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Geodynamic evolution of the Neogene intermontane Chota basin, Northern Andes of Ecuador

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Abstract — The development of intermontane basins with a thick non-marine sedimentary pile is one of the main characteristics of the Andean geodynamic evolution during the Neogene. The Chota basin is the northernmost Neogene intermontane basin recognized in the Andes of Ecuador. This basin is located in the Interandean Depression and presents a sedimentary fill of continental deposits.

The detailed stratigraphic and tectonic analysis of this basin allows for a new subdivision of the sedimentary sequence in four main units with a total minimum thickness of 2400 m. Sequence analysis suggests a cyclic evolution characterized by two megasequences. The first one, represented by the Chota Unit, displays an evolution from proximal to more distal facies (braided alluvial to lacustrine facies) during the opening of the basin. The second one, represented by the Santa Rosa Unit to the west, and the Peñas coloradas and Carpuela Units to the east, displays a thickening-coarsening evolution related with the filling of the basin and with the development of prograding alluvial fan deposits.

The structural analysis in the Chota basin shows two main tectonic events. The first event is responsible for the opening of the basin, and is the result of a tensional tectonic period with $\sigma 3$ along a N130°E direction. The second event caused the closing of the basin, as a result of a regional compressional regime with a N120°E trending, which then rotated to an E-W compressive trend.

The Chota Basin is interpreted as a Neogene intermontane basin, with a sedimentary fill controlled by a continuous tectonic deformation. The deposits of this basin recorded large scale geodynamic events and are a unique example for the study of the Neogene evolution of the Ecuadorian Northern Andes.

Resumen — Durante el Neógeno, el desarollo de cuencas intramontañosas con una potente sedimentación continental representa una de las principales características de la evolución geodinámica andina. La cuenca intramontañosa del Chota es la más septentrional y única reconocida en el norte de los Andes Ecuatorianos. Está situada en la Depresión Interandina y presenta un relleno conformado por sedimentos detríticos continentales de edad cenozoica.

El estudio estratigráfico permitió proponer una nueva división de la serie sedimentaria terciaria en cuatro unidades principales que alcanzan un espesor total mínimo de 2400 m. El análisis sedimentológico muestra una evolución cíclica, diferenciándose dos megasecuencias que caracterizan el relleno sedimentario de esta cuenca. La primera megasecuencia reprensentada por los depósitos de la Unidad Chota, muestra una evolución de facies proximales a facies mas distales (fluvial en trenza a lacustre) durante la apertura de la cuenca. La segunda megasecuencia, reprensentada por los depósitos de la Unidad Santa Rosa al oeste y las unidades Peñas Coloradas y Carpuela al este, muestra una evolución grano y estrato creciente, relacionada con la activación de reliefs y caracterizada por facies conglomeráticas de abanicos aluviales progradantes, adosados a fallas responsables del cierre de la cuenca.

El análisis estructural permitió definir dos eventos tectónicos principales: el primero es responsable de la abertura de la cuenca, provocada por una extensión con $\sigma 3$ de direccion N130°E. El segundo evento es responsable del cierre, provocado por una compresión N120°E la cual posteriormente rota hacia un eje compresivo E-W.

La cuenca del Chota esta interpretada como una cuenca intramontañosa neógena cuyo relleno está controlado por una deformación tectónica continua. Los depositos de esta cuenca son los testigos de eventos geodinámicos a gran escala y son únicos ejemplos para el estudio de la evolución Neógena de los Andes Ecuatorianos Septentrionales.

INTRODUCTION

During the Neogene, thick alluvial, lacustrine and volcanoclastic continental sedimentation took place in several intermontane basins located along the Interandean Depression. This N-S trending depression separates the Western and the Eastern Cordillera (Cordillera Real) of the Ecuadorian Andes. All of these basins present several common features, such as synsedimentary volcanism and deformation, and a geodynamic evolution controlled by displacement along regional faults limiting the basin margins (Marocco *et al.*, 1995).

The Chota basin is located in the Interandean Depression, 100 km northeast of Quito, in the northern Ecuadorian Andes (Fig. 1). This basin belongs to a string of

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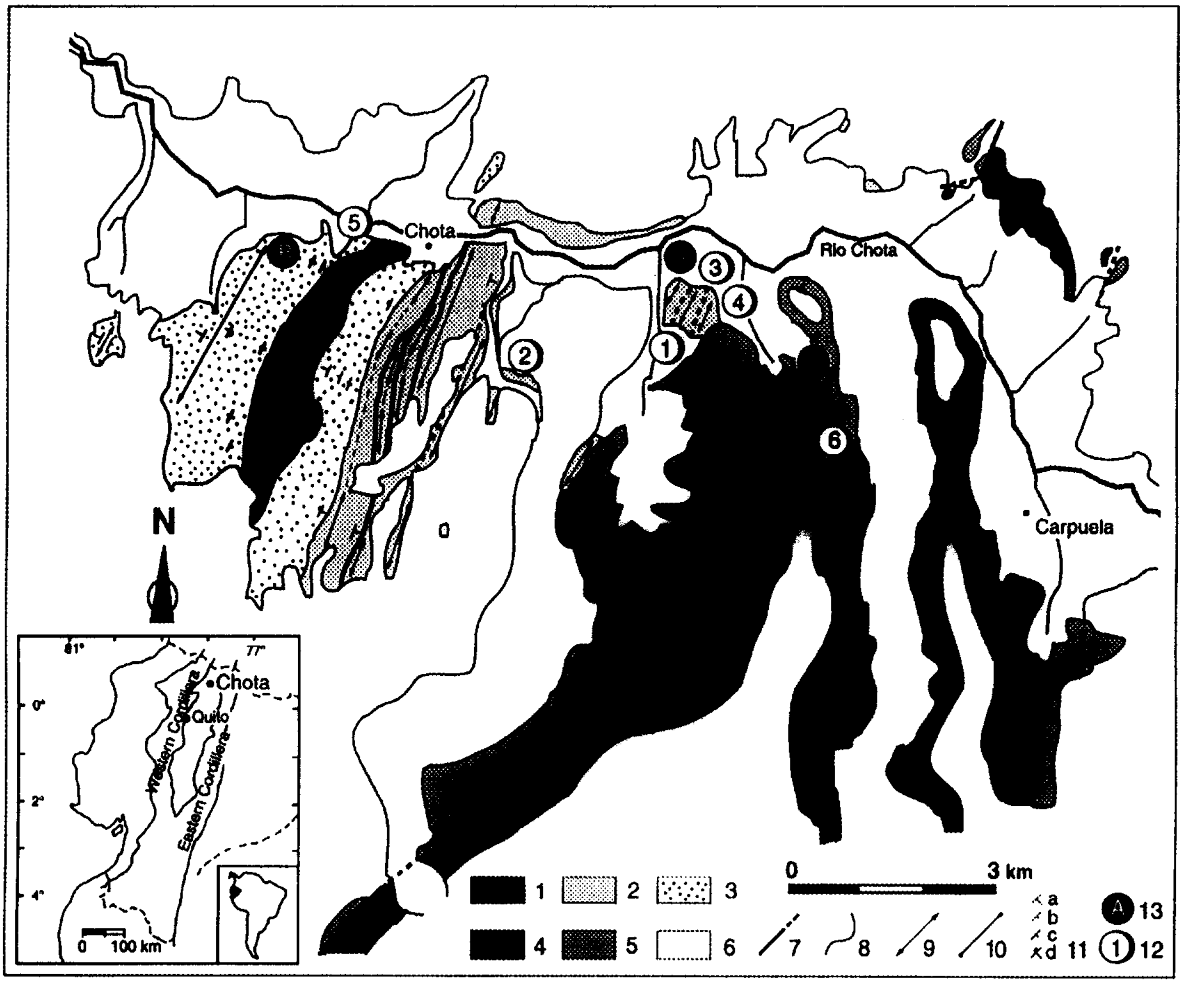

