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Abstract	The continental shelf and slope of southern Central Chile have been subject to a number of international as well as Chilean research campaigns over the last 30 years. This work summarizes the geologic setting of the southern Central Chilean Continental shelf (33°S–43°S) using recently published geophysical, seismological, sedimentological and bio-geochemical data. Additionally, unpublished data such as reflection seismic profiles, swath bathymetry and observations on biota that allow further insights into the evolution of this continental platform are integrated. The outcome is an overview of the current knowledge about the geology of the southern Central Chilean shelf and upper slope. We observe both patches of reduced as well as high recent sedimentation on the shelf and upper slope, due to local redistribution of fluvial input, mainly governed by bottom currents and submarine canyons and highly productive upwelling zones. Shelf basins show highly variable thickness of Oligocene-Quaternary sedimentary units that are dissected by the marine continuations of upper plate faults known from land. Seismic velocity studies indicate that a paleo-accretionary complex that is sandwiched between the present, relatively small active accretionary prism and the continental crust forms the bulk of the continental margin of southern Central Chile.

Keywords (separated by '-')	Southern Central Chile - Bathymetry - Shelf sedimentation - Shelf basins - Submarine faults - Seismicity - Fluid seepage
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ORIGINAL PAPER

Morphology and geology of the continental shelf and upper slope of southern Central Chile (33°S–43°S)

David Völker · Jacob Geersen · Eduardo Contreras-Reyes · Javier Sellanes · Silvio Pantoja · Wolfgang Rabbel · Martin Thorwart · Christian Reichert · Martin Block · Wilhelm Reimer Weinrebe

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Abstract The continental shelf and slope of southern Central Chile have been subject to a number of international as well as Chilean research campaigns over the last 30 years. This work summarizes the geologic setting of the southern Central Chilean Continental shelf (33°S–43°S) using recently published geophysical, seismological, sedimentological and bio-geochemical data. Additionally, unpublished data such as reflection seismic profiles, swath bathymetry and observations on biota that allow further insights into the evolution of this continental platform are integrated. The outcome is an overview of the current knowledge about the geology of the southern Central Chilean shelf and upper slope. We observe both patches of reduced as well as high recent sedimentation on the shelf and upper slope, due to local redistribution of fluvial input, mainly governed by bottom currents and submarine canyons and highly productive upwelling zones. Shelf basins show highly variable thickness of Oligocene-Quaternary sedimentary units that are dissected by the marine continuations of upper plate faults known from land. Seismic velocity studies indicate that a paleo-accretionary complex that is sandwiched between the present, relatively small active accretionary prism and the continental crust forms the bulk of the continental margin of southern Central Chile.

Keywords Southern Central Chile · Bathymetry · Shelf sedimentation · Shelf basins · Submarine faults · Seismicity · Fluid seepage

Introduction

The southern Central Chilean continental margin has been subject to geological and geophysical research for the last

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decades, resulting in a variety of different data sets from international and Chilean research cruises (Table 1). Some of the data are published in international peer-reviewed journals, but a number of data sets, and in particular those collected over recent years, remain yet unpublished. In addition, a few review articles and book chapters combine and summarize aspects of the conducted research, and especially the book "The Andes-Active Subduction Orogeny" (Oncken et al. 2006) provides an important overview. However, no review article summarizes the geologic setting of the continental shelf and uppermost slope of southern Central Chile. Here, we tie together the current knowledge about the geology of that part of the Chilean Shelf that has the best data coverage (between 33°S and 43°S) by reviewing previously published data sets and expand this knowledge by adding previously unpublished seismic reflection, bathymetric, seismological and biological data as well as data sets that were published in cruise reports and doctoral theses. The new data include (1) today's most comprehensive bathymetric data which we produced from swath bathymetric data of eight scientific cruises (Weinrebe et al. 2011) merged with a bathymetric data set of Zapata (2001); (2) unpublished sediment-echosounder data from the continental slope; (3) an unpublished seismic reflection line that runs N–S from 36.75°S to 40°S (SO161-25). The information that is assembled in this work covers the region with a highly variable density. While we provide seismic insights into some forearc basins (Arauco and Valdivia Basin, Fig. 1), we lack similar data of neighbouring basins. In total, there is still a lack of data for the comprehensive understanding of the continental shelf, such as of bathymetric mapping campaigns of the shelf, margin-parallel seismic reflection profile studies, drilling transects and bottom current measurements.

Geologic and tectonic framework of the southern Central Chilean continental margin

The convergent continental margin of southern Central Chile between 33°S and 43°S is characterized by a trench that is filled by up to 2.5 km of sediment. This sediment-filled part of the Peru–Chile Trench is limited by two elevated topographic features of the oceanic crust, the Juan Fernández Ridge that enters the subduction zone at 32°S and the Chile Ridge that subducts at the Chile Triple Junction at around 46°S (Fig. 1). The main structural elements across the marine part of the continental margin are the 40–80 km wide Peru–Chile Trench Basin, a young (late Pliocene–Pleistocene) frontal accretionary prism at the lower slope that is 5–40 km wide (Bangs and Cande 1997; Contreras-Reyes et al. 2010; Geersen et al. 2011a), a relatively smooth upper continental slope with sedimentary slope basins, thrust ridges, deeply incised submarine canyon systems and mass-wasting features and a continental shelf that is dissected by submarine canyons and partly shaped by mass-wasting features (Fig. 1; detailed maps Figures 2–6).

The tectonic framework of the southern Central Chilean continental margin is controlled by the subduction of the oceanic Nazca Plate underneath the South American Plate (Fig. 1). The Nazca Plate subducts obliquely with an angle of 80.1° at a rate of 66 mm/a (Angermann et al. 1999). The subduction rate has varied in the past and decreased ~40 % over the last 20 Ma (Somoza 1998; Oncken et al. 2006). The volume of the 5–40 km wide accretionary prism is not compatible with a continuous history of accretion over time periods of tens of millions of years, which implies episodic phases of tectonic accretion, non-accretion and erosion (Bangs and Cande 1997). Melnick and Echtler (2006a) argued that during Pliocene the margin shifted from erosive to accretionary mode in response to an increase in trench sedimentation rate, linked to fast denudation of the Andes and a coeval decrease of the subduction rate. Similarly, Kukowski and Oncken (2006) suggested that the southern Central Chile subduction zone has been in accretion mode since the Pliocene, following on a period of subduction erosion that started at least in the middle Miocene. The subduction process impacts on the evolution of the shelf and upper slope of southern Central Chile in a number of ways:

1. The subduction of submarine ridges, seamounts and thickened crust has led to mass removal and local subsidence of the marine forearc, for example at 33°S where the subduction of the Juan Fernandez Ridge is taking place. This process created accommodation space for marine forearc basins on the upper continental slope that form important depocentres for sediments close to the continental shelf (von Huene et al. 1997; Laursen et al. 2002).
2. Basal accretion of underthrust trench sediments has been made responsible for focused and localized uplift of coast and shelf segments in particular off Arauco Peninsula (Lohrmann et al. 2006). Here, ~1.5 km of uplift during Middle Pliocene has been reported (Melnick and Echtler 2006a; Melnick et al. 2006).
3. Oblique subduction of the Nazca Plate is responsible for the development of a forearc sliver, the Chiloé Microplate, that extends from the Chile Triple Junction at ~46°S to the Arauco Peninsula at ~38°S (Melnick et al. 2009). The Chiloé Microplate is decoupled from the stable South American Plate along the Liquiñe-Ofqui Fault Zone (LOFZ, Fig. 1), a prominent margin-parallel fault system that has been active in a transpressional dextral motion since the Pliocene (Cembrano et al. 2000; Rosenau 2004; Rosenau et al.

