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Gravity-driven large-scale deformation system in the Tumbes-Guayaquil forearc basin, Northern Andes (Northern Peru-Southern Ecuador)

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ABSTRACT

The offshore Tumbes-Guayaquil forearc basin in the accretionary prism of Northern Peru-Southern Ecuador shows evidence of gravity-driven large-scale deformation systems active during the Late Neogene-Quaternary period. Subsurface data and the construction of eight structural cross-sections show that the ~8 km-thick Oligocene-Quaternary sedimentary infill is detached seaward and completely decoupled from the underlying inner accretionary prism systems. The Corvina décollement in the Tumbes basin and the Posorja décollement in the Guayaquil basin constitute two thin-skinned gravity tectonic systems associated with kilometer-scale, updip "raft" extensional structures paired with downdip fold-thrust systems (Barracuda and Domito thrust systems). Although many previous studies have described the structural and stratigraphic architecture of the Tumbes-Guayaquil forearc basin, no model explicitly accounts for this anomalous large-scale gravity tectonics. We propose that this gravity tectonic style, more commonly observed in passive continental margins, is primarily controlled by the combination of tectonostratigraphic features, including crustal-scale transtensional deformation related to oblique convergence along the Northern Andean margin, basal décollement slope tilting, strong sediment accumulation, and the presence of overpressured shales.

1. Introduction

Because of their ability to record tectonic events, forearc basins are a key structural feature of oceanic subduction zones, although their dynamics still include some grey areas (e.g., Dickinson, 1995; Heuret et al., 2012; Tsuji et al., 2015; Noda, 2016; Vannucchi et al., 2016; Noda and Miyakawa, 2017). The offshore Tumbes-Gulf of Guayaquil forearc basin is part of the Northern Peruvian-Southern Ecuadorian accretionary prism developed over the Nazca (Farallon)-South American plate convergence system through the Late Cretaceous to Cenozoic period (Daly, 1989; Espurt et al., 2018; Aizprua et al., 2019; Jaillard, 2022, Fig. 1). The complex structural architecture and petroleum systems of this frontier forearc region have been strongly studied by academic and petroleum industry through numerous seismic reflection and exploration well data (e.g., Benitez, 1995; Deniaud et al., 1999; Deniaud, 2000; Collot et al., 2002; Higley, 2004a, b; Calahoranno, 2005; Fernández et al., 2005; Witt et al., 2006; Cobos, 2010; Espurt et al., 2018; Reynaud et al., 2018; Aizprua et al., 2019; Lemgruber-Traby et al., 2020; Guzmán et al., 2022; Márquez et al., 2022). These studies show that the Tumbes-Gulf of Guayaquil forearc basin is characterized by: (1) a massive Cenozoic prograding sedimentary infill containing ductile basal shale layers (Higley, 2004a,b; Espurt et al., 2018); (2) a large crustal-scale strike-slip fault zone, the Puná fault zone that crosses obliquely the forearc basin, leading to significant transtensional deformation favoring available space and sedimentary trapping in the forearc basin (Benitez, 1995; Deniaud et al., 1999; Deniaud, 2000; Cobos, 2010). The combination of these sedimentary and tectonic features might have exerted a strong control on the kinematics of structural growth of the forearc basin.

This paper aims to present an original contribution with eight

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structural cross-sections based on seismic reflection profiles and well data to understand the three-dimensional structure and dynamics of the Tumbes-Guayaquil forearc basin (Fig. 1). Here we present a new tectono-stratigraphic interpretation for the Tumbes-Guayaquil forearc basin, involving a tectonic style reported for the first time in the dynamics of the region. Results reveal a new view of the gravity tectonics that controlled the structural growth of the Tumbes-Guayaquil forearc depocenter. This large-scale gravity tectonics is active during the Late Neogene and the Quaternary in a context of ongoing oceanic subduction, rather classically observed in passive continental margins. We discuss the regional driving tectono-stratigraphic features controlling such atypical gravity tectonic style and its relationship with the geodynamic processes affecting the Northern Andean active margin.

2. Geological setting

2.1. Tectonic context

Currently, along the Northern Peruvian-Southern Ecuadorian active margin, the Nazca Plate is subducting N83°E-trending beneath the Northern Andes at a velocity of 60 mm/a (Villegas-Lanza et al., 2016, Fig. 1). The accretionary prism structure is characterized by the accretion of successive forearc depocenters, separated by thrust wedges involving continental, oceanic and sedimentary rocks (Espurt et al., 2018; Aizprua et al., 2019). The Tumbes and Gulf of Guayaquil offshore basins form an approximately 16000 km^2 large, thick Cenozoic forearc depocenter lying between coastal basement wedges (Carpitas, Zorritos, Pallatanga and Santa Elena) and outer wedges (Banco Peru and Domito) made of off-scrapped sediments (Fig. 1). The Tumbes and Gulf of Guayaquil basins are separated by the broad Barracuda antiform in the forearc basin center (Fig. 1; Fernández et al., 2005; Vega, 2009). The Gulf of Guayaquil basin is cut obliquely by the SW-trending Puná dextral strike-slip fault zone, which accommodates the relative motion of two crustal slivers: the North Andean Sliver, moving NE-ward and the Inca Sliver to the south, moving SE-ward (Nocquet et al., 2014; Alvarado et al., 2016; Villegas-Lanza et al., 2016, Fig. 1). The fault zone participates to the opening of the Gulf of Guayaquil basin (Deniaud, 2000; Witt et al., 2006). The collision of the Carnegie Ridge with the Ecuadorian margin could have controlled the North Andean Sliver NE-ward escape and favored the opening of the Gulf of Guayaquil during at least the Quaternary (Witt et al., 2006; Michaud et al., 2009, 2018, Fig. 1).

The historical seismicity of the Tumbes-Guayaquil forearc zone does not show large magnitude subduction earthquakes (only three ~ Mw 7–7.5 events in 1901, 1933 and 1953 were possibly tsunamigenic; Lockridge, 1984; Espinoza, 1992; Beauval et al., 2013; Ioualalen et al., 2014; Yepes et al., 2016; Chunga et al., 2018; Vaca et al., 2019). Low interseismic coupling and creeping on the subduction interface contrast with strong interseismic coupling regions to the north characterized by large earthquake occurrence (Chlieh et al., 2014; Nocquet et al., 2014; Villegas-Lanza et al., 2016). Crustal faults in the onshore and offshore