Fig. 1. Geologic map of the Chota basin. 1. Metamorphic basement; 2. Chota Unit; 3. Santa Rosa Unit; 4. Gavilanes breccias; 5. Peñas Coloradas and Carpuela Units; 6. Quaternary (undifferentiated); 7. Fault; 8. Normal contact; 9. Anticline axis; 10. Syncline axis; 11. Diping (a. < 50°; b. > 50°; c. vertical; d. reverse); 12. Location of studied folds; 13. Location of studied microfractures sites.

Tertiary Intermontane basins (Cuenca, Girón, Nabón, Loja and Vilcabamba) formed after the Paleocene-Eocene collision and accretion of oceanic terranes and during the Tertiary subduction of the Nazca plate under South America (Lavenu *et al.*, 1995). The margins of the Chota Basin consist of several major faults that limit the filling deposits from the basement, made up of metamorphic rocks of the Cordillera Real (the Paleozoic Ambuquí Group, according to Baldock, 1982; or the Late Jurassic Ambuquí and Pacheco lithotectonic subdivisions, according to Aspden and Litherland, 1992). The tectonic displacement along these major faults induced a control in the sedimentation of the filling deposits.

The purpose of this paper is to describe, on the basis of recent field work (Baudino *et al.*, 1991; Barragán, 1992), the evolution of the sedimentary fill and the different tectonic events that gave rise to the Chota Basin. In addition, we propose a redefinition of the classic stratigraphic scheme, and a coherent geodynamic model for the evolution of the Chota Basin.

REGIONAL STRATIGRAPHY

Until recently, the stratigraphic subdivision used for the Chota basin comprised two formations (Fig. 2), with differing lithologies, and a total thickness of almost 3000 m. These two formations are, from base to top, the conglomerates, tuffaceous sandstones, lignite interbeds and multicolored shales of the Tumbatú Formation, and the volcanic breccia, conglomerate and tuffaceous sediments of the Chota Formation (Hall In: Bristow and Hoffstetter, 1977).

The Tumbatú Formation is considered to be of Miocene age based on the presence of gastropod *Liris Aff. Minuscula* fauna (Bristow and Parodiz, 1982). In addition, there are a few radiometric age determinations of the volcanic rocks that overlie the Chota Formation along the Chota river: 6.31 ± 0.1 Ma and 6.30 ± 0.06 Ma in the western side (Angochahua Formation), and 3.65 ± 0.07 Ma in the eastern side (Barberi *et al.*, 1988).

Most of the Chota basin is covered by a thick sequence of volcanic, volcanoclastic, alluvial, and colluvial subhorizontal Plio-Quaternary deposits (Villalba, 1981).

Our field observations allow us to propose a new stratigraphic subdivision of the Neogene sedimentary fill of the Chota basin. Four units are defined (Figs. 2 and 3), each of them characterized by a particular depositional environment, source area, and related tectonic events.