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Table 1 Meta-information on cruises of German vessels SONNE and METEOR as well as raw bathymetric data sets are stored at the Bundesamt für Seeschiffahrt und Hydrographie (BSH) at http://www.bsh.de

Inventory of scientific cruises and geophysical data offshore southern Central Chile

Ruise/ship expedition	Method	Data	Latitudes	Partly published in	Cruise reports or chief scientist
RV SONNE SO101-102	Swath bathymetry	Along track	21°S–44°S	von Huene et al. (1997), this study	Hebbeln and Wefer (1995)
	Sediment echosounder	Along track			
	Reflection seismics	37 profiles		Flueh et al. (1998)	
				Laursen et al. (2002)	
				Laursen and Normark (2003)	
	Multicores	42 cores		Lamy et al. (1998, 2001)	
				Hebbeln et al. (2000)	
	Gravity cores	63 cores		Lamy et al. (1999)	
RV SONNE SO103	Swath bathymetry	Along track	31.5°S–34°S	This study	Flueh (1995)
	Sediment echosounder	Along track			
RV SONNE SO104	Swath bathymetry	Along track	20°S–32°S	Laursen and Normark (2002), this study	R. von Huene
	Sediment echosounder	Along track			
	Reflection seismics	14 profiles		von Huene et al. (1997)	
				Laursen et al. (2002)	
				Laursen and Normark (2002)	
				Ranero et al. (2006)	
RV SONNE SO156	Swath bathymetry	Along track	22°S–44°S	This study	Hebbeln (2001)
	Sediment echosounder	Along track			
	Multicores	163 cores		Muñoz et al. (2004)	
				Stuut et al. (2007)	
	Gravity cores	91 cores			
RV SONNE SO161	Swath bathymetry	Along track	23°S–38°S	This study	Reichert (2002)
	Sediment echosounder	Along track		This study	Flueh et al. (2002)
	Reflection seismics	35 profiles		Rauch (2005)	Wiedicke-Hombach (2002)
				Ranero et al. (2006)	
				Völker et al. (2006)	
				Contreras-Reyes et al. (2008)	
				Rodrigo et al. (2009)	
				Geersen et al. (2011b)	
	Gravity cores	29 cores		Völker et al. (2008)	
				Blumberg et al. (2008)	

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Table 1 continued

Inventory of scientific cruises and geophysical data offshore southern Central Chile

Ruise/ship expedition	Method	Data	Latitudes	Partly published in	Cruise reports or chief scientist
RV SONNE SO181	Swath bathymetry	Along track	31°S–47°S	This study	Flueh and Grevemeyer (2005)
	Sediment echosounder	Along track			
	Reflection seismics	4 profiles		Contreras-Reyes et al. (2008, 2010)	
				Scherwath et al. (2009)	
	Gravity cores	16 cores		Heberer et al. (2010)	
RV SONNE SO210	Swath bathymetry	Along track	33°S–38.5°S	Völker et al. (2012)	Linke (2011)
				Völker et al. (2011), this study	
	Sediment echosounder	Along track		This study	
	Gravity cores	14 cores		This study	
RRS James Cook JC23	Swath bathymetry	Along track	33°S–38°S	Völker et al. (2009)	Flueh and Bialas (2008)
				Geersen et al. (2011a), this study	
	Gravity cores	13 cores		Völker et al. (2009)	
	Sidescan sonar	4 profiles		Klaucke et al. (2012)	
	Wide-angle seismic	4 profiles		Moscoso et al. (2011)	
R/V CONRAD 2901	Reflection seismics	6 profiles	32°S–40°S	Bangs and Cande (1997)	
				Díaz-Naveas (1999)	
				Contreras-Reyes et al. (2008)	
				Scherwath et al. (2009)	
				Geersen et al.(2011a)	
R/V VIDAL GORMAZ 1994 (Thioplaca)	Multicores	5 cores		Fossing et al. (1995)	
				Lamy (1998)	
				Hebbeln et al. (2000)	
R/V VIDAL GORMAZ VG02	Swath bathymetry	Along track	31°S–34°S	This study	J. Díaz-Naveas
	Reflection seismics	18 profiles		Contardo et al. (2008)	
R/V VIDAL GORMAZ VG06	Swath bathymetry	Along track	32.5°S–37°S		J. Díaz-Naveas
	Reflection seismics			Contardo et al. (2008)	
RV METEOR M67	Swath bathymetry	Along track	33°S–37°S	This study	Weinrebe and Schenk (2006)
	Sediment echosounder	Along track			
	Gravity cores	8 gravity cores			
RV MELVILLE MV1004	Swath bathymetry	Along track	34°S–38°S		C. D. Chadwell
ODP leg 202	Drill cores	ODP sites 1233, 1234, 1235	35°S–40°S	Blumberg et al. (2008)	Mix et al. (2003)

Metadata on cruises of US research vessels are stored at the Geological Data Center of the Scripps Institute of Oceanography: http://gdc.ucsd.edu/

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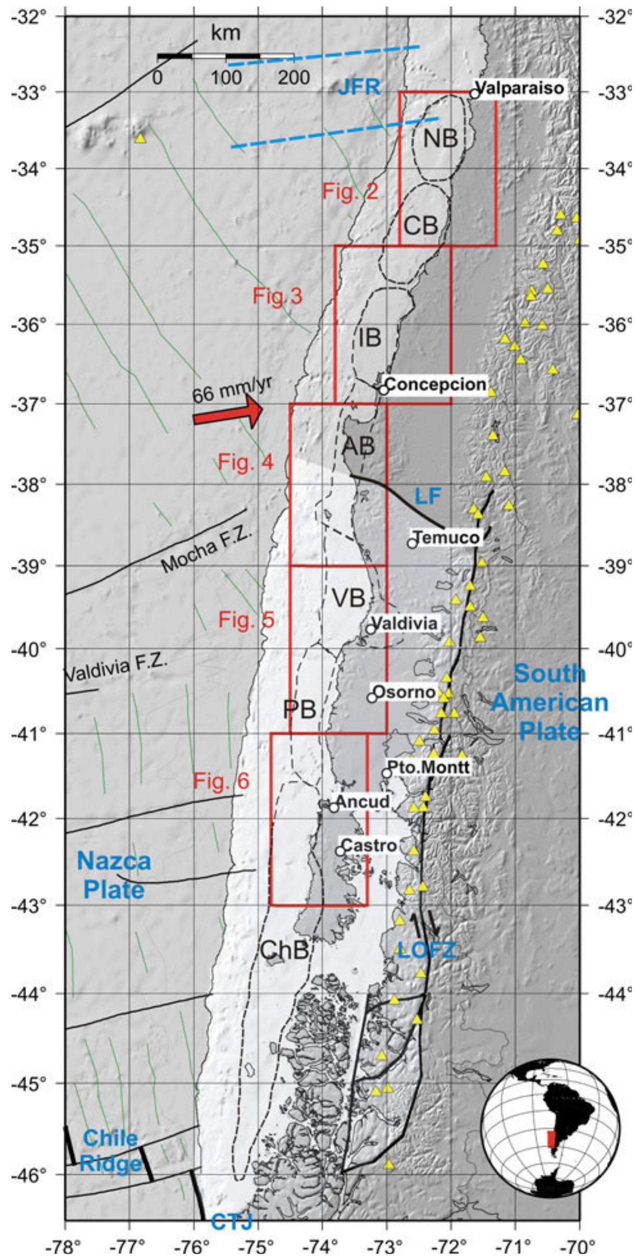

Fig. 1 Overview map of southern Central Chile with main tectonic units. *Boxes* indicate the positions of Figures 2–6. The *lighter shaded* area corresponds to the outline of the Chiloé Microplate (Melnick et al. 2009). The position of shelf basins (*stippled lines*) is according to Melnick and Echtler (2006b). *Yellow triangles* are Quaternary volcanoes of the Southern Volcanic Zone (Siebert and Simkin 2002). *LOFZ* Liquiñe-Ofqui Fault Zone, *LF* Lanalhue Fault, *JFR* Juan Fernández Ridge, *CTJ* Chile triple junction, *NB* Navidad Basin, *CB* Chanco Basin, *IB* Itata Basin, *AB* Arauco Basin, *VB* Valdivia Basin, *PB* Pucatrihue Basin, *ChB* Chiloé Basin

2006; Thomson 2002). The collision of the Chiloé Microplate that moves northward at a present rate of 6.5 mm/a (Wang et al. 2007) with the South American Plate in the region of the Arauco Peninsula is a likely cause for the existence of a number of SE-NW trending upper plate faults that are mapped in the terrestrial forearc (Melnick and Echtler 2006b; Melnick et al. 2009). Active shortening across such faults caused the orogenesis of the Nahuelbuta Coastal Range (Melnick et al. 2009). An indirect consequence of the differential uplift is the shift and reorganization of river networks on land and their respective submarine continuations (canyon systems) that cut deeply into the shelf and continental slope (Rehak et al. 2008).

4. The Chilean subduction zone produces powerful megathrust earthquakes of Mw > 8 almost in decadal intervals (e.g. Bilek 2010), and the historic record shows that these recur in spatially defined seismotectonic segments of the forearc (Lomnitz 2004). In the study area, the Mw 9.5 Great Chile Earthquake of 22 May 1960 and the Mw 8.8 Maule Earthquake of 27 February 2010 stand out as the largest and sixth largest ever instrumentally recorded earthquakes in the world. The earthquakes have historical recurrence times of 100–200 years per segment and cause coseismic horizontal motions of some 10 m and vertical motions of some metres of the coastal areas and the shelf (Cifuentes 1989; Barrientos and Ward 1990; Cisternas et al. 2005; Moreno et al. 2009; Farías et al. 2010). Megathrust earthquakes were historically and recently associated with tsunamis that devastated coastal areas and deposited specific tsunami deposits in estuaries (Cisternas et al. 2005; Vargas et al. 2011).

