Available online at www.sciencedirect.com
ScienceDirect
Earth and Planetary Science Letters 267 (2008) 453–467
EPSL
www.elsevier.com/locate/epsl

Nonlinear variations of the physical properties along the southern Ecuador subduction channel: Results from depth-migrated seismic data

Alcinoe Calahorrano B.[a,*], Valentí Sallarès[b], Jean-Yves Collot[a], Françoise Sage[a], Cesar R. Ranero[c]

[a] Géosciences Azur, Université de Nice Sophia-Antipolis, Institut de Recherche pour le Développement (IRD), Université Pierre et Marie Curie, Centre National de la Recherche Scientifique (CNRS), BP 48, 06235 Villefranche-sur-Mer cedex, France
[b] Unidad de Tecnología Marina-CMIMA, Consejo Superior de Investigaciones Científicas (CSIC), Passeig Maritím de la Barceloneta 37-49, 08003, Barcelona, Spain
[c] Institució Catalana de Recerca i Estudis Avançats (ICREA) at Instituto de Ciencias del Mar-CMIMA, Consejo Superior de Investigaciones Científicas (CSIC), Passeig Maritím de la Barceloneta 37-49, 08003, Barcelona, Spain

Received 15 June 2007; received in revised form 25 October 2007; accepted 29 November 2007
Available online 1 February 2008
Editor: C.P. Jaupart

Abstract

We use two high-quality pre-stack depth-migrated multichannel seismic profiles acquired to quantify physical properties variations of underthrust sediments along the first ~30 km of subduction off the erosional southern Ecuadorian margin. Seismic data show three zones along the subduction channel (referred to as Zones I, II and III) characterized by distinct velocity and velocity-derived physical properties, which are in agreement with values estimated from experimental results of deformation in granular media. These three zones result from transformational changes of underthrust sediments governed by fundamentally different physical processes that control their mechanical behavior at increasing confining pressures. Based on our observations and its comparison with experimental results, we argue that the transformations undergone by underthrust sediments as they dip into the subduction zone are the following: within Zone I, progressively increasing velocity (and decreasing velocity-derived porosity) indicates continuous sediment compaction, which must be accompanied by effective fluid drainage along the décollement and/or across the accretionary wedge. The underthrust material is here unconsolidated from a mechanical point of view. Laboratory experiments indicate that the dominant processes at this range of pressures are grain rolling, particle rotation and frictional slip at grain contacts. Within Zone II, velocity (and porosity) remains constant for ~16 km (SIS-72) and ~12 km (SIS-18). This suggests undrained conditions resulting in growing fluid overpressure at the subduction channel. Grain deformation is similar to Zone I. Within Zone III, velocity increases and porosity falls rapidly, indicating sediment compaction and subsequent release of over-pressured fluids, where grain deformation is likely to be elastic. This might be the dominant process until the grains attain their crushing strength, resulting in granular cataclasis and, eventually, in the collapse of the system. We suggest that over-pressured fluid release may induce hydrofracturation and it is likely to increase inter-plate coupling down from Zone III.

Keywords: subduction channel; velocity inversion; fluid overpressure; grain deformation

1. Introduction

In convergent margins, when subduction takes place, part of the oceanic and continental sediments cumulated in the trench is commonly dragged with the downgoing plate beneath the margin. This downgoing sediment form the so-called subduction channel (SC), a poorly consolidated and fluid-rich layer that is structurally squeezed between upper and lower plates

* Corresponding author. Instituto de Ciencias del Mar-CMIMA, Consejo Superior de Investigaciones Científicas (CSIC), Passeig Maritím de la Barceloneta 37-49, 08003, Barcelona, Spain. Tel.: +34 93 230 9500; fax: +34 93 230 95 55.
E-mail address: alcinoe@cmima.csic.es (A. Calahorrano B.).

0012-821X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2007.11.061

(Scholl et al., 1977; Shreve and Cloos, 1986). The SC has been clearly imaged using multichannel seismic (MCS) data along tens of kilometers beneath several accretionary margins like Nankai (e.g. Moore et al., 2001; Bangs et al., 2004), Barbados (e.g. Westbrook et al., 1982; Moore and Shipley, 1988) and Cascadia (e.g. Clowes et al., 1987; Davis and Hyndman, 1989; Hyndman et al., 1990).