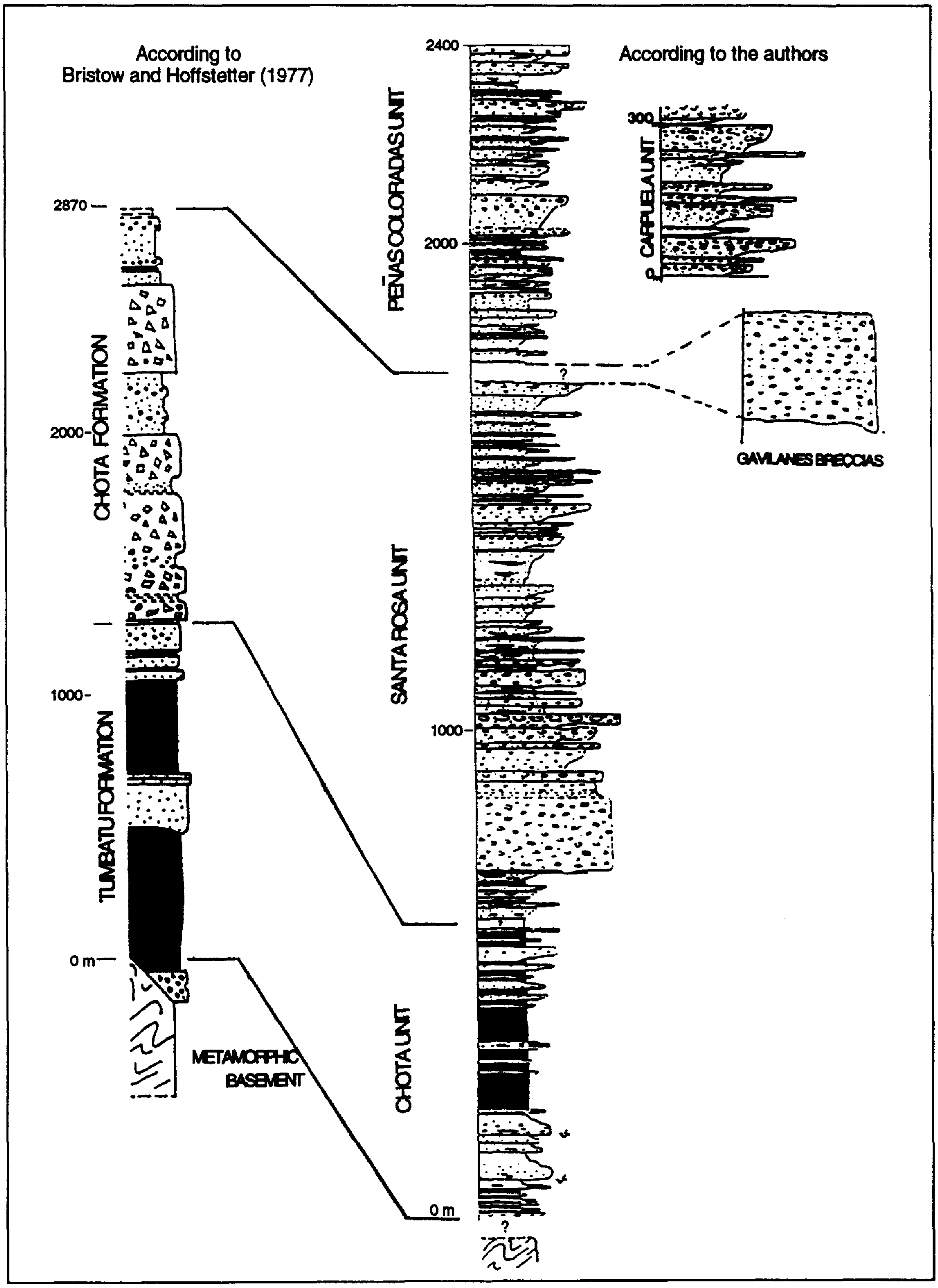

Fig. 2. Type stratigraphic columns for the Chota basin, according to Bristow and Hoffstetter (1977), and to the authors.

These are, from base to top: The Chota Unit, exposed mainly in the central part of the basin, the Santa Rosa Unit, developed on the western margin, and the Peñas Coloradas and Carpuela Units developed on the eastern margin of the basin.

THE SEDIMENTARY ENVIRONMENTS

In the Chota basin, the sedimentary rocks are continental with an important proportion of volcanic products intercalated in the sediments. Only fluviatile and lacustrine sedimentary environments have been recognized.

The fluviatile depositional environment

This depositional environment is characterized by basic fining upward sequences, 0.5 to 15 m thick. The vicinity of the source areas, confirmed by numerous intercalated debris flow deposits, and the exiguous area of the basin resulted in proximal braided river systems. The basic sequence starts with a lower conglomeratic or coarse microconglomeratic sandstone, with frequent large-scale cross stratifications and pebble imbrications, in scoured basal contact with overlying deposits. It corresponds to a channel filling deposit. At the top finer conglomerates of longitudinal bars may exist with coarse horizontal laminations (Collinson, 1986). Above the coarse facies come sandstone levels, with horizontal laminations, belonging to low water-level periods. Finally, the top of the sequence may contain several meters of clays or silts, with small diverging channels and/or paleosoils, that represent overbank deposits of the flooding plain. Elementary sequences are joined in large deca- or hectometric sequences showing coarsening upward or fining upward.

Other fluviatile deposits present in this basin belong to alluvial fans. The basic sequence is conglomeratic, 2 to 50 m thick. Coarsening upward can lead to enormous boulders, several meters in diameter, at the top of the sequence. The conglomerate beds generally do not show structures but can enclose layers of stream channel deposits. There are also sheetflood deposits, sieve deposits or debris flow deposits which imply periods of intense rain fall separated by more of less long periods of drought characteristic an arid to semi-arid climate (Walker, 1984). The clayey lower parts that may exist in alluvial sequences indicate a decline in the coarse sedimentation process (for example, a momentary break of the volcanic activity or long drought periods) that favour soil formation. In the Chota basin the alluvial fan deposits rest against the border faults and coarsen upward. Sequences that coarsen upwards develop when the energy and sediment input into the system do not diminish in time, and lead to coarse clastic sedimentation extending progressively farther into the basin. It implies a constant uplift of the source areas which kept in pace with the sedimentation rate.

The lacustrine depositional environment

In the lacustrine sedimentary environments, two types of facies are known: quiet sedimentation facies — with fine laminated deposits — and catastrophic sedimentation facies — with metric to decametric turbiditic layers and slumps — which can be related to tectonic (Noblet and Marocco, 1989) or climatic events. In the Chota basin only the first facies was recognized. Sedimentation in near shore zones is quite different from sedimentation in offshore zones (Matter and Tucker, 1978). Near shore clastic sedimentation is located near river mouths or along the shore line, transported by the action of lateral currents (Boggs, 1987). Away from the river mouths, sediments are finer, clayey and/or muddy with a strong animal and plant bioturbation in palustrine zones. Biochemical and evaporitic sedimentation may also be produced in these shallow zones. In offshore deeper zones, sediments are clayey or fine grained, white to yellow in color, well stratified with strata that can be followed hundreds of meters. Small turbiditic, low density Bouma type layers, measured in centimeters to decimeters can be intercalated. Biochemical sediments can also occur.

Some differences exist between sedimentation in hydrologically open and closed lakes. The first ones display a higher number of different facies and depositional structures linked to the presence of varied depositional zones (deltaic, palustrine, evaporitic and deep water) with predominantly clastic deposits. In hydrologically closed lakes, the sedimentation is mainly chemical, biochemical and evaporitic while the clastic sedimentation is limited.

THE FILLING SERIES OF THE RIO CHOTA BASIN

Chota Unit

The Chota Unit is mainly exposed in the central part of the basin, where it overlies, apparently directly, the metamorphic basement (Fig. 3). It conformably underlies the Santa Rosa Unit, and unconformably underlies the Peñas Coloradas Unit. Therefore, the Chota Unit is the oldest of these three units.

The Chota Unit is approximately 500 m thick, with two main sequences (Fig. 3). The lower 250 m represent sequence S1, which is composed of several minor thinning and fining-upwards alluvial sequences corresponding to braided river deposits. The conglomerate clasts are predominantly volcanic (basic and intermediate composition), and metamorphic with some intraclasts. The top of S1 is characterized by thick mudstone and clay intervals. This occurrence of a higher proportion of overbank deposits in braided rivers systems may be linked, in part, to climatic and orogenic factors (Shumm, 1968; Baker, 1978).