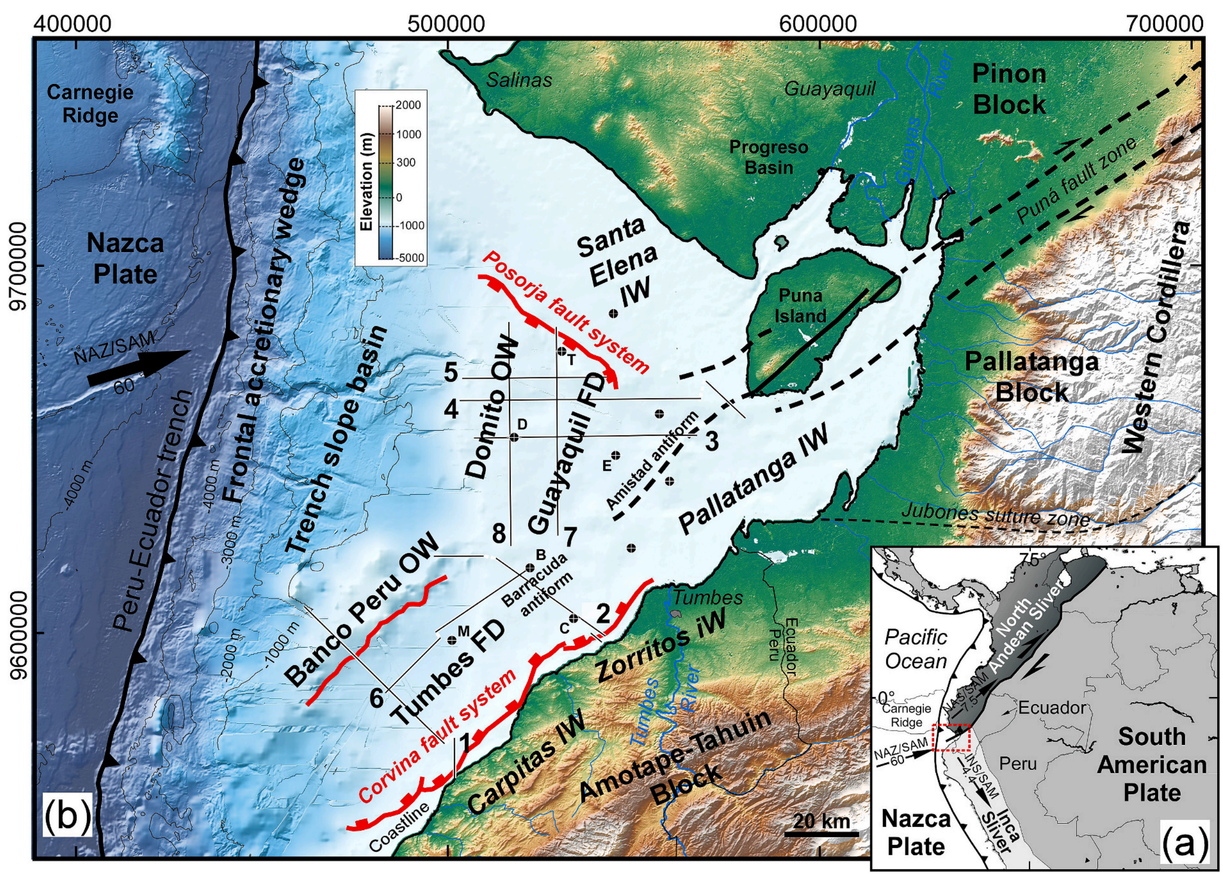

Fig. 1. Geodynamic and structural settings of the Tumbes-Guayaquil forearc basin. (a) Geodynamic map of the Central-North Andean active margin related to the Nazca-South American convergence plate system. The dotted red square indicates the location of the Tumbes-Guayaquil forearc basin. The black arrows show the relative convergence rate (mm/a) and the oblique convergence trend between the Nazca (NAZ) and South American (SAM) Plates and the relative motions of the North Andean Sliver (NAS) and the Inca Sliver (INS) in mm/a (from Villegas-Lanza et al., 2016). (b) Structural map of the Tumbes-Guayaquil forearc basin. The thick lines with numbers indicate the locations of the eight cross-sections (labelled 1 to 8) constructed in this study along seismic reflection profiles. The white and black circles correspond to exploration wells. M: Marina-1X well, C: Corvina-40-X-1 well, B: Barracuda-15-X-1 well, E: Esperanza-1 well, D: Domito-1 well, T: Tiburon-1 well. Major rivers are indicated in blue. Coordinate system is UTM zone 17S. IW: inner wedge; OW: outer wedge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

region of the Gulf of Guayaquil basin are seismically active (e.g., Puná fault zone), as revealed by strong to moderate present-day seismicity (Alvarado et al., 2018; Vaca et al., 2019) and morpho-tectonics analysis (Dumont et al., 2005).

2.2. Lithostratigraphy

Many previous works have described the Cenozoic sedimentary infill across the Tumbes and Gulf of Guayaquil basins and surrounding areas based on seismic profile and well data, correlated with field observations (e.g., Séranne, 1987; Benitez, 1995; Jaillard et al., 1995; Deniaud, 2000; Higley, 2004a, b; Fernández et al., 2005; Witt et al., 2006; Fildani et al., 2008; Vega, 2009; Cobos, 2010; Espurt et al., 2018; Aizprua et al., 2019; Reynaud et al., 2018; Jaillard, 2022; Aizprua et al., 2022). The lithostratigraphy is presented using the Corvina-40-X-1 well in Peru and the Esperanza-1 well in Ecuador (Fig. 2) and described hereafter.

In the study area, basement rocks are either exposed along the coast or revealed by exploration wells (Fernández et al., 2005; Vega, 2009; Riel et al., 2014; Espurt et al., 2018; Aizprua et al., 2019; Lajo-Yáñez et al., 2022; Jaillard, 2022, Fig. 1). In North Peru, the Amotape-Tahuin basement is formed by Paleozoic to Triassic metamorphic and granitic rocks, unconformably covered by terrestrial to marine Eocene or lower Oligocene strata forming the Carpitas and Zorritos inner wedges along the coast (Fernández et al., 2005; Vega, 2009; Espurt et al., 2018). In South Ecuador, the Pallatanga-Piñon basement shows upper Cretaceous oceanic terranes unconformably covered by Paleocene to Eocene, terrestrial and deep marine strata forming the Pallatanga and Santa Elena inner wedges (Riel et al., 2014; Aizprua et al., 2019; Jaillard, 2022).