Climate

The denudation rate of the Andes shows a distinct climatic component related to Hadley cell-driven precipitation regimes (Montgomery et al. 2001). The central part of the range (15°S–33°S) is in the subtropical belt of deserts, where there is little precipitation on either side of the range. To the south, Westerlies bring abundant moisture that precipitates at the western slopes of the Andes, resulting in a significant increase in the mean annual precipitation rate from <0.5 m/y at around 30°S to 2–3 m/y south of 38°S (Hoffmann 1975) and a mean annual river run-off of 0.25–0.5 mm/y (Fekete et al. 2000). In the vicinity of the Chile Triple Junction (46°S), apatite fission track ages from the western flank of the Andes imply that 3–4 km of denudation occurred in this region since ~17 Ma (Haschke et al. 2006).

Oceanographic features

The poleward Gunther Undercurrent (or Poleward Undercurrent) at 0.2–0.5 km water depth flows close enough to the edge of the shelf to induce coast-parallel southward

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sediment transport. Current velocities from 0.1 to 0.5 m/s at depths of 100–300 m were measured (Huyer et al. 1991; Pizarro et al. 2002). Shaffer et al. (1995, 1997, 1999) reported a mean value of 0.128 m/s and a maximum value of 0.689 m/s over a period of 6 years.

The coasts of Valparaíso and Concepción are well known zones of intense coastal upwelling (e.g. Djurfeldt 1989; Figueroa and Moffat 2000). These conditions lead to extremely high biogenic productivity (Daneri et al. 2000; Atkinson et al. 2002) and carbon fixation resulting in annual production rates of >200 g C/m^2 (Berger et al. 1987) which has a pronounced impact on the slope sedimentation (Hebbeln et al. 2000). South of 38°S, prevailing onshore winds of the Westerlies generally prevent coastal upwelling (Strub et al. 1998), but nonetheless areas of high primary productivity exist south of 40°S. Hebbeln et al. (2000) propose either advection of the Antarctic Circumpolar Current and/or river input as nutrient sources that sustain this effect. Tidal currents can have a strong effect on local deposition as they are very strong at the outlets of estuaries and in particular at the outlet of the Gulf of Ancud, the Chacao Channel (~4 m/s, Cáceres et al. 2003, Fig. 6).

Sediment input

The main source area for sediments deposited at the southern Central Chile continental margin is the western flank of the Andean Cordillera. Sediments are brought to the Pacific Ocean mainly by river systems (Lamy et al. 1998, 1999) that emerge from the Andean Cordillera, cross the Central Valley of Chile and the Coastal Cordillera and partly continue in submarine canyon systems. A fraction of the clastic material eroded from the Andes forms the fill of the Central Valley, another fraction is deposited in sedimentary basins of the submarine forearc and the open slope or is temporarily stored in the submarine canyons (Raitzsch et al. 2007). A second source of sediments is the Coastal Cordillera that reaches elevations of 2,200 m in the Valparaíso region (33°S) and almost 1,600 m in the Cordillera de Nahuelbuta (~37.5°S, Fig. 4). Strong precipitation and high river discharge transport huge amounts of terrigenous matter to the ocean between 35° and 39°S (suspended particles = 600–2,500 ton per month; http://www.dga.cl; Muñoz et al. 2004).

The Southern Volcanic Zone (SVZ) of the Andes (33°S–46°S) is associated with the Nazca Plate subduction (López-Escobar et al. 1993). The SVZ includes at least 60 historically and potentially active volcanic edifices in Chile and Argentina, three giant silicic caldera systems (Maipo, Calabozos and Caviahué) and numerous minor eruptive centres (Siebert and Simkin 2002; Stern 2004; Stern et al. 2007). Explosive volcanism has led to the deposition of ash fallout deposits in prehistoric and historic eruptions (e.g. Hildreth et al. 1984; Haberle and Lumley 1998; Naranjo and Stern 1998, 2004; Hildreth and Drake 1992; Sruoga et al. 2005), and the tephra layers are widespread over Chile and Argentina. A fraction of this volcanic ash has been deposited offshore (ODP leg 202 sites 1233, 1234,1235, Mix et al. 2003; Völker et al. 2006, 2009; Linke 2011).

The third major source of sediment particles is the biogenic production related to the coastal upwelling zones. Biogenic constituents vary in abundance and consist primarily of nannofossils and diatoms with less abundant silicoflagellates and foraminifers in general (Mix et al. 2003). Variations in the abundance and species composition of foraminifera are related to water productivity and regional variations of upwelling (Hebbeln et al. 2000). Patches of authigenic carbonates are observed at the seafloor in areas where methane seepage is reported (Linke 2011). The microbial process of anaerobic oxidation of methane is, however, mainly restricted to the Oxygen Minimum Zone below ~800 m water depth and is related to the high productivity areas of coastal upwelling (Treude et al. 2005).

Morphology of the continental shelf and upper slope

The morphological information described here and presented in Figs. 2, 3, 4, 5, 6 is the result of joining swath bathymetry data that were recorded on 12 cruises of research vessels SONNE, METEOR, VIDAL GORMAZ and JAMES COOK between 1995 and December 2010 (Table 1) and that mainly cover the continental slope with a gridded Chilean data set of the shelf morphology (Zapata 2001). The swath bathymetry data, in total more than 8,000 data files comprising about 1.1 billion soundings, were recorded with different swath bathymetry systems, but mostly with the Kongsberg EM-120 system. We processed the raw data using the MB-Systems software (Caress et al. 1996). Processing steps comprised the check of navigation data, interpolation of missing navigation values, calculation of water depth and positions of the footprints of the beams by ray tracing through the water column and removal of artefacts and erroneous data points. Processed data of the bathymetric systems were then combined into digital elevation models (DEMs) with a grid point density of 200 m. Then, we merged the grids with a clipped version of the gridded bathymetry data of Zapata (2001). The Zapata data set has a lower grid point density of about 800 m and lacks many details that show up in the raw bathymetry data, but as those seldom cover the shelf we use the Zapata data set as background information. We clipped the Zapata data to the water depth range of 0–400 m and included them to the grid

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calculation with a low weighting factor for the splines calculation of new grid points. The resulting grid is satisfactory for most of the shelf and slope areas, and however in some places, the interpolation between the high-density raw and low-density gridded data produces artefacts which we had to remove manually. Finally, the grids were combined with the land topography data of the Shuttle Radar Topography Mission (SRTM; Farr 2007).

Between 33°S and 43°S, the continental shelf is relatively narrow with a mean width of 30–40 km (Figs. 2, 3, 4, 5, 6). The width of the shelf from the coast to the shelf break at ~200 m water depth is narrower offshore prominent promontories as well as where the Coastal Cordillera is close to the coast such as offshore Valparaíso (33°S) and Pichilemu (34.5°S) (width 20 km), while coastal embayments such as the Golfo de Arauco (37°S) form regions of a wider continental platform (width 40 km). The maximum width is offshore Arauco Peninsula at Mocha Island and offshore Chiloé Island (~60 km).

At 41.8°S, the N–S trending coastline is interrupted by the Canal de Chacao that separates Chiloé Island from the mainland (Fig. 6). As the continental forearc subsides to the south, the Coastal Cordillera continues as the backbone of Chiloé Island, whereas the southward continuation of the Chilean Central Valley is drowned to form the shallow (<250 m) Golfo Corcovado and Golfo de Ancud between the mainland and Chiloé Island. This 45-km-wide (E–W) and 90-km-long (N–S) gulf is a semi-enclosed marine forearc basin in the back of Chiloé Island that is protected from the direct Pacific swell and unique