The upper 250 m (sequence S2) are laminated clayey (grey to black) to muddy (white to yellow) deposits with intercalated conglomerates and sandstones showing parallel and low angle cross lamination. These features, associated with evaporitic deposits, leaf impressions, organic rich layers and abundant fossilized gastropods point to near shore lacustrine deposits in a hydrologically open lake. The conglomeratic and sandy layers that appear toward the top of the sequence S2 are of two kinds. Those with normally graded pebbles and scoured basal contacts correspond to channel fill deposits, while those ungraded with poor sorting of clasts and sharp basal contacts can be interpreted as sheetflood units deposited under upper-flow conditions in shallow water (Van Der Wiel *et al.*, 1992). The presence of sheetflood deposits, reworked fossils and fossilized wood imply an increase in clastic input leading to the filling of the lake.

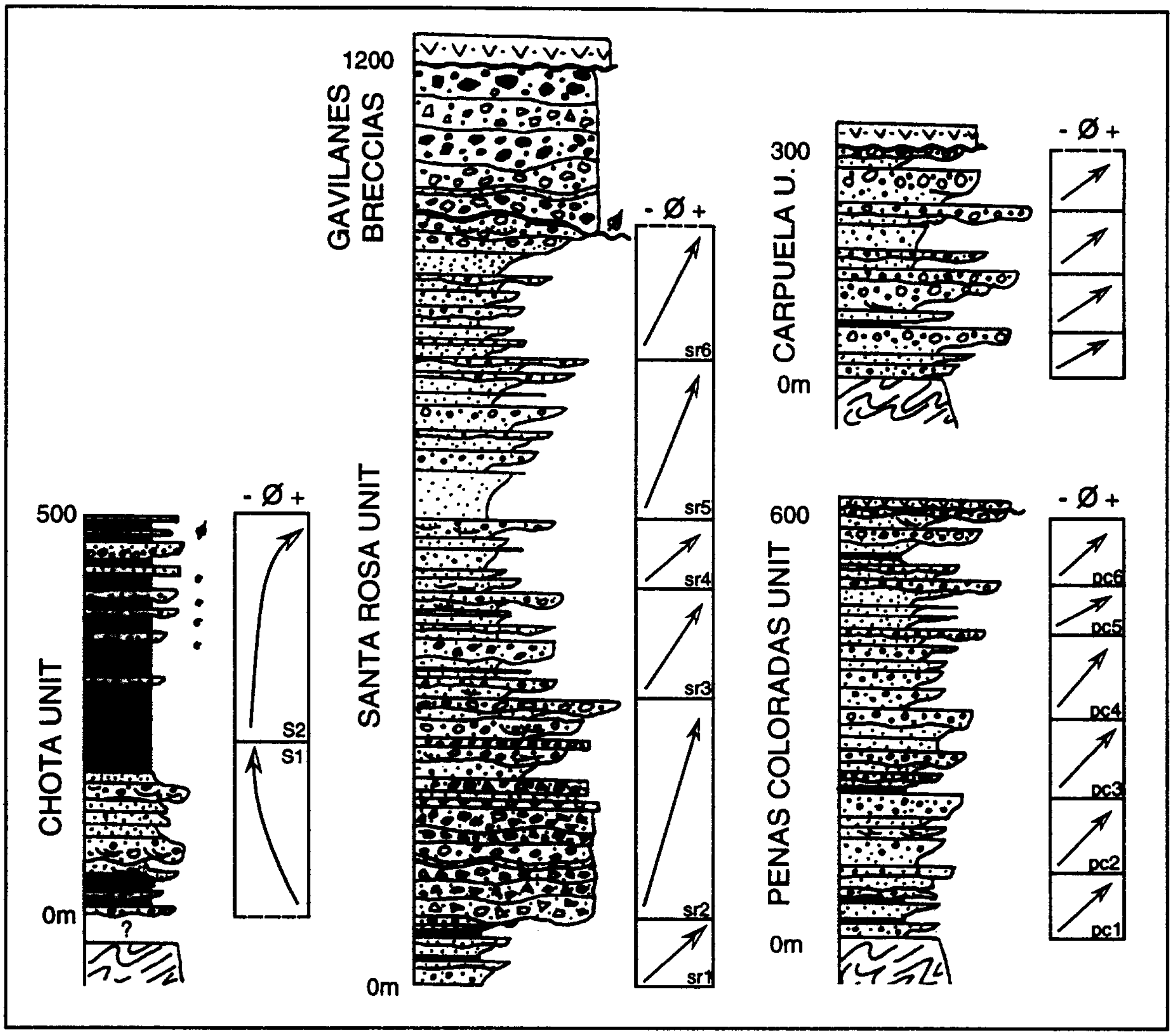

Fig. 3. Lithostratigraphic columns and sequence analysis of the Neogene units of the Chota basin.

Paleocurrent analysis of clasts imbrications and sedimentary structures suggest transport directions of terrigenous supply towards N10°E-N30°E in the alluvial sequence S1, and towards N25°E-N50°E in the lacustrine S2 sequence.

Santa Rosa Unit

The Santa Rosa Unit is developed on the western part of the basin, conformably overlying the Chota Unit. The western limit of outcrops could not be defined due to Quaternary cover. A few metamorphic basement outcrops present within this unit suggest that to the west it was developed not only overlying the Chota Unit, but also directly overlying the basement. Stratigraphic analysis of this unit indicates six thick sequences that reach a minimum total thickness of 1000 m (Fig. 3).

The clast composition of conglomerates is mainly of metamorphic clasts, with sedimentary clasts (at the base only), intermediate volcanic type clasts, and intraclasts. Pumice clasts are abundant throughout the unit in both fluviatile deposits and air-fall interlayer deposits.

The first sequence (sr1, 80 m thick) show basic sequences which characterize fluviatile deposits of alluvial fans. The clasts in conglomeratic layers are less than 10 cm in diameter. Sandstones, generally cross stratified and incised by conglomeratic channels, are dominant and interpreted as prograding sandy deposits. Clays and silts of overbank deposits are also present in a high proportion. These features point to lower alluvial fan deposits.