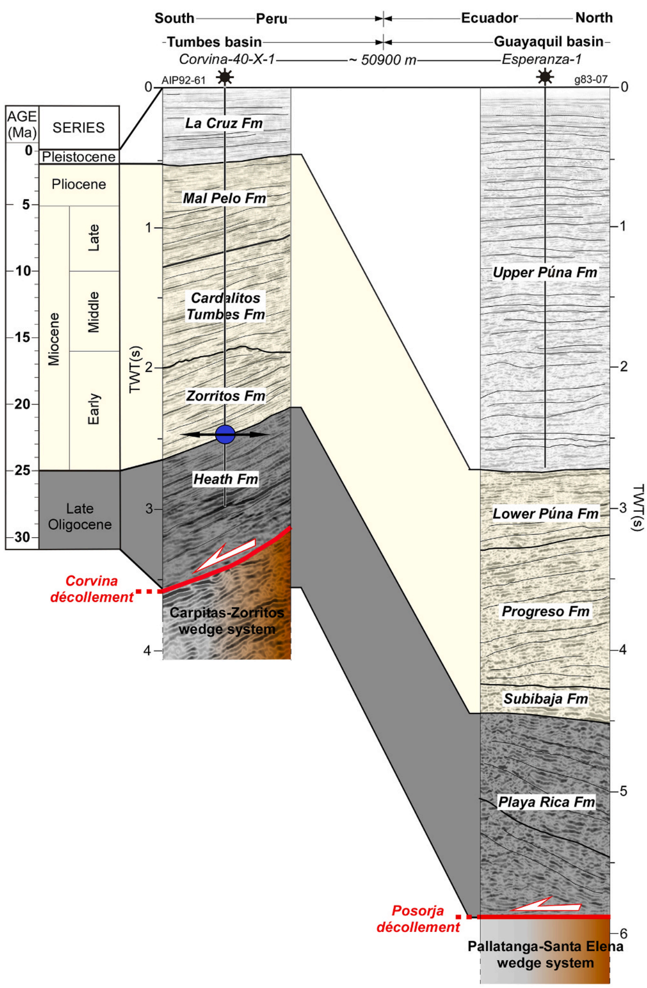

Fig. 2. Stratigraphy of the Tumbes-Guayaquil forearc basin and lateral correlations in between based on the Corvina-40-X-1 (total depth ~4321 m Peru) and Esperanza-1 (total depth ~ 4000 m Ecuador) wells (For location, See Fig. 1). We have established a lateral correlation between the lithological nature and the ages of the formations. The upper Oligocene shales of the Heath Playa-Rica source rock correspond to top of overpressure conditions indicated by a blue circle with arrow (Fildani et al., 2005; Lemgruber-Traby et al., 2020; Perupetro S.A data). This blue circle indicates overpressured zone in the Corvina-40-X-1 well (Perupetro S.A data). Fm: Formation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The sedimentary infill of the Tumbes-Guayaquil forearc depocenter is underlined by the upper Oligocene ductile deep marine shales (Heath Formation in Peru/Playa Rica Formation in Ecuador; Fig. 2). These shales form a potential source rock and are expected to have generated hydrocarbons in the deeper parts of the depocenters (Fildani et al., 2005; Lemgruber-Traby et al., 2020). The upper Oligocene shales are overlain by lower Miocene coarse-grained fluviodeltaic to deep-marine strata (Zorritos Formation in Peru/Subibaja Formation in Ecuador). These siliciclastic strata are unconformably overlain by middle Miocene-Pliocene marginal marine and deltaic strata (Cardalitos, Tumbes, and Mal Pelo Formations in Peru/Progreso and Lower Puná Formations in Ecuador), and finally by Quaternary claystones, sands, and dolomitized limestones (La Cruz Formation in Peru/Upper Puná Formation in Ecuador; Benitez, 1995; Deniaud, 2000; Fildani et al., 2005; Cobos, 2010; Reynaud et al., 2018; Fig. 2). Distal equivalents of the Tumbes-Guayaquil forearc depocenter sedimentary sequences are involved in the Banco Peru and Domito outer wedges (Fig. 1).

3. Subsurface structural data and interpretations

To illustrate the structural architecture and kinematics of structural growth of the offshore Tumbes-Guayaquil forearc basin, we show five, E– to ESE-trending serial cross-sections (labelled 1 to 5; Fig. 4) perpendicular to the forearc basin axis (approximately parallel to the thrust transport direction) and three ~ N- to NE-trending cross-sections (labelled 6 to 8; Fig. 5) parallel to the forearc basin axis (approximately parallel to the extensional trend in Guayaquil basin) (Figs. 1 and 3). Cross-sections 1, 2 and 6 are located in the Tumbes depocenter, and cross-sections 3, 4, 5, 7 and 8 in the Guayaquil depocenter (Figs. 1 and 3). The geology of these cross-sections has been interpreted using fifteen seismic reflection profiles (AIP92-19, Z1-3D extracted from Z1 seismic cube, VMX09-23, PC99-01, AIP92-61, VMX09-71, OXY98-114, AIP92-60, g83-s23e, g83-s23, g83-s23w, gt83-w23, s-9, g83-s09, g83-01, g83-n16, g83-n29; Supplementary Material Figs. S1 and S2) in second two-way travel time (sTWT) and six exploration wells (Marina-1X, Corvina-40-X-1, Barracuda-15-X-1, Esperanza-1, Domito-1, Tiburon-1) provided by Perupetro S.A. and Petroecuador (Figs. 4 and 5). The cross-sections range from 44 km to 58 km in length and reach 6–8 sTWT (second two-way travel time) in depth. Well data indicate that the entire sedimentary pile is relatively homogeneous across the basin. The seismic velocity values increases with depth from ~1800 m/s to ~3000 m/s through the Quaternary-Oligocene sedimentary section (Cobos, 2010; Espurt et al., 2018). We also used all available seismic reflection profile data and previously published data (Benitez, 1995; Deniaud, 2000; Collot et al., 2002; Fernández et al., 2005; Witt et al., 2006; Cobos, 2010; Espurt et al., 2018; Aizprua et al., 2019, 2022) to construct an isopach map of the Quaternary infill in sTWT of the Tumbes-Guayaquil forearc depocenter (Fig. 3).

3.1. Structures

The structural architecture of the Tumbes-Guayaquil forearc basin, off the coast of northern Peru and southern Ecuador, is described from south to north, from the Tumbes forearc depocenter to the Guayaquil forearc depocenter (Figs. 4–6).