Physical and mechanical properties of subducting material strongly influence the shape and tectonic deformation of the margin (Davis et al., 1983; Lallemand et al., 1994). The subducting material contains pore-filling fluids in variable amounts depending on the nature and thickness of the underthrust sediment deposit. In high-permeability conditions, pore fluids are expelled as a response to the rising pressure resulting from the landward-increasing load of the overriding-plate. Sediment framework will mainly support this load and will be progressively compacted. In the case that a significant part of fluids remain trapped within pores, which typically occurs when subducting sediments are rapidly buried beneath the margin and permeability conditions are low, the overburden pressure is transferred into increasing fluid over-pressures along the décollement and/or within the sediment column (e.g. Bangs et al., 1990). Fluid pressure variations are believed to play a major role in controlling deformation processes and fault dynamics along subduction zone megathrusts (Moore, 1989; Le Pichon et al., 1993; Moore and Saffer, 2001; Sage et al., 2006). Such deformation processes include frontal accretion, wedge thickening by out-of-sequence thrusting, subduction erosion, and underplating (Cloos and Shreve, 1988). Understanding the physical behaviour of underthrust material is critical because it controls mechanical processes such as inter-plate friction, hydrofracturing (Sibson, 1981), and the location of the décollement (e.g. Le Pichon et al., 1993; McIntosh and Sen, 2000). In addition, they also influence mass and fluid budgets (e;g. Saffer and Bekins, 1998), heat transfer (e. g. Hyndman et al., 1995) and the down-dip physical and chemical transformations of subducted material (e.g. Kastner et al., 1991). These transformations that occur as the plate drives deeper into the subduction zone are believed to play an important role on both the location of the seismogenic zone (e.g., Vrolijk, 1990) and the amount of co-seismic slip propagation (e.g., Moore and Saffer, 2001).

Physical properties of the SC material deeply rely on the kinematics, margin stress regime, sediment supply and water content, in combination with the age and crustal structures of both the downgoing and overriding-plates. At present day, the knowledge of the physical properties of the SC material is limited to direct measurements of sediment porosity/density and seismic velocity obtained during scientific drilling at the leading edge of sediment prism (<~4 km from the trench and <2 km below sea floor, bsf). This is the case, for example, of the accretionary prisms of Nankai (Moore et al., 2001) and Barbados (Mascle et al., 1988; Moore et al., 1995), as well as the frontal prism of Costa Rica (Bolton et al., 2000). In contrast, only few indirect estimates of subduction channel porosity and fluid content at greater depths and distances from the deformation front (>10 km) are available to date. Some of the few examples are the accretionary complexes of Barbados (Bangs et al., 1990) and Oregon (Cochrane et al., 1994; Yuan et al., 1994), where SC porosity and fluid pressures have been estimated based on Normal Move Out (NMO) velocity analysis of MCS data. Likewise, von Huene et al. (1998) used Prestack Depth Migration (PSDM) of MSC data to estimate porosity and dewatering at the accretionary margin of Alaskan. Finally, numerical modeling of consolidation and dewatering based on borehole chemical and physical data measured at the margin's toe has been also made in Barbados (Stauffer and Bekins, 2001) and Nankai (Saffer and Bekins, 1998).

In this paper, we use MCS data acquired across the erosional margin of southern Ecuador during the SISTEUR-2000 survey (Collot et al., 2002) to (1) identify the main structures of the margin, (2) obtain the seismic velocity field by means of PSDM, and correspondent depth-images, (3) calculate velocity-derived porosity at SC, as well as effective and pore pressure to quantify fluid overpressure variations and dewatering along some ~30 km of subduction, and (4) discuss the causes and implications of estimated physical properties, both across and along the strike of the margin.

2. Tectonic setting

At the South Ecuador margin, offshore the Gulf of Guayaquil, the Nazca plate subducts eastwards beneath South-America at ~55 mm/yr (Trenkamp et al., 2002) (Fig. 1). In addition to normal plate convergence, the Ecuador margin, as part of the so-called North Andean Block, moves north-eastwards in response to subduction obliquity in Colombia and strain partitioning of north-western South American plate. The North Andean Block motion occurs along a major NE-trending right-lateral strike–slip fault system (e.g. Winter et al., 1993; Ego et al., 1996) at a rate of ~6±2 mm/yr (Trenkamp et al., 2002). This motion is believed to have favored the opening the Gulf of Guayaquil by N–NE extension (Ego et al., 1996; Witt et al., 2006) (Fig. 1).

Recent work based on MCS and swath bathymetry data acquired during the SISTEUR survey shows that the Ecuador margin is dominantly erosional and characterized by extension (Collot et al., 2002; Calahorrano, 2005; Sage et al., 2006). Despite this overall erosional behaviour, the margin off the Gulf of Guayaquil is fronted by a ~3–10 km-wide sediment prism. The volume and nature of terrestrial sediment supplied to the trench or conveyed by the Nazca plate vary considerably along this area. This variability is mainly associated to the erosion and sediment transport of the Andes, the presence of the Grijalva Fracture Zone (GFZ) and the Carnegie Ridge, and the marine currents. The erosion of the Andean Western Cordillera provides several hundred meters of terrigenous sediments transported northwards to the trench by the Esmeraldas river, and southwards by the Guayas river up to the Gulf of Guayaquil (Fig. 1). Sand turbidites with abundant wood fragments characterizing the surficial trench deposits in the northern margin (Collot et al., 2005) corroborate the erosion/transport of clastic material, and illustrate sediment variation along the trench while contrasting this deposits with dark-green hemipelagic mud with high