The second sequence (sr2, 300 m thick) shows an increase in volcanoclastic materials. The first 200 m are almost exclusively made of debris flow deposits and other epiclastic rocks with intercalated volcanic breccias and andesitic lavas. In the upper part strictly defined alluvial fan deposits reappear. The lack of overbank deposits can be explained by an increased clastic input in the lower fan areas, but sieve deposits and sheetflood deposits indicate more proximal facies of middle to upper fan areas.

Sequences sr3, 4 and 5 also display middle to upper fan deposits. The proportion of sandstone increases but maximum clast size of the conglomerates remain roughly constant. Towards the top, some of these sandstones contain scattered cobbles up to 50 cm in diameter, and thin pumice and gravel lenses are often present at various levels. They could be interpreted as hyperconcentrated-flow deposits realised under conditions of waning flow energy (Smith, 1986; Pierson and Scott, 1985). Debris flow and sheetflood deposits are also present. These three sequences belong to the same sedimentary environment as sequence sr2, but the proportion of coarse volcanoclastic deposits is less here. This may correspond to a waning activity of volcanic centers to the west or a climatic change. The second option seems more probable because the proportion and size of pumice fragments remain constant.

In the last sequence clayey and silty overbank deposits are present, with laminated sandstones and conglomerates in scoured basal contacts. Associated with sieve deposits they indicate a middle alluvial fan depositional environment. The proportion of conglomerates and the average clast diameter decrease, while the proportion of finer deposits increases. The lesser input of coarse clastic material, compared to the previous sequences, might reflect an eroded topography linked to waning tectonic activity, considering that neither changes in climate nor volcanic activity seem justified.

Paleocurrent studies indicate that clastic deposits of the Santa Rosa Unit come from uplifted metamorphic and volcanic areas located toward the west side of the basin. Contemporaneous with the uplift, volcanic centers located in the western edge of the basin were active during all of the deposition of the Santa Rosa Unit.

A group of massive and chaotic deposits (**Gavilanes breccias**) are found atop the alluvial fan sequences of the Santa Rosa Unit overlying them unconformably (Figs. 1 and 3). These deposits reach a total thickness of 200 m and are composed of debris flow deposits, with charred debris at the base, volcanic breccias and epiclastic sediments. Faulting, folding and good lithification of the Gavilanes breccias suggest that they could be older than Quaternary in age. If the relations between the Gavilanes breccia and the lower Pliocene Angochahua volcanics are confirmed (DGGM, 1978), as suggested by the similar lithology and depositional environment, it would imply that the Santa Rosa Unit is probably of pre-Pliocene age. These ages are compatible with the radiogenic date of 6.3 ± 0.1 Ma obtained in the western part of the basin (Barberi *et al.*, 1988). These deposits strongly eroded the previous ones and were apparently deposited on a preexisting topography. This implies an erosional period which might be related to tectonic or climatic changes.

Peñas Coloradas Unit

The Peñas Coloradas Unit is exposed in the eastern part of the basin (Fig. 1), where it displays a fault contact with the metamorphic rocks of the Ambuquí subdivision, and an unconformable angular contact with the Chota Unit. This latter observation suggests that its deposition may have started later that of the Santa Rosa Unit which conformably overlie the Chota Unit. The Peñas Coloradas Unit is approximately 600 m thick (Fig. 3) and is formed by six thickening and coarsening sequences (pc1 to pc6), with the lower one developed directly over the basement. Close to the basin's eastern border, mainly proximal facies deposits representing portions of the mid and upper alluvial fan are seen. The more western outcrops display very fine-grained deposits that represent the lower alluvial fan.

The presence of sheet flow, debris flow, and sieve deposits could indicate semi-arid to arid climatic conditions (Walker, 1984). The terrigenous supply is mostly from a metamorphic source (Ambuquí subdivision rock-types), and a volcanic source is also evident. A lesser input of coarse volcanoclastic material explain the higher proportion of fine grained deposits compared to the sequences of the Santa Rosa Unit.

Average paleocurrent directions vary from N270°E to the east, to N0° in the south, suggesting that the Peñas Coloradas Unit was fed from the relief, probably limiting the basin through faults oriented N30°E and N80°E respectively. Thus, the Peñas Coloradas Unit represents the progradation of alluvial fans towards the west related to the development of basement faults limiting the basin to the east and south-east.

Carpuela Unit

The Carpuela Unit is exposed in the eastern part of the Chota basin, 1 km south of Carpuela (Fig. 1), isolated from the rest of the filling deposits. It displays a fault contact with the metamorphic rocks of the Pacheco subdivision that represents its basement. This unit, 300 m thick, consists of four thickening and coarsening sequences (Fig. 3). These sequences are characterized by coarse-grained conglomeratic facies from proximal zones defining the progradation of alluvial fans. The source is identified as mainly metamorphic (rocks of the Pacheco subdivision), as well as volcanic. Paleocurrents indicate transport from west to east. The thickness and coarsening upwards of these deposits imply that they were feed by tectonically active zones.

Peñas Coloradas and Carpuela Units are unconformably capped by volcanic deposits mainly composed of pyroclastic flows and air-fall deposits, apparently coming from an eastern source.

Sedimentary evolution of the Chota basin

The sedimentary filling of the Chota basin is defined by four units organized in two megasequences. The first one (M1), corresponds to the deposition of the Chota Unit; it begins with braided alluvial systems that evolve from proximal to more distal facies (sequence S1). The change from fluviatile to lacustrine depositional environments in the transition from sequences S1 to S2 indicates a deepening of the basin. The presence of slumps and synsedimentary normal faults in the lacustrine deposits of sequence S2 suggests that this evolution is directly related to increases in the subsidence rate rather than in climatic or eustatic changes.

The second megasequence (M2) represents the deposition of the Santa Rosa Unit to the west, and the Peñas

Coloradas and Carpuela Units to the east. M2 is characterized by conglomeratic facies of prograding alluvial fans related to activity along the faults defining the basin margins. These faults resulted in the reactivation and maintenance of adjacent reliefs, both to the west and to the east, with a thickening and coarsening development that defines the closure of the basin.

STRUCTURAL ANALYSIS

The Neogene continental sediments of the Chota basin are affected by important synsedimentary and postsedimentary deformation. The purpose of this structural analysis is to describe the main tectonic events recorded in the Chota basin sedimentary fill and their relative timing.