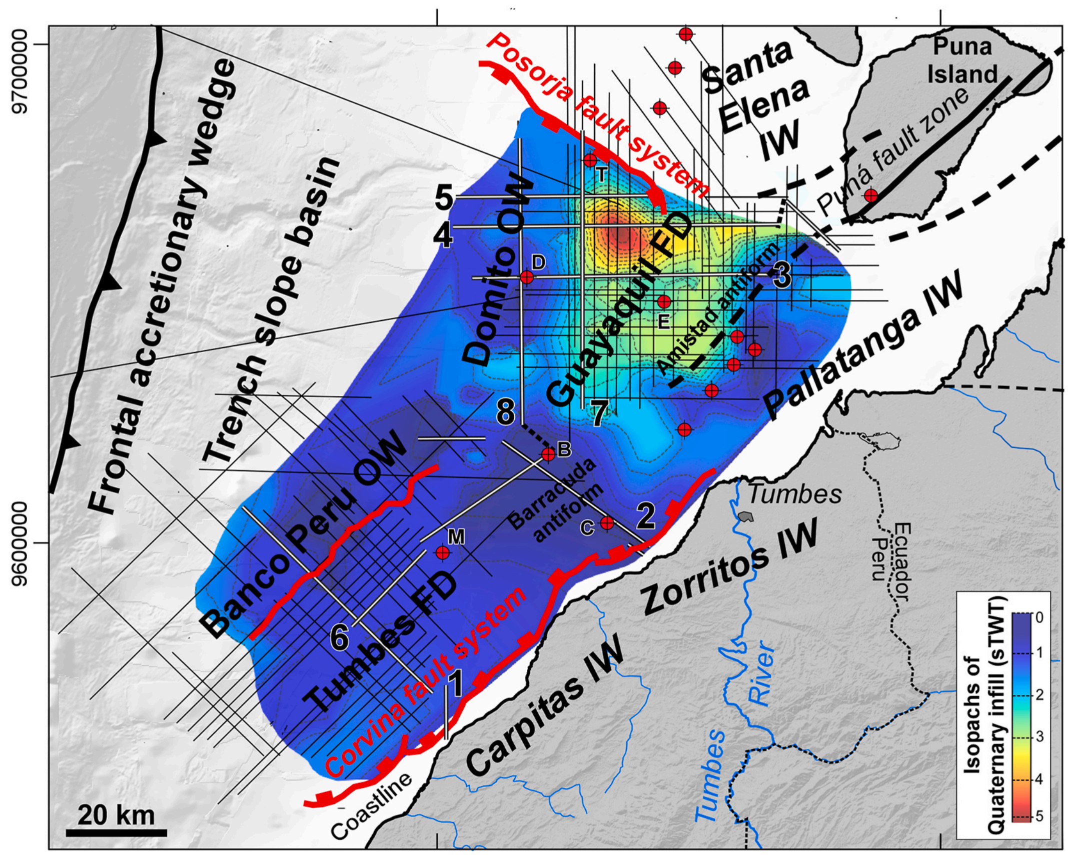

Fig. 3. Isopach map in sTWT of the Quaternary infill (La Cruz and Upper Puná Formations; as described in Fig. 2). The map reveals the position of the Guayaquil and Tumbes depocenters. The dotted contouring lines are 250 ms and intervals is 50 m. Location of available subsurface data are indicated: thin black lines are seismic profiles and red circles are exploration wells. The lines with numbers labelled and wells annotated with a letter are those used in this study. M: Marina-1X well, C: Corvina-40-X-1 well, B: Barracuda-15-X-1 well, E: Esperanza-1 well, D: Domito-1 well, T: Tiburon-1 well. Bathymetric data are extracted from the GEBCO site. Coordinate system is UTM zone 17S. FD: Forearc depocenter. IW: inner wedge; OW: outer wedge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.1.1. *The Tumbes forearc depocenter*

The Tumbes forearc depocenter develops ahead of the Carpitas-Zorritos inner thrust wedge system involving metamorphic/granitic rocks and Cenozoic sediment (Fernández et al., 2005; Vega, 2009; Espurt et al., 2018). Cross-sections 1 and 2 (Fig. 4a and b and 6a), perpendicular to the trend of the forearc basin, show that the Tumbes forearc depocenter consists of a seaward-thickening sedimentary wedge of about 40–45 km-long. It contains a sedimentary section thicker than ~6 sTWT (~7.2 km) in thickness composed mainly by Oligocene-Neogene strata and thin Quaternary section of ~0.6 sTWT (~400m) (Fig. 3). The sedimentary pile is deformed by NE-trending listric normal faults of the Corvina fault system (Fig. 4a and b). Normal faults dip regionally basinward (with rare counter-regional faults) and branch downward onto a NW-dipping décollement level, the Corvina décollement, developed in the Oligocene ductile shales of the Heath Formation. The seaward sliding of the sedimentary cover of the Tumbes depocenter along the Corvina décollement is associated with typical rollover folds (Dula, 1991; Xiao and Suppe, 1992, Fig. 4a and b). Neogene and Quaternary strata in the hanging walls of listric normal faults are characterized by reflectors that exhibit fan-shaped geometries (Fig. 6a).

Seaward, the sedimentary pile is deformed by the 15 km-long Barracuda antiform (Fernández et al., 2005; Vega, 2009; Brusset et al., 2018) mainly developed on cross-section 2 (Fig. 4b and 6a). This structure is formed by thin-skinned imbrications of NW-verging thrusts connected at depth into the Oligocene ductile shales of the Heath Formation. The thrust branches upward into several blind back-thrusts that define a triangle zone (Fig. 6a). The Barracuda antiform can be interpreted as a compressional structure accommodating the downdip gravitational sliding of the Corvina fault system as proposed by Vega (2009). The interpretation of the seismic profiles suggests that the Corvina décollement connects downdip to the Banco Peru outer wedge (Fig. 4b and 6a). This wedge is made of off-scrapped distal Cenozoic sediments including oceanic mafic bodies (intrusive and volcanic) accreted above the subducting oceanic Nazca crust (Fig. 4a and b; Shepherd and Moberly, 1981; Fernández et al., 2005; Espurt et al., 2018). The southwestern side of the Banco Peru wedge is cut by the NNE-trending SE-dipping Banco Peru normal/strike-slip fault zone (Figs. 3 and 4a). This latter is only developed of the Tumbes depocenter and intersects the sea floor.

The NE- trending cross-section 6 (Fig. 5a), parallel to the trend of the depocenter, reveals that the NE-trending geometry of the basin remains similar to those revealed by the NW-trending cross-sections. However, the cross-section 6 shows NW-trending fault system including NE- and SW-dipping listric normal faults involves the Oligocene to Quaternary strata (Witt et al., 2006; Auguy et al., 2017; Brusset et al., 2018). This fault system and these several thin-skinned imbricates are connected at depth into the flat-lying Oligocene shale level of the Heath Formation (Fig. 4a and b and 5a).

3.1.2. *The Guayaquil forearc depocenter*

The Guayaquil forearc depocenter develops above the Pallatanga-Santa Elena inner thrust wedge system involving upper Cretaceous oceanic terranes and Paleocene-Eocene sediments (Aizprua et al., 2019). The wedge system is cut by the Puná crustal fault zone (Fig. 3). This fault zone runs SW-ward into the Guayaquil forearc depocenter through the

