Tectonophysics 730 (2018) 48–62

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Prolonged extension and subsidence of the Peruvian forearc during the Cenozoic

Willem Viveen[a,*], Fritz Schlunegger[a,b]

[a] Grupo de investigación en Geología Sedimentaria, Sección de Ingeniería de Minas, Departamento de Ingeniería, Pontificia Universidad Católica del Perú, Av. Universitaria 1801, San Miguel, Lima, Peru
[b] Institute of Geological Sciences, University of Bern, Baltzerstrasse 1 + 3, CH-3012 Bern, Switzerland

A R T I C L E I N F O

Keywords:
South America
Tectonics, convergent margin
Subduction zone
Nazca plate
Nazca ridge

A B S T R A C T

Ocean-continental subduction zones are commonly associated with compressional stress fields, which ultimately result in regional uplift of the overriding plate. This has particularly been inferred by most studies for the western margin of the Peruvian Andes. However, local geological observations have contested this idea. Here, we present a review of existing local and international literature supplemented by new structural and geomorphic observations that suggest that nearly the entire central (15° to 11° S latitude) and northern Peruvian forearc (11° to 6° S latitude) are under extension with a slight tendency to transtension instead of compression, and that this region has experienced a prolonged period of subsidence since the middle-late Eocene, interrupted by short pulses of uplift. In contrast, the southern Peruvian forearc (15° to 18° S latitude) has experienced (trans) tension from the middle-late Eocene until recent in combination with uplift. The central and southern Peruvian forearc that was influenced by the passage of the Nazca ridge experienced transtension and subsidence until the middle-late Miocene and alternating phases of compressional and transtensional tectonics afterwards. These new findings on the geodynamic development of the Peruvian forearc need to be considered in future reconstructions of the mechanisms at work within this subduction zone.

1. Introduction

The Peruvian forearc has been considered as presumably the world's most classical example of a subduction zone between an oceanic and continental plate, where subduction processes led to a predominantly compressive regime (Isacks, 1988; Suárez et al., 1983; Sobolev and Babeyko, 2005). This has particularly been the case for the central-northern part of the Peruvian forearc, where slab flattening paired with a decrease in the convergence rate of the Nazca and South American plates since the late Miocene has been considered to cause large-scale compression (Espurt et al., 2008; Ramos and Folguera, 2009; Flament et al., 2015). The ensemble of these conditions was considered to result in compression and uplift particularly of the forearc regions (Yañez and Cembrano, 2004; Espurt et al., 2008; Ramos and Folguera, 2009; Ramos, 2010; Flament et al., 2015). In addition, it has also been proposed that the subduction of the buoyant Nazca ridge is paramount to flattening of the slab and the establishment of a compressive regime (Espurt et al., 2008; Ramos, 2010). This interpretation stems from the presence of a rapidly uplifting forearc in northern Chile and southern Peru as evidenced by a pronounced structural high (i.e., the Coastal Cordillera) and raised marine terraces (Ortlieb and Macharé, 1990; Macharé and Ortlieb, 1992; Regard et al., 2010; Pía Rodríguez et al., 2013; Fig. 1) with significant seismic activity. The preferred interpretation of a compressive regime led to a view where reverse faulting has occurred all along the Peruvian forearc (Sempere and Jacay, 2007) thereby fostering the consideration of an overall, compressive regime. More recently, however, modelling studies have shown that subduction and the south-eastward migration of the buoyant Nazca ridge is responsible for crustal uplift above the ridge and in front of the leading edge of the ridge, whereas subsidence prevails at the trailing edge of the ridge (Martinod et al., 2013, 2016; Zeumann and Hampel, 2015; Fig. 1). Field evidence supporting these results is limited to risen marine terraces surrounding the ridge (Macharé and Ortlieb, 1992; Saillard et al., 2011). Similarly, the observed subsidence in the forearc, for instance in the area of Lima (LeRoux et al., 2000; Fig. 1), was attributed to the crustal extension caused by passage of the ridge (Martinod et al., 2013; Zeumann and Hampel, 2015). Accordingly, the isostatic effects related to the convergence of the Nazca and also Carnegie ridges have either been interpreted as being representative of the deformation style of the entire forearc (for instance Espurt et al., 2008), or these mechanisms have been considered to drive the deformation pattern in local domains as far north as 10° S (Hampel, 2002). Besides, uplift and subsidence