The margins of the Chota basin are major faults that separate the sedimentary fill from the metamorphic rocks of the Ambuquí and Pacheco subdivisions. This type of margin is not clear towards the north and west because of the thicker Quaternary volcanoclastic sequence that covers the Chota basin. The faults were only identified along the east and southeast borders of the basin, which were found to correspond to large reverse and reverse strike-slip faults, oriented N0° to N40°E and N50°E to N80°E, respectively (Fig. 1). The paleocurrent directions suggest that N-S to N30°E faults along the western margin generated the relief that fed the thick alluvial fan sequences of the Santa Rosa Unit.

Some examples of the study of the type of structural deformation affecting the units in the basin follow, based on measurements of folds and microfractures found in each of them. In order to define the stress regime responsible for the fracture and fold distribution, the method of microtectonic data inversion was used, which allows the determination of the stress tensor for each sampled population of striated microfaults (Carey, 1979), from the observed relative displacement along the planes. The computed stress vectors characterize a tectonic event at each particular site during each deformational period.

Chota Unit

A structural analysis identified synsedimentary normal faults, striking N-S to N80°E, associated with a distensive stress s3 oriented N130°E (Fig. 4.1 and 4.2).

Reverse faults are present at all scales of observation, some of them as reactivated normal faults (Fig. 4.3), and are associated with the intense folding undergone by this unit. Microtectonic analysis of these structures resulted in the identification of a compressive axis s1 oriented N120°E. The same stress regime generated an intense postdepositional folding deformation of this unit. Verging folds have been displaced to the west, with axes striking N25°-35°E (Fig. 4.A).

A family of reverse faults, striking N350°E to N10°E (Fig. 4.4), indicates a compressive regime with s1 striking N82°E.

Santa Rosa Unit

This unit presents overturned folds verging to the east related to a syndepositional event of shortening. Fold axes strike N30°E, defining a compressive tectonic regime with s1 oriented N120°E approximately (Fig. 4.B). Several reverse and dextral-reverse faults can also be observed in this unit, striking N0° to N40°E and N50°E to N80°E respectively. According to the microtectonic analysis, these faults are due to a compressive regime with the main axis s1 oriented N82°E (Fig. 4.5). Relative chronology of the two compresional events could not be determined.

The discordant deposits of the **Gavilanes breccia** are also deformed, but the type of stress generating the deformation could not be identified due to the scarcity of structural evidence.

Peñas Coloradas Unit

A structural analysis of microfractures in this unit allows us to identify a compressive stress regime (Fig. 4.6) with the main axis s1 striking N90°E approximately. This stress regime generated reverse faults striking N0° to 40°E, and dextral faults striking N60°E to N80°E.

This unit has also undergone a syndepositional folding deformation characterized by folds which strike N350°E to N10°E, with large curvature radius. An E-W synsedimentary compressive event is responsible for the formation of these structures (Fig. 4.C).

Carpuela Unit

The only deformation identified in these deposits is a conspicuous synclinal fold resulting from E-W compression, with a large curvature radius with axis N-S, similar to that described for the Peñas Coloradas Unit. Although it was not possible to find synsedimentary structures in this unit, the very nature and the great thickness of these coarsening up alluvial deposits imply an intensive contemporary tectonic activity generating feeding reliefs.

Peñas Coloradas and Carpuela Units are unconformably overlain by Quaternary subhorizontal volcanoclastic deposits. The absence of other tectonic events suggest that the shortening responsible for the deformation in both the Peñas Coloradas and Carpuela Units could be the same.

Tectonic evolution of the Neogene Chota River Basin

Structural analysis supports the existence of three successive tectonic events of deformation undergone by the Neogene deposits of the Chota basin:

1) An extensional event with s3 oriented N130°E, producing (a) sinistral displacements along N60°E striking faults, (b) normal synsedimentary faults oriented N-S to N40°E, and (c) sliding structures affecting the Chota Unit.

2) A compressive event with s1 striking N120°E, affecting the Chota and Santa Rosa Units, contemporaneous with