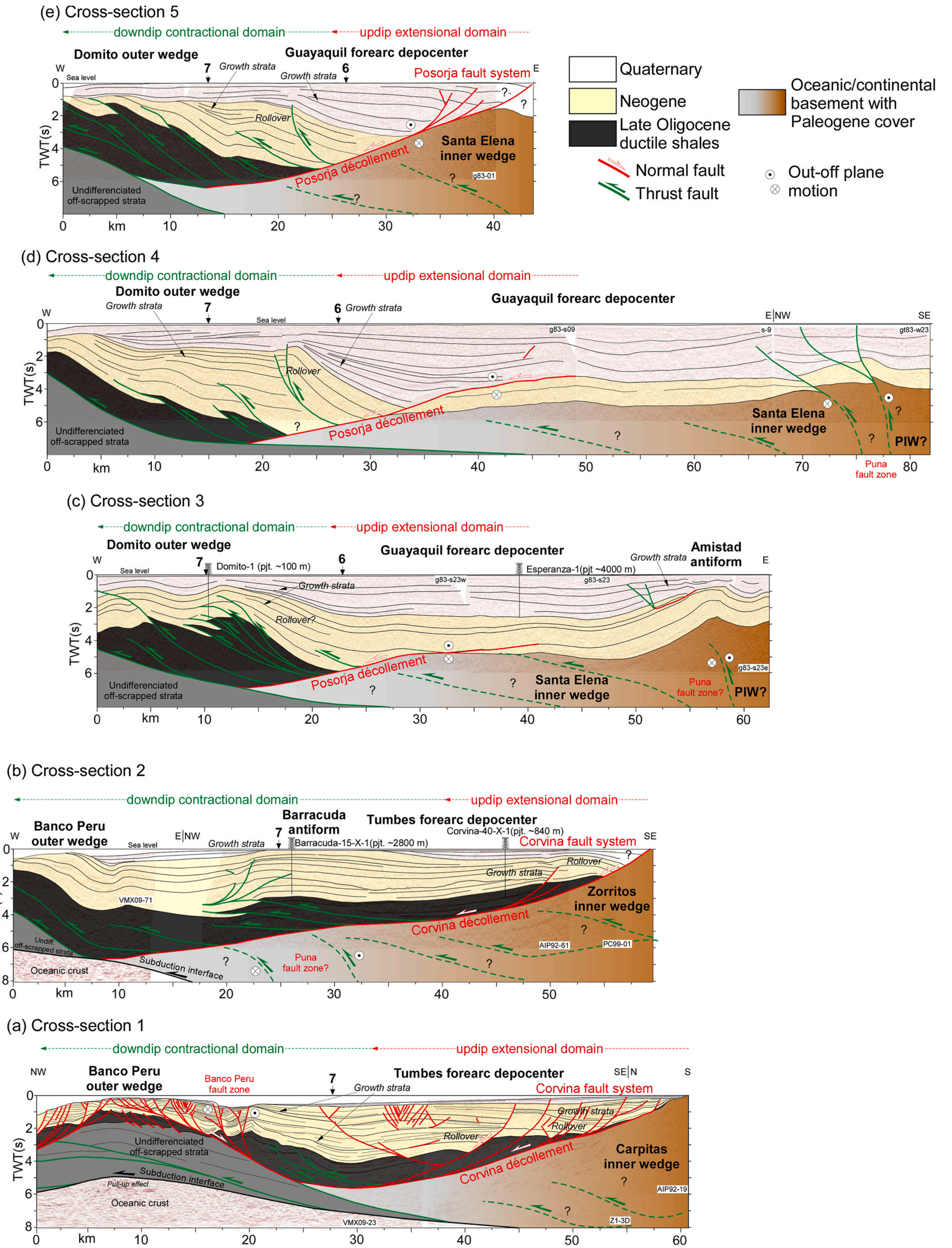

Fig. 4. Along-dip interpreted serial cross-sections of the Tumbes-Guayaquil forearc basin. For location, please refer to Figs. 1 and 3. The seismic profiles AIP92-19, Z1-3D, PC99-01, AIP92-61, VMX09-71, g83-s23e, g83-s23, g83-s23w, gt83-w23, s-9, g83-s09, g83-01 have been calibrated with the wells Domito-1, Esperanza-1, Corvina-40-X-1 wells. PIW: Pallatanga inner wedge. pjt.: projected.

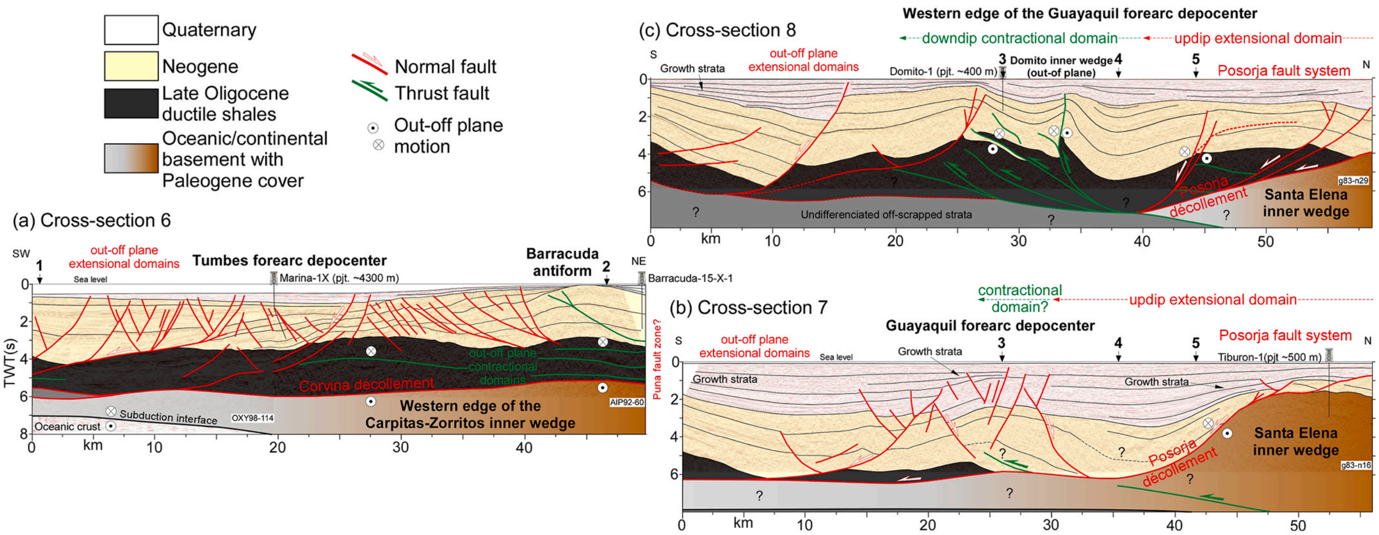

Fig. 5. Along-strike interpreted cross-sections of the Tumbes-Guayaquil forearc basin. For locations, please refer to Figs. 1 and 3. The seismic profiles g83-n16, g83-n29 and OXY98-114 have been calibrated with the Tiburon-1, Domito-1, Barracuda 15-X-1 and Marina-1X wells. pjt.: projected.

Amistad antiform as suggested by seismic reflection and seismicity data (Witt et al., 2006; Vaca et al., 2019; Aizprua et al., 2019, 2022, Figs. 3 and 4c,d,e). It probably extends farther SW beneath the Barracuda antiform, although seismic reflection profiles do not show a fault zone beneath the Corvina décollement (Fig. 4b). Cross-sections 4, 5 and 6 (Fig. 4d and e), perpendicular to the trend of the Guayaquil forearc depocenter, show that the depocenter consists of a seaward-thickening sedimentary wedge of a maximum length of 50 km (decreasing to 30 km northward) and has an up to ~7.3 sTWT (~9 km-thick) Oligocene to Quaternary sedimentary section in its center. The Guayaquil forearc depocenter is marked by a much thicker Quaternary section than in the Tumbes depocenter, in excess of ~5 sTWT (~6 km) (Figs. 3 and 4d). Cross-sections show that the sedimentary pile is deformed by NW-trending listric normal faults of the Posorja fault system along the southern edge of the uplifted Santa Elena High (Fig. 3). In cross-sections 3, 4 and 5, the structural style consists of a broad deep rollover fold along the hanging wall of the Posorja décollement developed into the Oligocene ductile shales of the Playa Rica Formation (Fig. 4c,d,e). Upward, the décollement connects to inter-sequence lithologic contrast zones (e.g., erosional unconformities (Benitez, 1995; Deniaud, 2000); intra Neogene or Neogene-Quaternary interface along cross-sections 3 and 4) or reach the surface (northern cross-section 5). Like in the Tumbes forearc depocenter, the rollover folding is characterized by reflectors depicting spectacular fan-shaped geometries in the upper Neogene and especially in the Quaternary sediments (Fig. 4c,d,e and 6b).

Along-dip cross-sections 3, 4 and 5 (Fig. 4c,d,e) show that the Posorja décollement connects downdip with a ~25 km-large zone dominated by thin-skinned compressional structures deforming the Oligocene-Quaternary sequences. Seismic profiles show that some thrusts deform the rollover fold developed along the hanging wall of the Posorja décollement, while other thrusts, farther downdip, are associated with the Domito outer wedge (Fig. 4c,d,e and 6b). Cross-sections 7 and 8, parallel to the basin trend (Fig. 5b and c) show that the Posorja and Domito fault systems are associated with secondary NW-trending listric normal/strike-slip faults connected downdip into the Oligocene flat-lying shale layer.