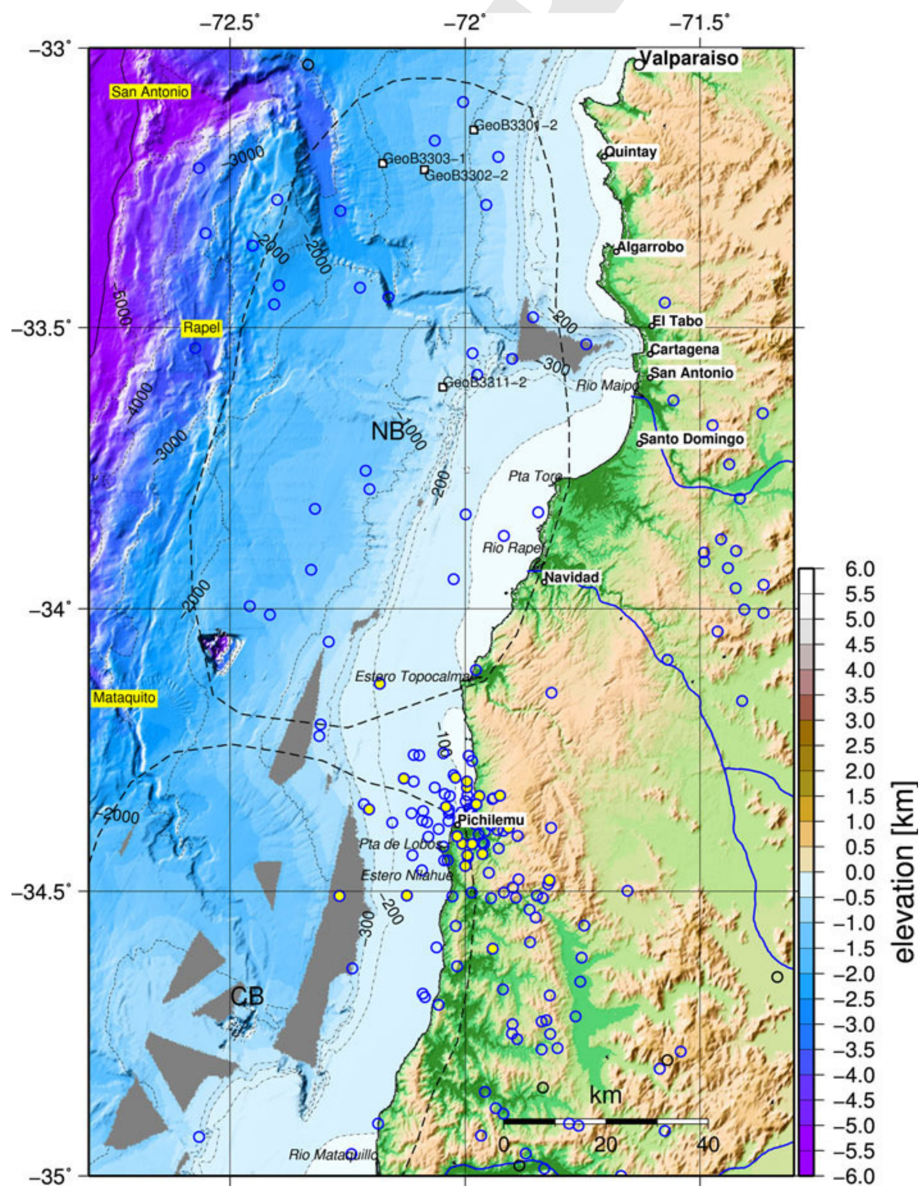

Fig. 2 Bathymetric map of the Chilean shelf and upper slope from 33°S to 35°S. *Blue circles* denote epicentres of aftershocks of the Feb 27, 2010, Mw 8.8 Maule earthquake (Servicio SismológicoLine 444: Either “of Jurassic age and” or “inner prism, presumably of Jurassic age, represents” de Chile, ssn.dgf.uchile.cl, time window of 27.02.2010–13.04.2010). The Pichilemu seismic sequence of the 11.03.2010 (Farías et al. 2011) is highlighted by *yellow fill*. *Square symbols* indicate sediment samples described by Hebbeln et al. (2000) and Lamy et al. (1998). *Stippled black lines* correspond to outlines of shelf basins. Bathymetric information is composed of a data set of a number of RV SONNE cruises, RRS JAMES COOK cruise JC23 and a shallow-water data set compiled by Zapata (2001). Land topography was extracted from the SRTM data set (Farr et al. 2007), absence of bathymetric information is indicated as *grey areas*. Slope canyon names are in *yellow boxes*

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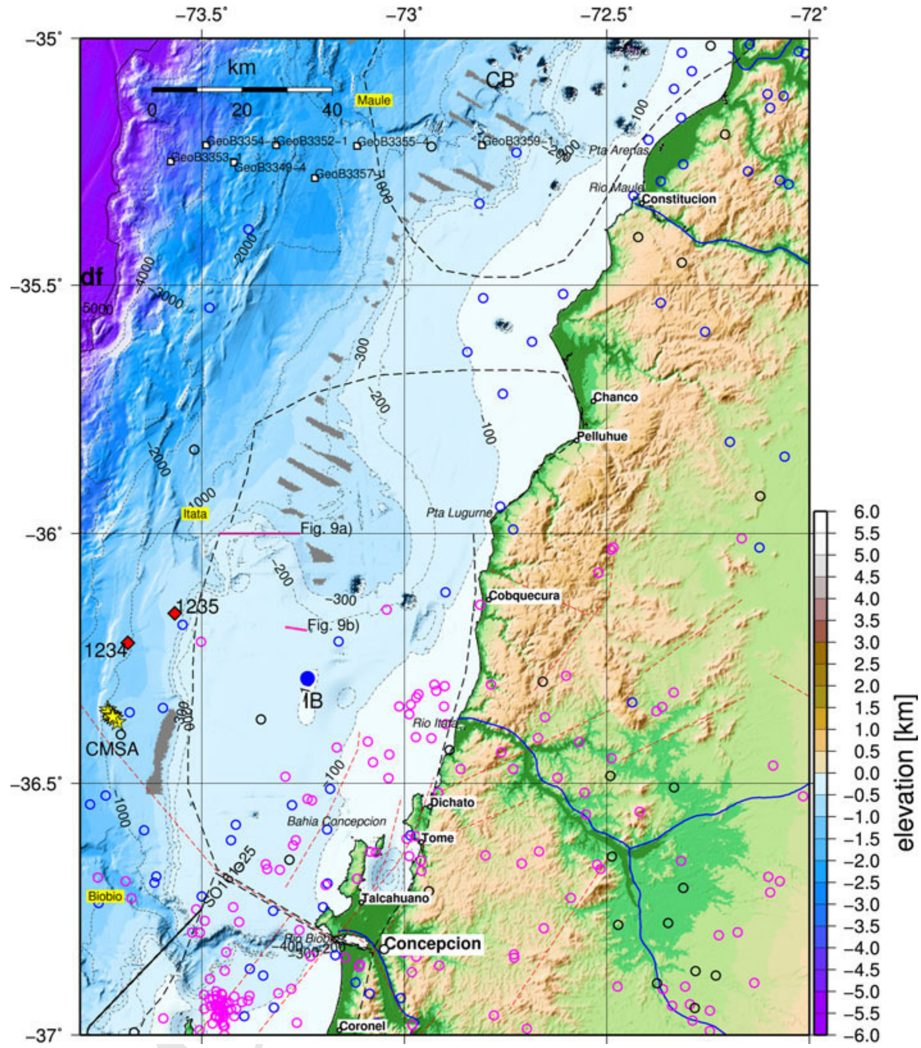

Fig. 3 Bathymetric map of the Chilean shelf and upper slope from 35°S to 37°S (Maule Province). *Black lines* indicate the position of seismic profiles of the SPOC project shot on RV SONNE cruise SO161 (Reichert 2002). *Pink lines* indicate PARASOUND sediment-echosounder profiles that are referred to in the text. *Circles* denote epicentres of main and aftershocks of the Maule earthquake (Servicio Sismológico de Chile, ssn.dgf.uchile.cl, time window of 27.02.2010–13.04.2010 *blue*, main shock: *blue filled*) and of Bohm et al. 2002 (*magenta*). *Red diamonds* indicate ODP leg 202 drill sites. *Square* symbols indicate sediment samples described by Hebbeln et al. (2000) and Lamy et al. (1998). *CMSA* concepción methane seepage area. *Yellow stars* show observations of biocommunities related to gas seepage (Sellanes et al. 2004; Sellanes and Krylova 2005). *Stippled black lines* correspond to outlines of shelf basins. Absence of bathymetric information is indicated as *grey areas*

for Chile in this respect. With the subsidence of the Central Valley to below sea level, the coastline south of 42°S directly touches the Central Cordillera of the Andes and forms a fjord coast.

The shelf edge lies at a water depth range of 150–300 m. It is well defined where the shelf is wider such as offshore the Golfo de Arauco (37°S, Fig. 4), west of Mocha Island (38.2°S Fig. 4) and offshore Chiloé Island. Offshore Arauco Peninsula, the shelf edge is at some places indented by headscarps of ancient giant slope failures (Geersen et al. 2011b).

