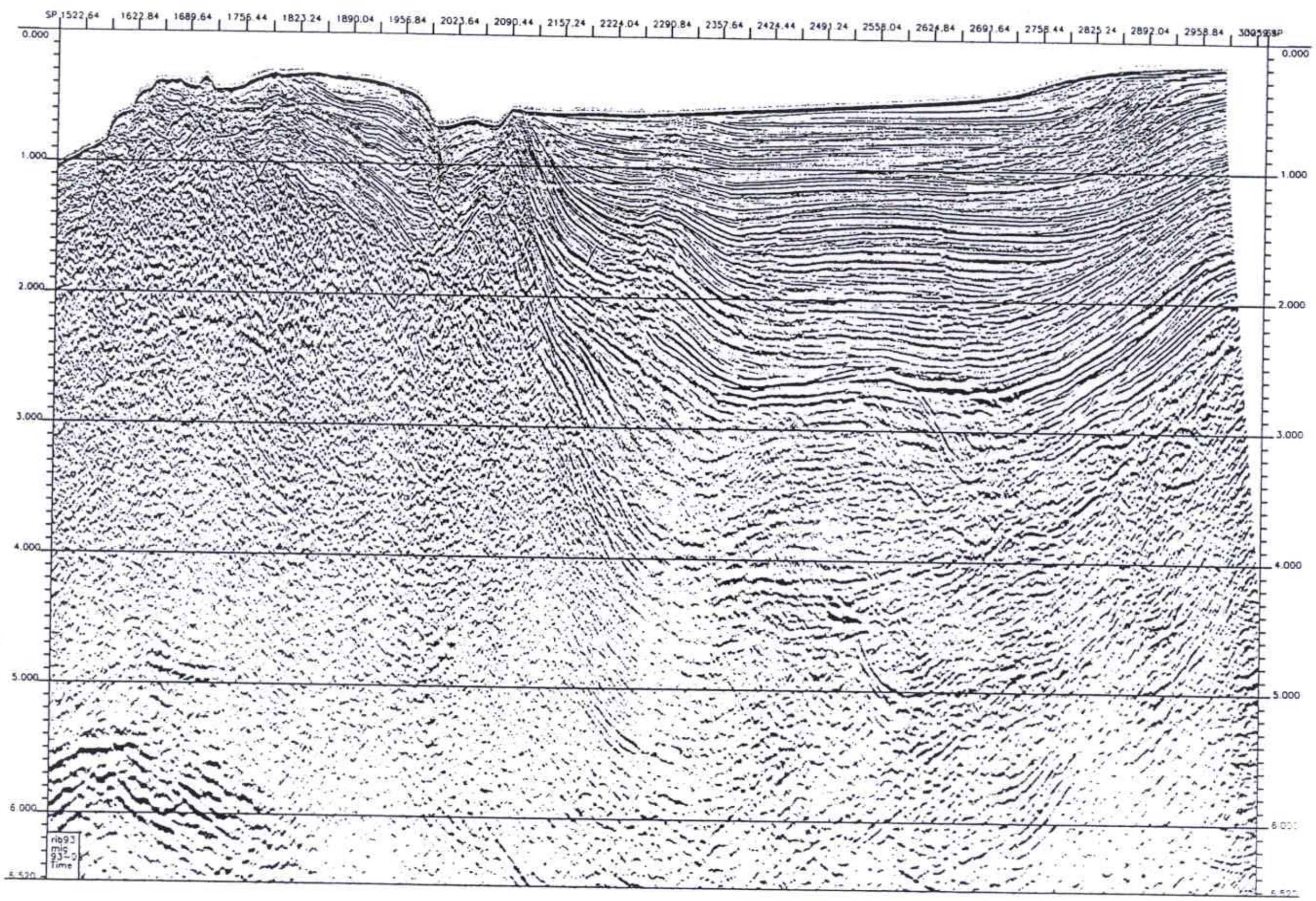


Figure 22

Figure 22. Offshore Talara basin, seismic showing multiply-stacked basins.