3.2. Kinematics and timing of deformations

The subsurface data presented in the previous sections clearly show that the structural architecture of the Tumbes-Guayaquil forearc basin is characterized by two thin-skinned deformation domains: an updip extensional zone defined by raft structures and a downdip contractional zone defined by fold-thrust systems (Figs. 4 and 5). The two domains are connected by narrow translational zones (~7 km) through décollements located in the Oligocene ductile shales (Heath and Playa Rica Formations) that lie directly above the seaward slope of the inner wedges (Fig. 6). The downdip fold-thrust structural systems are complex and comprise interference between structures related to frontal accretion-subduction and gravitational tectonics. In the Tumbes forearc depocenter, we interpret that the downdip Barracuda compressional structure balances part of the extension accommodated higher on the slope by the Corvina fault system (Fig. 4a and b). Thus, the growth of the Barracuda structure was mostly controlled by the downdip gravitational sliding of the Corvina raft system (Vega, 2009). Like the Tumbes forearc depocenter, part of the sedimentary infill of the Guayaquil depocenter is gravitationally rafted along the Posorja décollement toward the sea (Fig. 4d and e). Although the structures of the Banco Peru and Domito wedges are more compatible with frontal accretion related to subduction, we interpret that part of the thrusting and folding in these outer wedges could be therefore associated to gravitational tectonics. For instance, we interpret the current form of the rollover fold in cross-section 5 (Fig. 6a) as significantly deformed by a series of three thrusts connected onto the seaward-dipping Posorja décollement.

The sedimentary infill of the Tumbes-Guayaquil forearc basin contains syntectonic horizons that constrain the timing of deformation. Growth strata and submarine unconformities reveal that the Corvina-Barracuda structure of the Tumbes depocenter was active in the Middle(?)-Late Neogene (Fig. 4a and b; Brusset et al., 2018; Espurt et al., 2018). The onlap of the Quaternary strata on the Barracuda antiform and the truncation of its crest domain at the seafloor suggest ongoing deformation and uplift through the Quaternary until the present-day (Fig. 4b and 5). Seaward, the deformation of the Banco Peru outer accretionary wedge is attested by the pinch out of the Neogene-Quaternary strata (Fig. 4a and b; Brusset et al., 2018; Espurt et al., 2018). In the Guayaquil forearc depocenter, the activity of the Posorja raft system is recorded by spectacular Late Neogene and Quaternary growth strata fanning (Witt et al., 2006, Fig. 4c,d,e). The strong Quaternary sedimentation in the Guayaquil basin is related to large extensional displacement along the Posorja raft system. Synchronous and somewhat younger thrusting and folding in the Domito outer thrust wedge is locally recorded by upper Neogene and Quaternary growth strata (Fig. 4c,d,e). Deformation in this outer thrust wedge might therefore result from the combined effect of frontal accretion and gravitational sliding of the Posorja raft system.

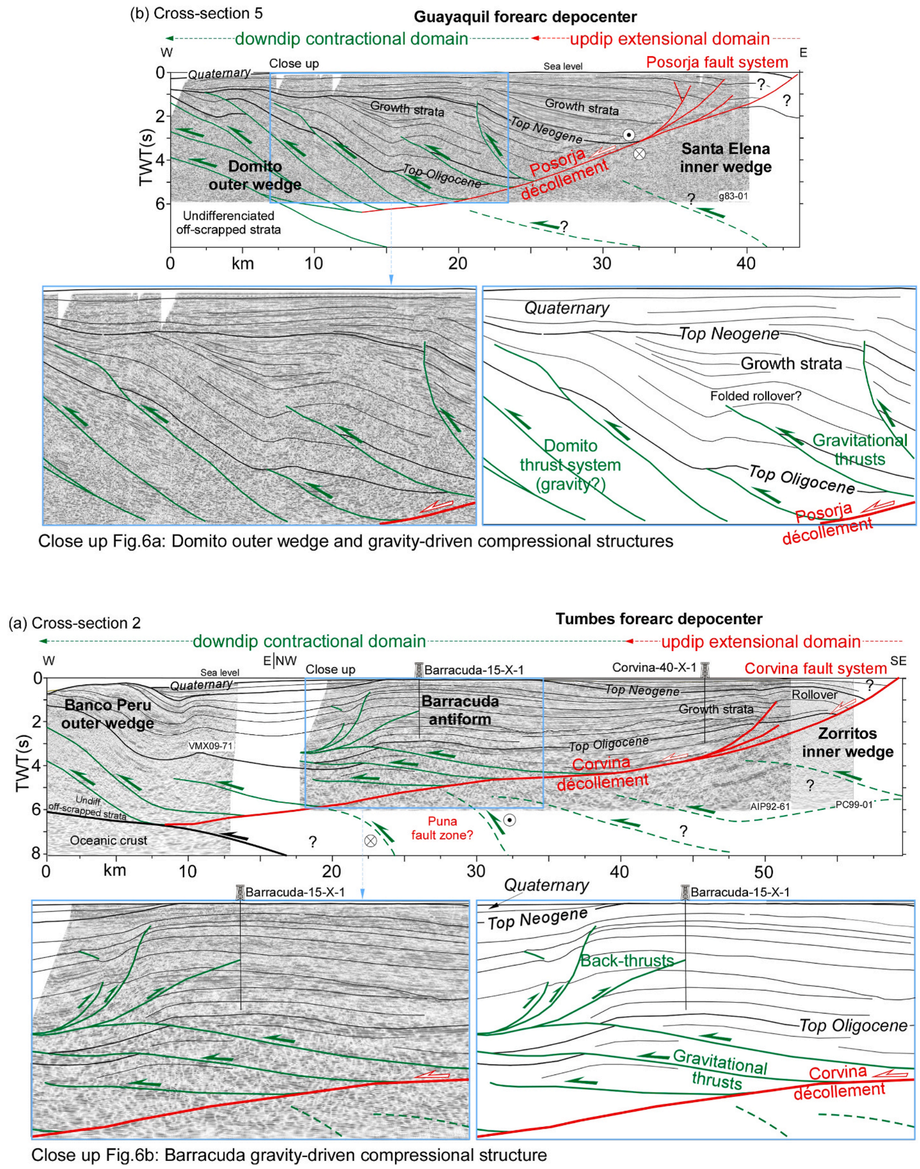

Fig. 6. Line drawing of seismic profiles along the cross-sections 2 and 5 (See Fig. 4 for locations). The seismic close ups show the detail of the downdip fold-thrust belts balancing part of the extensional displacement of the updip Corvina and Posorja raft systems.

The Quaternary to present-day emplacement of a regional transtensional stress regime in the forearc basin is partly accommodated by potential recent submarine strike-slip structures. For instance, the activity of the Puná fault-related Amistad antiform is recorded by Quaternary growth strata on the northwestern limb of the antiform (Fig. 4c; Witt et al., 2006). The recent activity of some fault segments (e. g., Puná and Banco Peru transtensional faults) is attested by fault scarps offsetting the seafloor (Fig. 4a; Witt et al., 2006).

4. Discussion: gravity tectonics in a forearc basin

The large-scale gravity-driven deformation system observed in the Tumbes-Guayaquil forearc basin is similar to that classically observed in deltaic systems along passive continental margins (e.g., Morley and Guerin, 1996; Stewart, 1999; Hooper et al., 2002; Rowan et al., 2004; Bilotti and Shaw, 2005; Ahmed et al., 2022). In the following, we discuss some of the key tectono-stratigraphic features responsible for the establishment of the gravity tectonic style through an active accretionary prism (Fig. 7).