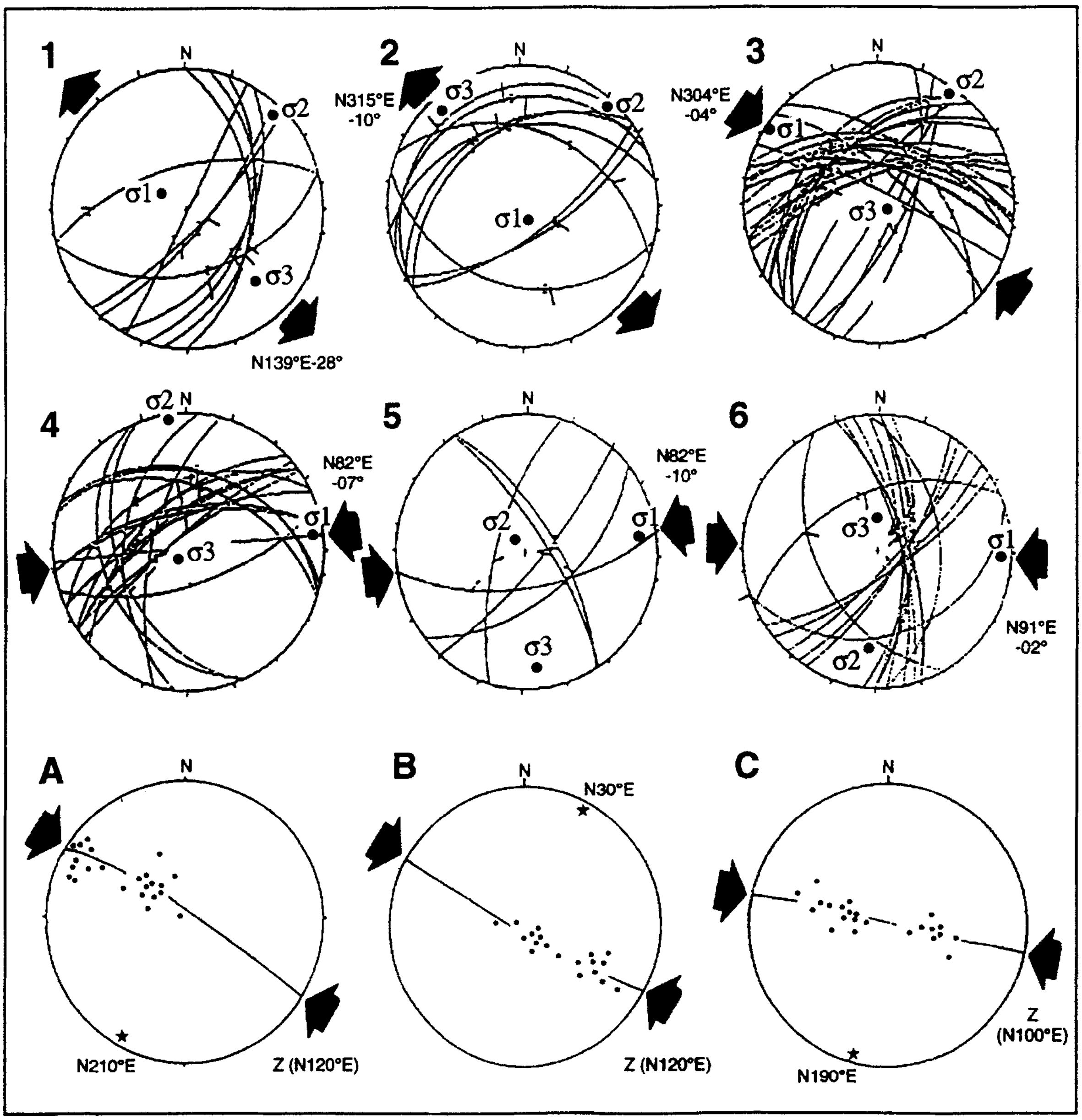

Fig. 4. Diagrams of fault families used in the determination of stress tensors in the microfracture stations, and structural diagrams of fold axes in the sedimentary sequence of the Chota Basin. Lines over fault planes represent measured striations.

the deposition of the latter. This event generated reverse movement along N0° to N50°E trending faults, and dextral-reverse movements along the N80° faults. This event is responsible for the development of east-verging synsedimentary folds affecting the Santa Rosa Unit deposits and also of west-verging postsedimentary folds affecting the Chota Unit deposits. The latter are probably due to the reactivation of inherated east-diping normal faults.

3) A compressive event with s1 oriented N90°E affecting all units and generating reverse displacements along the N-S to N40°E striking faults, and dextral displacements along the N60°E to N80°E striking faults. The large curvature radius folds with N-S axis in the Peñas Coloradas and Carpuela Units can also be ascribed to this tectonic event, which is also contemporaneous with the deposition of the Peñas Coloradas Unit. This synsedimentary character could not be confirmed for the Carpuela Unit althought it seems to be probable.

The change in the orientation of the main stress produced a transition from an extensional tectonic regime coeval with the deposition of the Chota Unit, to a compressive tectonic regime coeval with the deposition of the other units. Furthermore, this change characterizes two distinct successive events in the evolution of the basin: its opening under extension and its closure under compression. The study of the syndepositional sedimentary structures and lacking of unconformity between the Chota and the Santa Rosa Units indicate that the transition was progressive.

MODEL FOR THE GEODYNAMIC EVOLUTION OF THE NEOGENE CHOTA BASIN

Sedimentologic and tectonic analyses of the deposits filling the Neogene Chota basin allow us to present a model for its geodynamic evolution which consists of two main stages.

The **opening** of the basin which took place before or during the Miocene times, mostly as a consequence of extension and displacements along normal faults striking N-S to N40°, and sinistral displacements along N50°E to N80°E striking faults. This extension was caused by a transtensional event with s3 striking N130°E. Interplay of these faults generated a NE-SW depression with contemporaneous installation of a braided river system flowing NE, represented by the deposits at the base of the Chota Unit (Fig. 5.1). Subsequent lacustrine deposits with abundant syndepositional normal faults and slumps indicate a deepening of the basin related to an increased velocity of