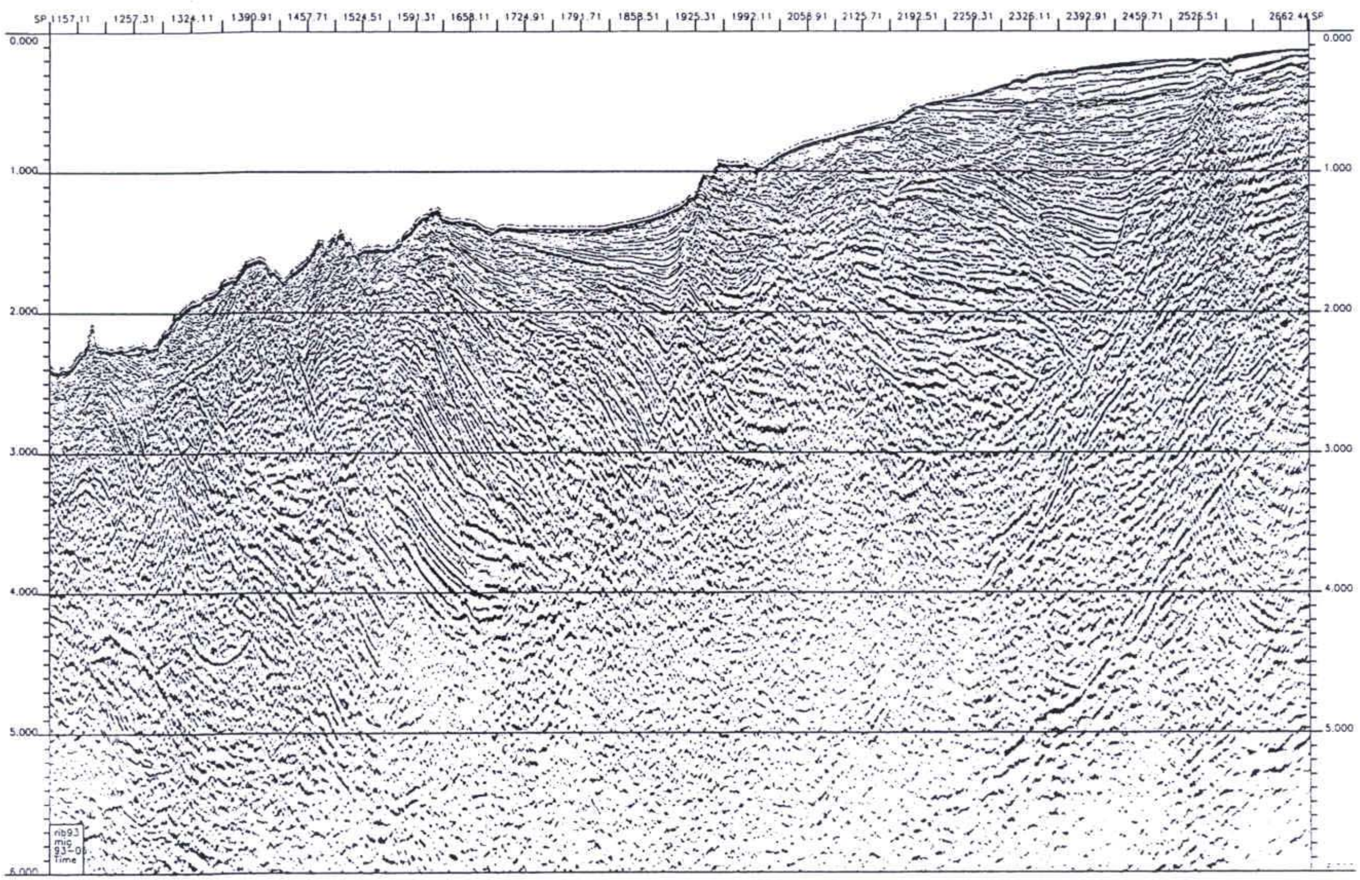


Figure 23

Figure 23. Offshore Talara basin, seismic showing extension of strike-slip faults and transtensional rotation of faulted blocks.