The upper continental slope shows a relatively smooth morphology and is inclined at low angles (2–4°) to a water depth of 2,000 m. Below 2,000 m water depth, the slope morphology is less regular with steep slope segments (up to 30°) alternating with roughly trench-parallel belts of less steep and even landward verging seafloor. This irregular morphology is caused by the continuous deformation of the ~4 Ma young accretionary prism that forms the lower continental slope.

Submarine canyon systems

A number of submarine canyons dissect the continental slope and partly cut into the shelf to connect directly to feeding river systems. We use the nomenclature of Rodrigo (2010). From north to south, the submarine canyons are (1) San Antonio Canyon, connected to the mouth of Río Maipo (Hagen et al. 1996; Laursen and Normark 2002, Fig. 2); (2) Rapel Canyon; (3) Mataquito Canyon between 34°S and 34.7°S that is possibly linked to Río Mataquillo/Mataquito (Fig. 2); (4) Maule Canyon, connected to Río Maule (Fig. 3); (5) Itata Canyon, connected to Río Itata (Fig. 3); (6) the prominent BíoBío Canyon (with its major confluence Santa Maria Canyon) that cuts deep into the shelf and forms a direct continuation of the BioBío River (Fig. 3); (7) Lleulleu Canyon (or Paleo-Pellahuen Canyon) directly north of Mocha Island once formed the marine continuation of Pellahuen River before the latter was deflected due to uplift of Arauco Peninsula according to Rehak et al. (2008, Fig. 4); (8) Imperial Canyon is a canyon that is

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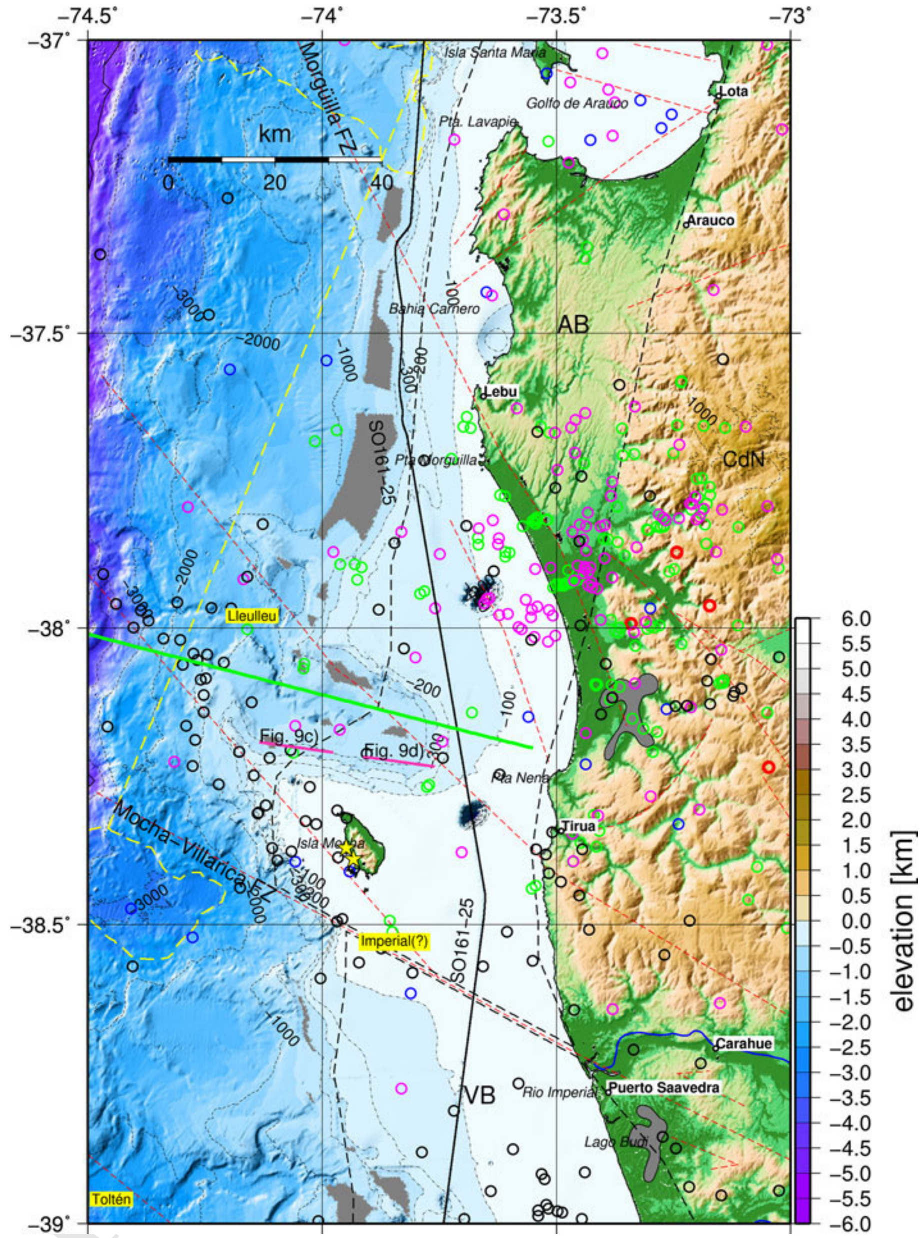

Fig. 4 Bathymetric map of the Chilean shelf and upper slope from 37°S to 39°S (Arauco Peninsula). *Black lines* indicate the position of seismic profiles of the SPOC project shot on RV SONNE cruise SO161 (Reichert 2002). *Pink lines* indicate PARASOUND sediment-echosounder profiles that are referred to in the text. *Yellow stippled lines* denote headwall and sidewalls of giant slope failures of Geersen et al. (2011b). *Circles* denote epicentres (*blue*: main and aftershocks of the Maule earthquake, Servicio Sismológico de Chile, ssn.dgf.uchile.cl/, *magenta*: Bohm et al. 2002, *red*: main and aftershocks of the 1960 earthquake, Engdahl and Villaseñor 2002 in the time window of 21.05–25.05.1960, *green*: Haberland et al. 2006, *black*: Dzierma et al. submitted). *Yellow stars* show observations of gas seepage at Mocha Island (Jessen et al. 2010). The wide-angle seismic profile of Contreras-Reyes et al. (2008) is depicted as *green line*. *Red stippled lines* show tectonic faults mapped on land between 36°S and 42°S by Melnick and Echtler (2006b). *CdN* Cordillera de Nahuelbuta. *Stippled black lines* correspond to outlines of shelf basins. Absence of bathymetric information is indicated as *grey areas*

supposed to incise the shelf directly south of Mocha Island but is unresolved in our data set as we lack precise shelf bathymetry and as the slope is deformed by a giant slope failure (Geersen et al. 2011b); (9) Tolten Canyon might be related to the river systems of Tolten and Imperial, but we lack precise bathymetric data of the shelf area to test the relationship (Fig. 4); (10 and 11) Lingue Canyon and Callecalle Canyon, two closely spaced submarine canyon systems lie offshore Valdivia: the northern one seems to be related to the exit of Río Valdivia, whereas the southern one might rather be connected to Río Bueno (Fig. 5). Both canyons were confusingly referred to as Río Bueno, CalleCalle or Tolten Canyons (Thornburg et al. 1990; Völker et al. 2006; Raitzsch et al. 2007; Rehak et al. 2008); (12) Chaihuin Canyon south of Valdivia is not resolved in our data; (13) Chacao Canyon in continuation of the Chacao Channel (Fig. 6) and (14) Cucao Canyon offshore Chiloé Island (Fig. 6). As a number of the canyons cut deeply into the shelf, they should form effective traps for sediment that is transported coast-parallel on the shelf by bottom currents.