* Corresponding author.
E-mail address: wviveen@pucp.pe (W. Viveen).

https://doi.org/10.1016/j.tecto.2018.02.018
Received 10 May 2017; Received in revised form 21 February 2018; Accepted 25 February 2018

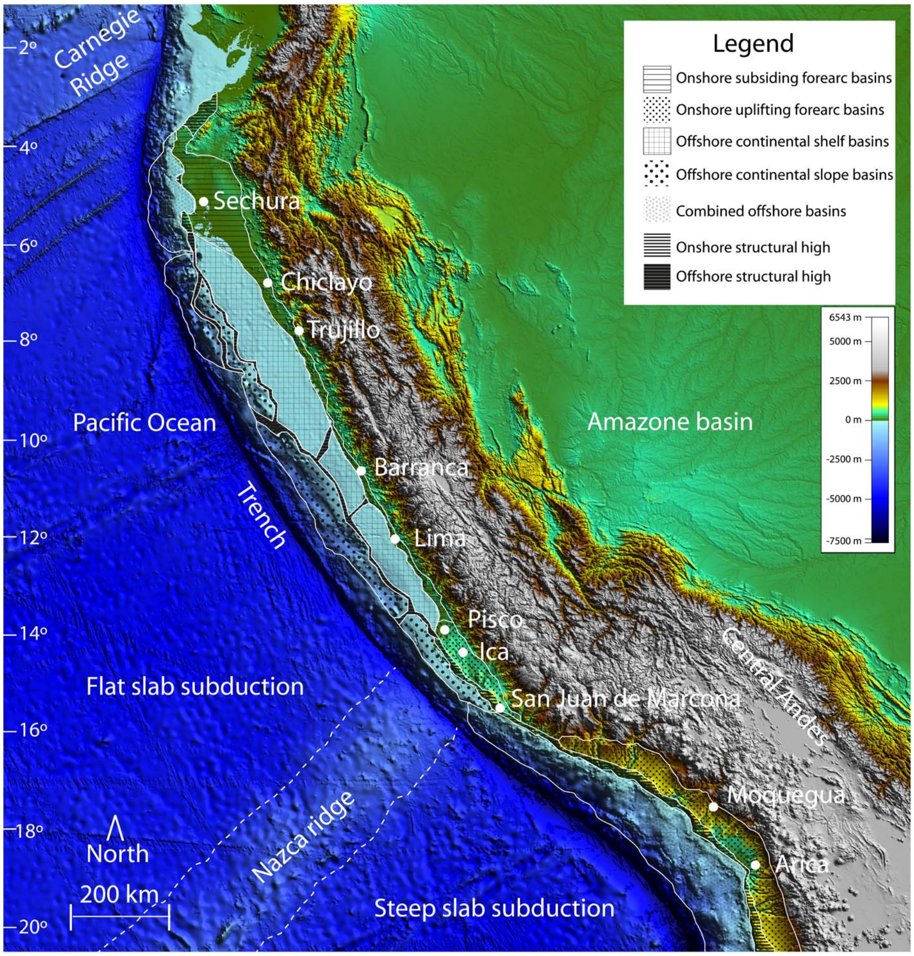

Fig. 1. Digital Elevation Model of western South America and the east Pacific Ocean floor. GEBCO-2014 30-arc second grid (GEBCO, 2014). Blue colours indicate submarine surface elevations, other colours terrestrial elevations. Outlined are the main elements of the Peruvian forearc such as the terrestrial subsiding and uplifting forearcs, submarine shelf and slope basins as well as the structural highs and the Carnegie and Nazca Ridges. Classification based on Zuñiga-Rivero et al. (1998b) and Macharé et al. (1986). Note the coincidence between flat slab subduction and subsiding, onshore forearc basins and structural highs on the one hand, and steep slab subduction and uplifted forearc basins and structural highs, on the other hand. Current theories on plate convergence dynamics predict the opposite pattern: uplifting areas in correspondence to flat slab subduction and subsiding areas in correspondence to steep slab subduction. This suggests that the angle of the subducting slab is not responsible for the observed forearc geomorphology. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