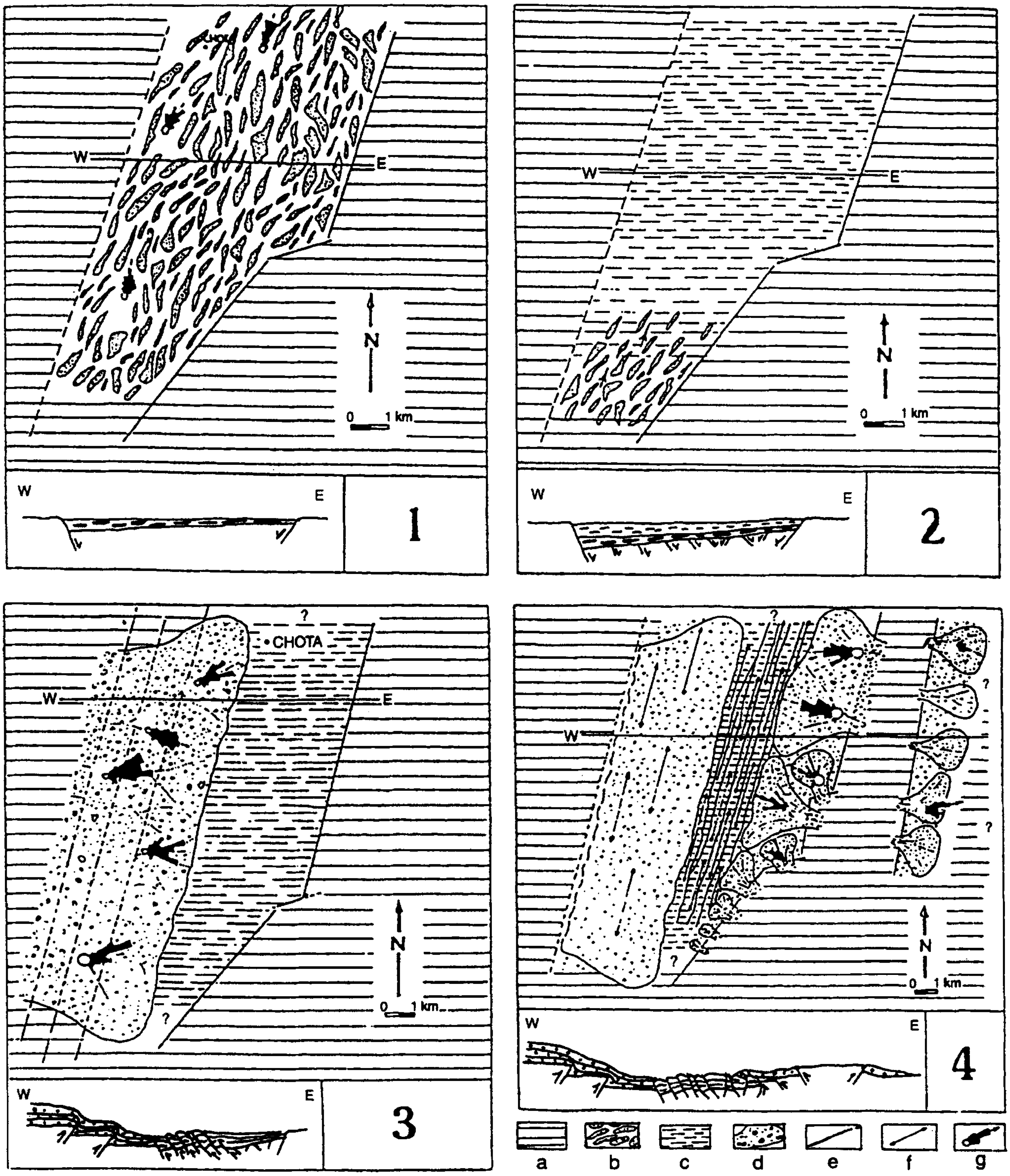

Fig. 5. Schematic palaeogeographic map and synthetic cross section of each formation of the Chota basin infilling. 1. Fluviatile deposits of the Chota Unit (sequence S1); 2. Lacustrine deposits of the Chota Unit (sequence S2); 3. Alluvial fans of the Santa Rosa Unit (west); 4. Alluvial fans of the Peñas Coloradas and Carpuela Units (east); a. Relief zone and source; b. Fluviatile depositional setting; c. Lacustrine depositional setting; d. Alluvial fan depositional setting; e. Marginal basin fault; f. Fold axis; g. Paleocurrent direction.

tectonic subsidence (Fig. 5.2). In fact, the change from an alluvial to a lacustrine environment suggests a process of retrogradation of the more proximal environments, as indicated by the thinning and fining of the overall sequence deposits. Higher up in the section, sandstone and conglomerate beds with paleocurrents from the SW indicate the gradual filling of the lacustrine basin. The Chota Unit thus represents the disposition of a fining- and thinning-upwards megasequence controlled by the interplay of normal faults corresponding to the opening phase in the evolution of the basin during the Neogene.

The second stage — **the closure** — in the evolution of the basin is characterized by a change in the source area and in the depositional environments. A gradual change towards a compressive tectonic regime with s1 oriented NW-SE allowed the interplay of reverse faults striking N-S to N30°E, and led to the development of marked reliefs along the western side of the basin. This change is recorded by the deposition of the Santa Rosa Unit, which represents the progradation of alluvial fan proximal facies towards the east (Fig. 5.3). In this unit, sedimentary structures indicate a volcanic activity contemporaneous with its deposition. According to available data, the age of the Santa Rosa Unit is pre-Pliocene, probably Late Miocene.

The rotation of the main compressive stress vector s1 to an E-W direction generated dextral faults striking N50°E to N80°E and reverse faults striking N-S to N40°E. These faults resulted in the development of reliefs along the eastern margin of the basin, with outcrop of the metamorphic basement lifted as a pop-up structure, and generated the deposition of the Peñas Coloradas and Carpuela Units. Both units represent the progradation of alluvial fans, towards the west in the case of the Peñas Coloradas Unit, and towards the east in the case of the Carpuela Unit, probably as two synchronic subbasins (Fig. 5.4). Thus, the development of coarse-grained alluvial-fan directly related with faults, first to the west (Santa Rosa Unit) and then to the east (Peñas Coloradas and Carpuela Units), implies a diachronism in the development of the reliefs.

The Santa Rosa, Peñas Coloradas and Carpuela Units constitute a thickening- and coarsening-upwards megasequence deposited under a compressive tectonic regime. This second stage in the evolution of the basin corresponds to the closure of the Neogene Chota basin resulting from a reorientation of the main tectonic stress vectors.

CONCLUSIONS

The Neogene continental deposits filling the Chota intra-arc basin are subdivided into four units characterized by distinct depositional environments and styles of deformation. These units record a period in the evolution of the basin covering at least from the Miocene to the early Pliocene, with a minimum total thickness of 2100 m.

Structural analysis indicates a geodynamic evolution of the basin consisting of two main stages, the opening and closure. The first one is characterized by a thinning- and fining-upwards megasequence (M1) resulting from a transtensional tectonic regime and development of a subsiding depression oriented NE-SW. The second stage is characterized by a thickening- and coarsening-upwards megasequence (M2) originated by the gradual change to a compressive tectonic regime. This regime resulted in basement uplifts and new source areas leading to the filling of the Chota basin first at the west and then at the east.

This evolution in two megasequences has been recognized in other Andean Neogene sedimentary basins of Southern Ecuador (Noblet *et al.*, 1988; Marocco *et al.*, 1990; Marocco *et al.*, 1993; Mediavilla, 1991; Izquierdo, 1991; Fierro, 1991; Baudino *et al.*, 1994). In those basins the geodynamic evolution is linked to strike-slip faults movements during ongoing Neogene tectonism (Lavenu *et al.*, 1995).

The present study of the Neogene Chota basin also show an ongoing tectonic evolution from opening to closing. The second stage is linked to the functioning of reverse and reverse strike slip faults. Furthermore, the study of synsedimentary deformations in the Chota basin suggest a west to east displacement of the compresional deformation during the closure phase of its evolution, a process quite similar to that observed in the Bolivian Altiplano (Baby *et al.*, 1990). It is possible that the closure of the Chota basin resulted from the advance of the deformation of the Andean Chain towards the east. This process could be related to movements along antithetic (backthrust) reverse faults which resulted in the development of subbasins represented by the Santa Rosa Unit to the west and the Peñas Coloradas and Carpuela Units of the east. The Chota Basin is thus interpreted as an intermontane intra-arc basin developed under a compressive regime during its longer evolutionary stage (closure), and with sedimentary fill controlled by continuous tectonic activity.

The deposits of the Chota basin records larger scale geodynamic events and represent a unique example for the study of the Neogene evolution of the Andes of northern Ecuador. They show that this area of the Interandean Depression has experienced an important Neogene compressional deformation. More detailed studies are needed (age determinations in progress will be especially useful) in order to make comparisons with other areas of the northwestern Andes.

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