The role that canyon systems play in supplying sediment to the trench is evidenced by the submarine fan systems that exist at the exits of the larger canyons (Valdivia Canyon, Tolten Canyon, BioBio Canyon). These submarine fans are asymmetrical and their northern (downslope) morphology contrasts to their southern (upslope) morphology as they have compositional structures (fan lobes) to the south and lag deposits and erosional structures

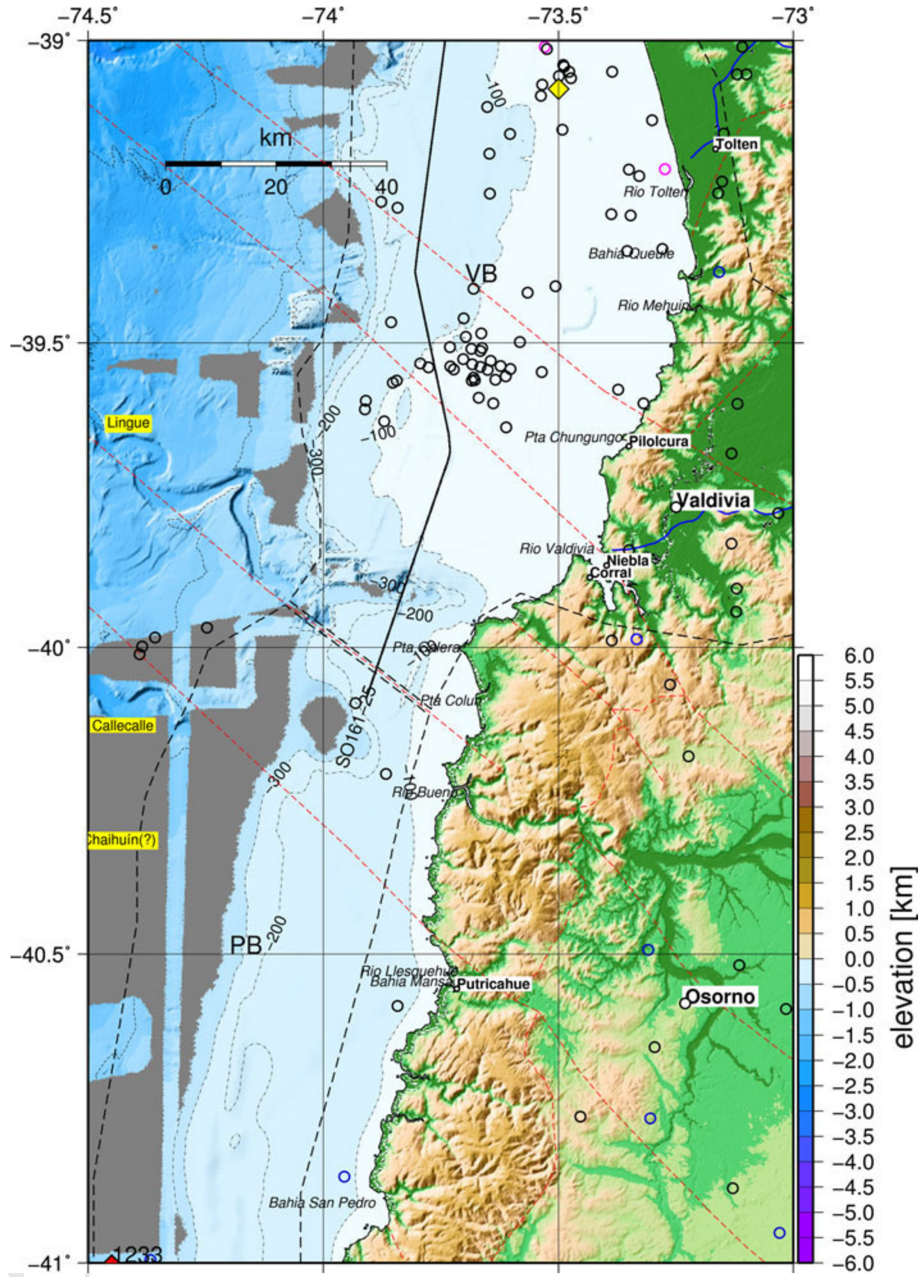

Fig. 5 Bathymetric map of the Chilean shelf and upper slope from 39°S to 41°S (Valdivia). *Black lines* indicate the position of seismic profiles of the SPOC project shot on RV SONNE cruise SO161 (Reichert 2002). *Circles* denote epicentres (*blue*: main and aftershocks of the Maule earthquake, Servicio Sismológico de Chile, ssn.dgf.uchile.cl/, *magenta*: Bohm et al. 2002, *black*: Dzierma et al. submitted) *Red stippled lines* show tectonic faults mapped on land between 36°S and 42°S by Melnick and Echtler (2006b). A *yellow diamond* refers to an exploration well, referenced in the text. *Stippled black lines* correspond to outlines of shelf basins. Absence of bathymetric information is indicated as *grey areas*

(furrows) to the north (Thornburg et al. 1990; Völker et al. 2006, 2008). Within the Peru–Chile Trench, a submarine channel of 3–5 km width and up to 200 m depth (the Chile Axial Channel) that is inclined northwards cuts into the flat-lying trench sediments (Völker et al. 2006). At its southern end, the channel appears to be in direct continuation of the Chacao Canyon from where it continues northward over more than 1,000 km to the Juan Fernández Ridge and possibly beyond. The distributary channels of most submarine fans connect directly to this axial channel, in a way that it appears to form a natural northward pathway for sediments that exit from the submarine canyons. At the exit of the San Antonio Canyon, sediments have ponded behind an accretionary ridge and were deposited as overbank deposits to the south of a distributary channel that breaches the ridge (Laursen and Normark 2002).

Forearc Basins and upper plate fault zones

Between 33°S and 43°S, a number of marine shelf forearc basins are known from seismic and petroleum exploratory well investigations of the Chilean state oil company Empresa Nacional del Petróleo (ENAP) (Mordojovic 1981; González 1989, Fig. 1). Two of these basins (Arauco and Valdivia Basin) were covered by seismic sections of RV

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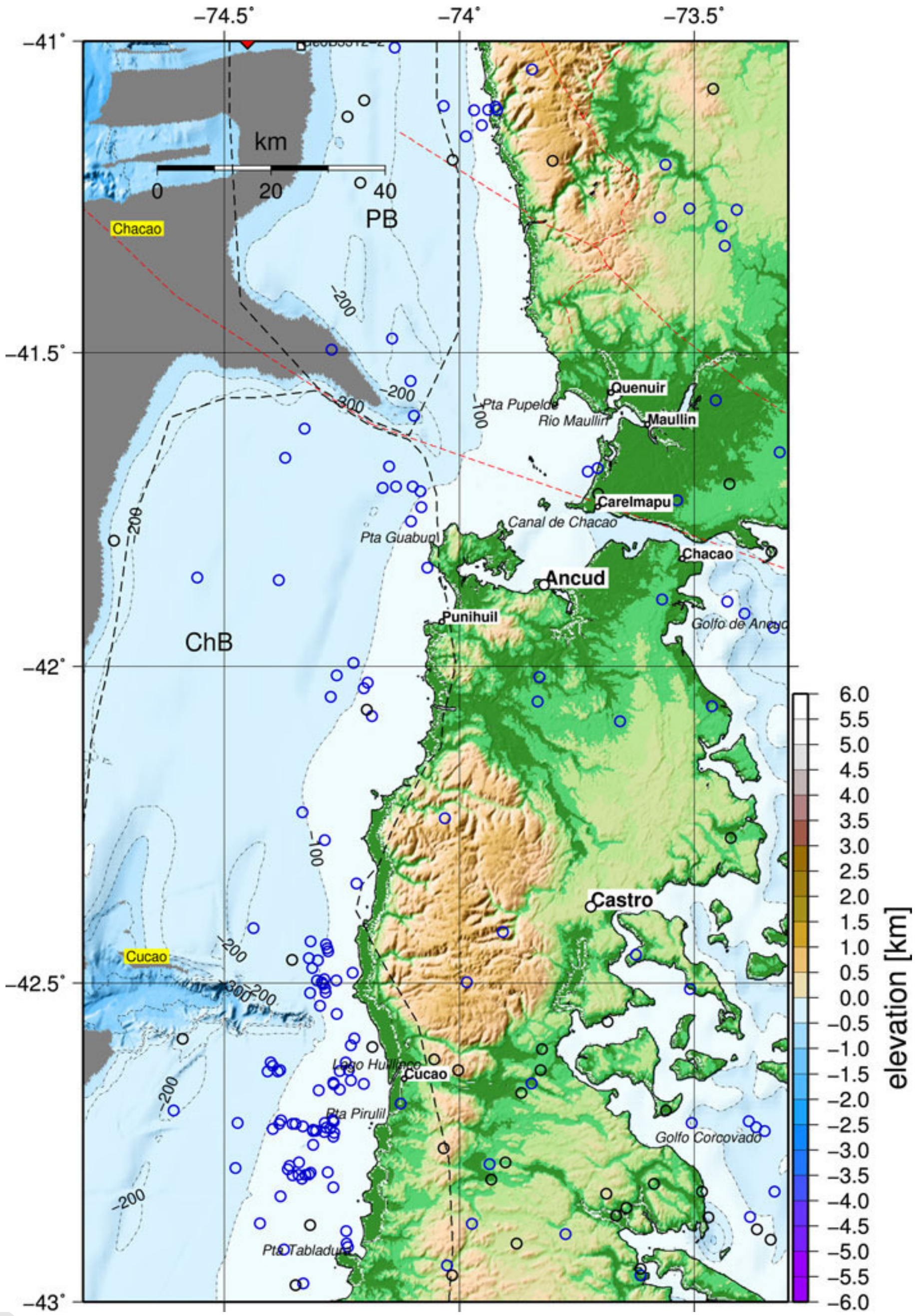

Fig. 6 Bathymetric map of the Chilean shelf and upper slope from 41°S to 43°S (Chiloé Island). *Circles* denote epicentres (*black*: Dzierma et al. submitted, *dark blue*: Lange et al. 2007). *Red stippled lines* show tectonic faults mapped on land between 36°S and 42°S by Melnick and Echtler (2006b). *Stippled black lines* correspond to outlines of shelf basins. Absence of bathymetric information is indicated as *grey areas*

SONNE cruise SO161 (Reichert 2002) as part of the project “Subduction Processes off Chile” (SPOC) in 2001. We show a 375-km-long deep reflection seismic line (SO161-25, Fig. 7) that roughly follows the trend of the coast line (Figs. 3, 4, 5) in combination with the stratigraphic information from Mordojovic (1981) and González (1989) to document the structure of the two forearc basins. We further trace the positions of upper plate faults in the marine forearc and investigate their impact on basin structure.