4.1. Oblique convergence and crustal-scale transtensional deformation

The Northern Peru-Southern Ecuador accretionary prism system exhibits a complex three-dimensional structural architecture resulting from successive stages of deformation through the Mesozoic to Cenozoic period, including the Farallon-Nazca Plate subduction dynamics, crustal block accretion, ridge collision, and motion of forearc sliver (Benitez, 1995; Deniaud, 2000; Gutscher et al., 2002; Jaillard et al., 2004; Witt and Bourgois, 2010; Riel et al., 2014; Espurt et al., 2018; Hernández et al., 2020; Aizprua et al., 2022; Jaillard, 2022). Post-Oligocene clockwise rotations in the coastal areas of Ecuador and Northern Peru (Kissel and Laj, 1989; Mitouard et al., 1990; Siravo et al., 2021) are related to oblique convergence and partitioning of the deformation in the Northern Andes subduction zone (Fig. 7; Alvarado et al., 2016). This induced change and vertical rotation of the maximal stress in the forearc zone and the oblique reactivation of inherited fault and suture zones between crustal blocks (Aizprua, 2021). For instance, the development of NE-trending strike-slip fault (e.g., NE-trending Banco Peru and Puná strike-slip faults) and NW-trending normal faults could be the consequence of the NE-ward tectonic escape of the continental North Andean

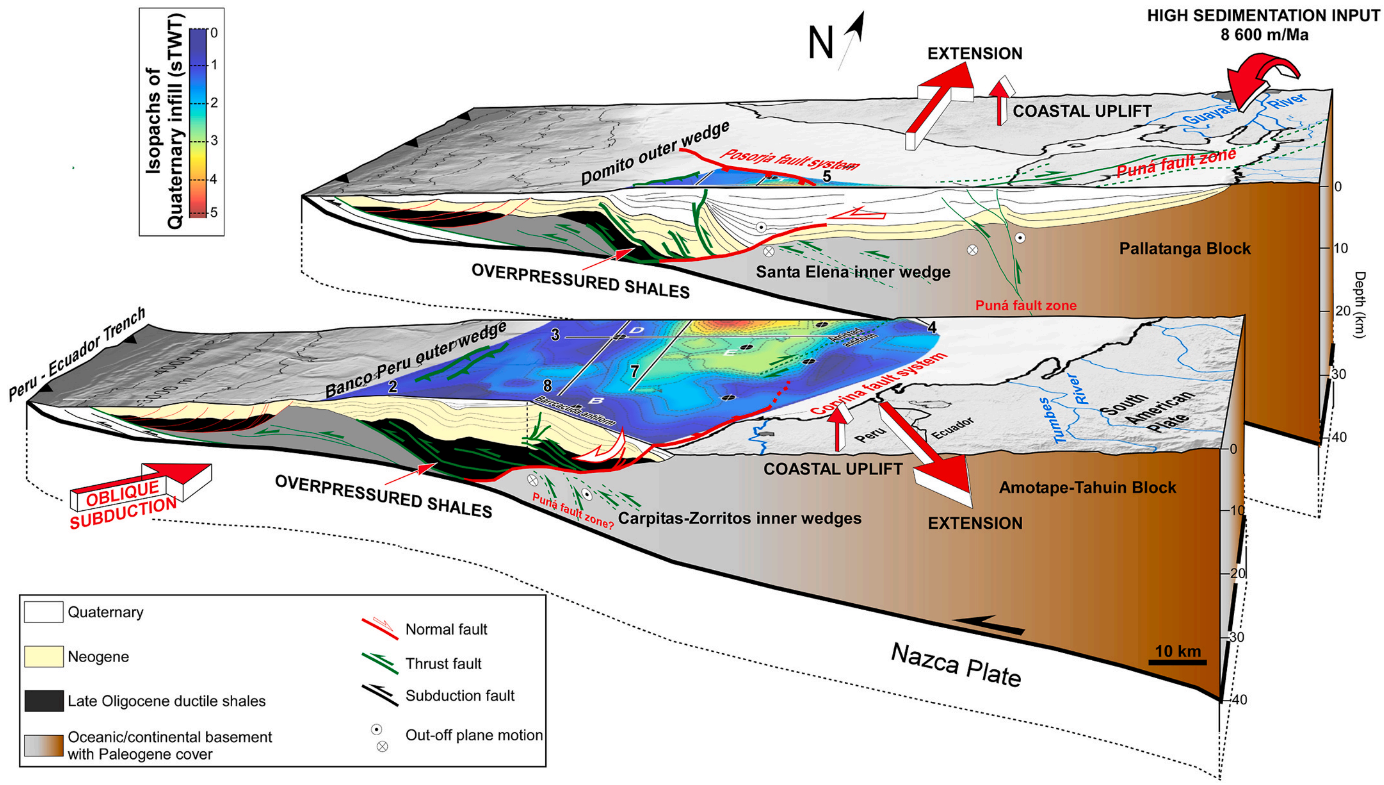

Fig. 7. Three-dimensional structural model illustrating the tectono-stratigraphic features leading to the gravity-driven large-scale deformation system in the Tumbes-Guayaquil forearc basin in relation to the geodynamic setting of the Northern Peruvian-Southern Ecuadorian subduction zone. See text for further explanations.

Sliver during at least the Quaternary (Deniaud, 2000; Witt et al., 2006; Bourgois, 2013; Nocquet et al., 2014; Villegas-Lanza et al., 2016; Espurt et al., 2018). This modern crustal-scale transtensional regime in the accretionary prism (Noda and Miyakawa, 2017) might have favored the creation of accommodation space for gravity-driven deformation in the Tumbes-Guayaquil forearc basin (Fig. 7).

4.2. Basal décollement slope tilting

Gravity tectonics can be influenced by the dip of the basal décollement level (Mauduit et al., 1997; Rowan et al., 2004). For instance, Mauduit et al. (1997) demonstrated that an increase in basal slope dip increases noticeably the gravity sliding and the amount of extensional deformation. This increase in basal slope dip can be caused by a margin tilt induced by differential uplift across the margin. Indeed, the coastal domain of the Tumbes-Guayaquil forearc basin shows evidences of uplift characterized by the presence of large Plio-Pleistocene perched marine terraces sequences (called Tablazos), located at more than 300 m above sea level (Séranne, 1987; DeVries, 1988; Pedoja et al., 2006). These morpho-tectonic markers recorded the uplift of the Carpitas-Zorritos, Pallatanga and Santa Elena inner wedges during at least the Quaternary period (Pedoja et al., 2006; Regard et al., 2012; Bourgois, 2013; Espurt et al., 2018). We propose that the gravitational failure in the offshore Tumbes-Guayaquil forearc basin is partially controlled by the seaward tilting margin related to the uplift of the inner wedges. This is comparable to the continental passive margin of Namibia where the uplift event controlled the gravity sliding in the Orange basin (De Vera et al., 2010). The Quaternary uplift of the Northern Peruvian and Southern Ecuadorian active margins largely coincides with the major sedimentary and gravity tectonic activity in the Tumbes-Guayaquil depocenter (Fig. 7).