through ridge passage were considered as temporal effects (Martinod et al., 2013), and the area surrounding Lima was interpreted to have already recovered its pre-deformation state (Krabbenhöft et al., 2004). In addition, offshore seismic data show the existence of large-scale normal faults striking parallel and perpendicular to the margin and the existence of horst-graben systems affecting middle-late Eocene to recent sedimentary rocks and sediments along the entire margin (Von Huene and Lallemand, 1990; Hagen and Moberly, 1994; Clift et al., 2003; Von Huene and Ranero, 2003; Krabbenhöft et al., 2004; Clift and Hartley, 2007; DeVries Klein et al., 2011; Herbozo et al., 2013: Fig. 1) that seem incompatible with the presence of a purely compressive regime in the forearc. Crustal extension has also been described for the coastal region in northern Chile and even farther south (Hoffmann-Rothe et al., 2006; Encinas et al., 2008, 2012; Aron et al., 2013; Philippon and Corti, 2016). Likewise, the presence of a 1000-km-long and up-to 100-km-wide, flat, coastal forearc plain that stretches at elevations of only 20 to 30 m asl (Fig. 1) suggests the occurrence of sediment accumulation in a subsiding environment. This appears difficult to reconcile with pure compressional conditions, at least for longer time scales. As far as we are aware of, none of the studies on the dynamics of the Peruvian forearc incorporate information from this coastal plain making up approximately two-thirds of the entire continental onshore forearc (Fig. 1).

Here, we present morphotectonic, remote-sensing and structural evidence based on which we infer the occurrence of subsiding basins bounded by normal and transtensional faults along the onshore and offshore forearc between 6° and 18° S latitude. To this extent, we mapped new lineaments along the entire Peruvian forearc on the basis of satellite images and fieldwork that we combine with a review of literature including the results of geophysical surveys. Based on these data, we will argue that a large part of the Peruvian margin above the flat-slab segment has experienced long-term period of sediment accumulation in response to subsidence at least since middle-late Eocene-Oligocene times, with possible interruptions by short-term uplift pulses. Literature information indicates that the Peruvian and Chilean segments that are undergoing steep slab subduction also experienced extensional to transtensional tectonics before the onset of basin inversion. Accordingly, we will argue that the geologic history of the Peruvian forearc has been characterised by a normal to transtensional regime during most of the time.

2. Methods

Lineament mapping was carried out on basis of 30-m and 90-m SRTM DEMs (Reuter et al., 2007) and Microsoft Bing aerial photography in ArcGIS 10.1. The criteria for identifying structural lineaments were observations of straight lines visible on the hillshade DEM cutting hillslopes and ridges, and delineating landscape segments by sharp boundaries. Only the larger, regional-scale lineaments were mapped. Comparisons were made with Microsoft Bing images to exclude lineaments resulting from errors in the DEMs, or from misinterpretations of straight lines that represent roads and other infrastructural works.

All polyline lineaments were separated in single, straight lines using the Shapes to segments tool (Jenness, 2014) in ArcGIS 10.1. Rose diagrams of the single line lineaments were then constructed using the Polar plots tool (Jenness, 2014) in ArcGIS 10.1. Representations of the lineament directions were weighted based on accumulated lineament length, making it possible to objectively compare first, second and lower order lineaments. First-order lineaments tend to be the longest ones whereas second and lower order lineaments are increasingly