From North to South, shelf forearc basins are Navidad, Chanco, Itata, Arauco, Valdivia, Pucatrihue and Chiloé basins (Fig. 1). The basins have their respective depocentres at the continental shelf, taper towards coast and trench and are separated by basement highs. The creation of the basins between 34 and 45°S is related to subsidence of the present shelf and sectors of the slope by >1.5 km between 10.9 and 3.6 Ma (Melnick et al. 2009).

South of 38°S, the boundaries between the individual forearc basins correlate with inferred marine continuation of prominent upper plate faults (Figs. 4, 5, 6) that have been described by Melnick and Echtler (2006b) and Melnick et al. (2009). Upper plate faults that strike in SE–NW direction, oblique to the convergence direction of the Nazca Plate, are

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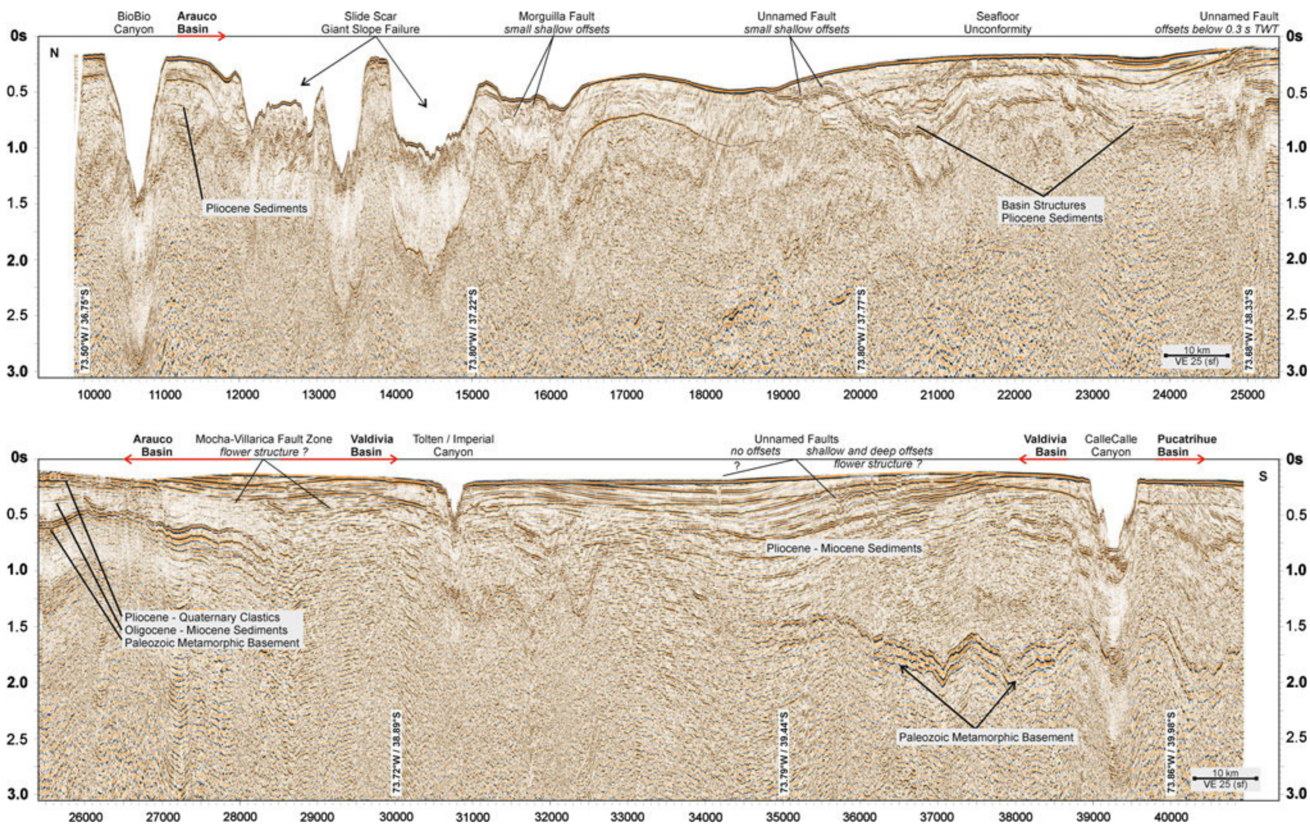

Fig. 7 Seismic reflection profile SO161-25 across Arauco and Valdivia Basins (Figs. 3, 4, 5) from 36.75°S to 38.33°S (*upper panel*) and 38.33°S to 40°S (*lower panel*) showing major tectonic structure and sedimentary units of the basins

likely the result of the northward motion of the Chiloé Microplate and its collision with the South American Plate in the region of the Arauco Peninsula (37.5°S). Some further upper plate faults are located within individual basins.

The seismic section SO161-25 (Fig. 7) was acquired with a recording time of 14 s two-way travel time (TWT). It runs along the shelf in North–South direction from 36.75°S to 40°S along the axes of the Arauco Basin, the Valdivia Basin and the northernmost area of the Pucatrihue Basin (Figs. 3, 4, 5). As only a very small part of the entire Pucatrihue Basin is imaged by the seismic line, the basin is not discussed in detail.

Arauco Basin

The Arauco Basin extends over an area of 8,000 km^2 from the latitude of Concepción in the North to the Mocha Island in the South (Fig. 1). In seismic line SO161-25 (Fig. 7), it is displayed from the start of the section to the common mid-point (CMP) 28500 at −73.693/−38.718. Around CMP 10600 (−73.559/−36.799), the V-shaped BioBio Canyon cuts about 900 m into the shelf. Between CMPs 11900 and 15100 (−73.685/−36.905 to −73.804/−37.234), the seafloor shows two depressions of 7 and 15 km width and up to 650 m depth, separated by a bathymetric high (at around CMP 13700, −73.790/−37.077). The depressions represent indentations that belong to the upslope part of a giant submarine slope failure that removed more than 350 km^3 of slope sediment, continental framework rock and compacted accretionary wedge material. The slope failure affected the full width of the continental slope and shifted the shelf break further landwards (Geersen et al. 2011b).

The Arauco Basin can be subdivided into a northern, central and southern part based on the seismic reflection pattern. In the northern part (start of the seismic section to CMP 18500 at −73.833/−37.608), only the upper 0.5 s TWT of the subsurface shows distinct seismic reflectors that likely represent Pliocene sediments (all information about stratigraphic units after Mordojovic 1974 and González 1989). Towards greater depth, reflections appear chaotic and disturbed. In this part of the seismic section, it is impossible to locate the Palaeozoic metamorphic basement. In the central part of the Arauco Basin (CMP 18500–25000, −73.833/−37.608 to −73.678/−38.328), distinct reflectors are visible down to a depth of about 1 s TWT. Seismic reflectors that again likely represent Pliocene sediments are heavily folded and form two basin structures. At the flanks of the basins, reflections are truncated by the seafloor unconformably. The southern part of the Arauco Basin between CMPs 25000 and 28500

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(−73.678/−38.328 to −73.693/−38.718) shows a distinctly different seismic reflection pattern. Here, some high-amplitude reflectors that likely represent Palaeozoic metamorphic basement are observed between depth of 0.5–0.75 s TWT. A zone of lower reflectivity on top of that unit may correspond to Oligocene–Miocene sediments, whereas the shallowest subsurface is formed of Pliocene to Quaternary clastic sediments. The latter unit is represented by high-amplitude reflectors. In this area, the continental shelf is exceptionally wide (up to 60 km) with Mocha Island exposed up to 390 m above sea level. The proximity of the Palaeozoic metamorphic basement to the seafloor may be caused by high uplift rates in this area.