4.3. Sediment accumulation

The Tumbes-Guayaquil forearc basin is characterized by a 7 to 9 km-thick upper Neogene-Quaternary coarse-grained fluviodeltaic to deep-marine sedimentary pile (Deniaud et al., 1999; Deniaud, 2000; Witt et al., 2006; Cobos, 2010, Figs. 4 and 5). The Quaternary sedimentary pile alone can exceed 5 km-thick in the Gulf of Guayaquil basin and records sedimentation rate with a maximum rate of up to 8600 m/Ma (Deniaud, 2000). Today, ongoing basin filling is sustained by more than twenty rivers (the Guayas river in Ecuador and the Tumbes river in Peru are the major ones) draining the Andean reliefs towards the Pacific margin (Salomons et al., 2005), associated with a sedimentary particle discharge estimated about 30 Mt/a (Milliman and Farnsworth, 2013). Thus, the massive sedimentary load could have strongly controlled gravitational raft tectonic instabilities in the Tumbes-Gulf of Guayaquil forearc basin. For instance, Mauduit et al. (1997) demonstrated that the sedimentation increases the rate of displacement and overall extension along a décollement. This implies that the shear stress parallel to the décollement is a function of the overburden of the sedimentary pile for a given angle of the basal slope. Furthermore, this massive sedimentary load would cause an increase in the shear stress within the décollement which, deforms and controls the geometry of the décollements. Further quantitative analyses of the bed-parallel slip along décollements are required to better illustrate the development of these shales décollement-related gravitational raft tectonics (e.g., Chapman and Williams, 1984; Delogkos et al., 2017; Alsop et al., 2020). In addition, restored cross-sections are needed to quantify the amounts of extensional and compressional deformations and to evaluate lateral compaction in the downdip fold-thrust systems (Butler and Paton, 2010; De Vera et al., 2010; Scarselli et al., 2016). Meanwhile, the geometry of the tectonic system is conformable with gravitational raft tectonics type described in passive continental margins (e.g., Rowan et al., 2004; De Vera et al., 2010; Scarselli et al., 2016). This indicates that massive sedimentary load strongly controlled gravitational raft tectonic instabilities in the Tumbes-Gulf of Guayaquil forearc basin.

4.4. Overpressured shales

Shales and fluid pressures are very important in gravity tectonics (Hesthammer and Fossen, 1999; Oldenziel et al., 2002; Rowan et al., 2004). Shale can behave as a viscous-plastic solid involving brittle and ductile fractures if the deviatoric stress approaches the strength of the shale (Rowan et al., 2004; Wood, 2010; Soto et al., 2021). Interestingly, fluid pressures are observed in the Corvina-40-X-1 well, located at the southeastern border of the Tumbes depocenter (Figs. 1 and 2). They can be found below fluid retention depth (zRFD) of ~3.1–3.3 km where extensional stress exists based on the deviated borehole failure analysis (data provided by Perupetro S.A.). The sonic data acquired in the Corvina 40-X-1 well show that there is a high sonic slowdown at 3.7 km-depth, above Oligocene Heath Formation sequences. This implies a different compaction and burial history and an overpressure stress state (Fig. 2; data provided by Perupetro S.A.; Fildani et al., 2005; Lemgruber-Traby et al., 2020). The top of the overpressure zone corresponds to the top of the ductile shales of the Oligocene Heath Formation (Fig. 2) and results in a reversal of the Vp (2500 m/s to 3000 m/s; data provided by Perupetro S.A) in the ductile deep-marine shales of the Oligocene Heath/Playa Rica Formation compared to the overlying coarse-grained fluviodeltaic to deep-marine strata. According to our structural interpretations, the sedimentary cover of the Tumbes-Guayaquil forearc basin is detached below the overpressure zone in the ductile shales of the Oligocene Heath/Playa Rica Formation (Figs. 2, 4, 5 and 7; Corvina and Posorja décollements). As in many continental passive margins, the pore fluid pressures would promote the development of the Corvina and Posorja normal fault systems which are connected at depth in the décollement layer (Figs. 2, 4, 5 and 7; e.g., Mourgues et al., 2009; Ahmed et al., 2022). Moreover, in the context of a prograding deltaic system like in the study area, fluid pressures can decrease near the coast and increase in the seaward side of the basin, where the sedimentary thickness increases (Mourgues et al., 2009). This is coherent with the location of Posorja décollement that develops in the deepest depocenter of the Guayaquil forearc depocenter (Figs. 2, 4, 5 and 7). Consequently, friction at the level of the overpressured shales is reduced throughout the Tumbes-Guayaquil forearc depocenter. Thus, the sedimentary load of the Tumbes-Guayaquil forearc basin and the presence of overpressured shales promote low frictional properties at depth, which might control the trenchward displacement of the Banco Peru and Domito outer thrust wedges.

4.5. Seismicity

The study area is characterized by low interseismic coupling on the subduction interface (Chlieh et al., 2014; Nocquet et al., 2014; Villegas-Lanza et al., 2016). Few historical subduction earthquakes with intermediate magnitudes are located in the region (e.g., Beauval et al., 2013). However crustal faults are seismically active in the onshore and offshore region of the Gulf of Guayaquil basin (e.g., Puná dextral fault zone; Fig. 5), as revealed by national earthquakes catalogue (Alvarado et al., 2018). The gravitational sliding on the basal décollement levels is slow and appears aseismic, due to overpressured shales, sedimentary loading and tectonic strains. This raises the question of whether the basal décollement levels could accommodate stresses such as fault. It follows that we cannot exclude that aseismic slip on the basal décollements may be triggered by either dynamic or static stress changes (Du et al., 2003). One is dynamic stress change or transient deformation generated by the passage of seismic waves and the other is the static stress change associated with a nearby faulting process. Both possibilities are likely under the local seismo-tectonic conditions. Concerning the gravity sliding at the sea-bottom, the absence of slope (since we are on the continental shelf), of overhanging sedimentary mass (the sea-bottom is rather flat) and of an above significant water layer (only several tens of meters to some hundreds of meters), make that potential intra-basin tsunamis are unlikely and the associated tsunami hazard is therefore almost null.

In addition, a potential tsunami that could be triggered by an earthquake on the Puná dextral strike-slip fault is also unlikely because of the dominant strike-slip component of the event and its short-length segments that imply moderate magnitudes along the fault. Instead, in the study area and nearby coastal areas, the tsunami hazard is related to a subduction earthquake occurring near the trench on the subduction interface (Ioualalen et al., 2014).

5. Conclusion

We propose a new structural interpretation for the Tumbes-Guayaquil forearc basin involving a tectonic style reported for the first time in the dynamics of the area. Our results provide a model for the evolution of a forearc basin, belonging to an accretionary prism, which exhibits widespread gravitational tectonic instabilities in the Late Neogene-Quaternary interval. Subsurface data and the construction of structural cross-sections show that the forearc basin is detached seaward from the underlying accretionary prism and deformed by large-scale, updip listric normal fault systems (Corvina and Posorja raft systems) associated with downdip fold-thrust systems (Barracuda and part of the Domito thrust systems). The décollement layer is located within the Oligocene ductile shales of the Heath/Playa Rica Formation. We propose that this gravity tectonic style, rather observed in passive continental margins, is primarily controlled by the combination of tectonostratigraphic features including crustal-scale transtensional deformation related to oblique convergence along the Northern Andean margin and opening of the basin along the Puná fault zone, basal décollement slope tilting related to the Quaternary coastal uplift, the massive sediment accumulation, and the presence of overpressured shales.

Author statement

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andrea Peuzin reports was provided by University of Côte d'Azur. Andrea Peuzin reports a relationship with University of Côte d'Azur that includes: employment.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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