In the onshore area of the Arauco Basin, a series of prominent SE-NW striking upper plate faults are described that appear to continue into the marine forearc (all information about position of continental faults from Melnick and Echtler 2006b and Melnick et al. 2009) (Figs. 4, 5, 6). Among those faults, the Morgüilla Fault is inferred to intersect the seismic line SO161-25 around CMP 16000 (−73.827/−37.331). In this area, seismic reflectors in the shallow subsurface are discontinuous, whereas towards greater depth, no reflectors or seismic units are observed that could indicate the position and the dip of the Morgüilla Fault. Offsets in the seismic reflections in the shallow subsurface indicate that the Morgüilla fault has been active in the Pleistocene and Pliocene. Also, the Morgüilla fault seems to develop into a flower structure in shallow depth as is indicated by the presence of repeated small offsets.

Further to the south, two unnamed faults that branch into a single fault zone in the continental forearc are inferred to border the central part of the Arauco Basin. This area is characterized by the folded basin structure between CMPs 18500 and 25000 (−73.833/−37.608 to −73.678/−38.328). At the northern end of the basin structure, several small (0.1–0.3 s TWT) offsets are observed down to a depth of about 1 s TWT indicating ongoing deformation and faulting since the Pleistocene. At the inferred position of the southern branch of the unnamed fault between CMPs 24500 and 25000 (around −73.684/−38.300), the seismic signature changes significantly. Here, the basin structure is replaced by the high-amplitude reflections (at a depth of 0.5–0.75 s TWT) that likely represent the Palaeozoic metamorphic basement in the southern part of the Arauco Basin. Seismic reflections are truncated at various positions in the subsurface. However, the shallowest reflectors (in the upper 0.2 s TWT of the sub-seafloor) show no prominent offsets, indicating that this fault has been inactive over the Pleistocene.

The southern end of the Arauco Basin is located around 38.5°S at the Mocha-Villarica Fault Zone (MVFZ). Here, the Palaeozoic metamorphic basement appears to be suddenly truncated. Moreover, several small offsets are observed in the shallow sedimentary sequence indicating that the MVFZ possibly develops into a flower structure at shallow depth and that activity has not ceased.

Valdivia Basin

The Valdivia Basin lies between Mocha Island in the North and CalleCalle Canyon in the South and, like the Arauco Basin, extends over an area of about 8,000 km^2. In seismic section SO161-25 (Fig. 7), it is present from around CMP 28500 to CMP 39000 (−73.693/−38.718 to −73.816/−39.877). At around CMP 30750 (−73.736/−38.969), the Tolten/Imperial Canyon cuts about 250 m into the shelf sediments. Towards the south, the basin is bordered by the CalleCalle Canyon that offsets the seafloor more than 500 m. In the southern part of the basin, high-amplitude reflections between 1.5 and 2.0 s TWT depths likely indicate the top of the Palaeozoic metamorphic basement. The seismic signature of the continental basement is similar to the one described for the southernmost part of the Arauco Basin. Between CMP 28500 (−73.693/−38.718) and 35000 (−73.789/−39.443), the reflections of the Palaeozoic metamorphic basement are lacking. Reflectors in the upper part of the basin do not show offsets at CMP 35000, which would indicate the presence of a fault zone, but rather seem to fade away. Therefore, we speculate that the cause of the absence of basement between CMP 35000 (−73.789/−39.443) and the southern end of the Arauco Basin is that here the profile is located further offshore and thus runs west of the seaward edge of the continental basement. Layered seismic reflections that indicate the presence of a thick sedimentary sequence, likely Pliocene and Miocene sediments, are observed in the upper 0.5–1.5 s TWT of the subsurface over the entire Valdivia Basin. This is in contrast to the Arauco Basin where the sedimentary sequence is much thinner and the basement is met at much shallower depth.

In the Valdivia Basin, two prominent, but unnamed faults are known (Fig. 5) that could intersect the seismic line SO161-25. At the position of the northern of these unnamed faults around CMP 34000 (−73.797/−39.332), no prominent offsets are observed in the seismic line, indicating that faulting is not active here. At the position of the southern fault around CMP 36000 (−73.760/−39.553), the shallow sediments as well as the continental basement are persistently offset up to 0.1 s TWT, indicating that this fault develops in a series of parallel faults or a flower structure at shallow depth. Faulting at this location seems to be active, as offsets are found directly below the seafloor reflection. Due to the lack of resolution in greater depth, it is unclear how this fault evolves towards depth.

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Seismo-tectonics of the marine forearc

The continental shelf of Southern Central Chile is tectonically deformed at different scales by different mechanisms the common origin of which is the (oblique) plate convergence and subduction of the down-going plate. Here, we combine information on epicentres from a number of local seismological networks to provide a more uniform picture. Data are from Dzierma et al. (submitted), Lange et al. (2007), Haberland et al. (2006) and Bohm et al. (2002). We added epicentres of the main shock and aftershocks of the 1960 earthquake (Engdahl and Villaseñor 2002) as well as of the 27 February of 2010, Mw 8.8 Maule earthquake (Servicio Sismológico de Chile, ssn.dgf.uchile.cl/). The corresponding intra-crustal seismicity is partly diffuse, partly localized in clusters (Figs. 2, 3, 4, 5, 6). Basically, three types of seismicity distributions can be observed in the marine forearc:

1. The trench-normal component of plate convergence leads to compressional deformation of shelf sediments and continental basement. The megathrust, as a whole, is clearly visible in the seismicity distribution. Inside the overriding forearc, however, the compression leads to a rather diffuse band of seismicity in which individual faults are difficult to identify. The frequency of these forearc events is much higher north than south of 36°S. Focal planes indicate mainly thrusting in the forearc on planes subparallel to the trench (e.g. Barrientos 2007).
2. The northward motion of the Chiloé Microplate (or Chiloé Sliver, Melnick et al. 2009) with respect to the stable Andean foreland to the east along the arc-parallel LOFZ decreases northwards from 46°S to 38°S (Rosenau et al. 2006; Wang et al. 2007). This velocity gradient may have been partly accommodated by internal deformation of the Chiloé fore-arc sliver, consistent with contractional and transpressional fault zones in the Arauco Region that strike oblique to the margin, such as the Lanalhue Fault and MVFZ (Melnick and Echtler 2006a, b; Rosenau et al. 2006; Melnick et al. 2009). At some of these faults zones clusters of seismicity are observed that locate down to lower crust and uppermost mantle levels (Dzierma et al. submitted). Some clusters located offshore indicate that the marine forearc is getting sheared in NW–SE direction in addition to the overall background compression. They show the offshore extrapolations of the MVFZ south of Mocha Island (Haberland et al. 2006; Dzierma et al. submitted) and of a nameless fault NW of Valdivia close to the slip maximum of the 1960 Valdivia earthquake (Dzierma et al. submitted). The seismicity cluster along the offshore extrapolation of the MVFZ may have been persistent between 2004 and 2009 because it was observed by both Haberland et al. (2006) and Dzierma et al. (submitted).
3. Faulting of the down-going plate seems to continue from the outer rise—where it is related to plate bending—until beneath the forearc where it is related to the megathrust process. This is evident from fault displacements cutting through the entire overriding plate down into the plate interface as imaged by seismic reflections (Sick et al. 2006). Linear seismicity clusters locating beneath the forearc near the plate interface and in the down-going plate indicate that this faulting is an ongoing process (Dzierma et al. submitted). Two of these clusters were found beneath the Valdivia Basin NW of Tolten and W of Mocha Island.

Paleo-accretionary complex beneath the continental shelf

Information on the structure of the continental crust that lies beneath the continental shelf and upper slope, underneath and seaward of the sedimentary basins has been obtained by seismic investigations over the last ~20 years (e.g. Bangs and Cande 1997; Contreras-Reyes et al. 2008, 2010; Scherwath et al. 2009; Moscoso et al. 2011). Here, we summarize recent observations on this issue.

Figure 8 shows a typical cross-section of the marine forearc off southern Central Chile. The frontal accretionary prism is 5–40 km wide (Contreras-Reyes et al. 2010) and abuts the truncated continental basement (inner prism) that extends seaward from beneath the shelf (Bangs and Cande 1997). This inner prism, presumably of Jurassic age, represents a paleo-accretionary prism. This paleo-accretionary wedge in turn abuts the Paleozoic continental metamorphic basement that is exposed on land in the Coastal Cordillera. The Coastal Cordillera south of 34°S is mainly built by two units, the Western and Eastern Series, that constitute coeval parts of a Late Palaeozoic paired metamorphic belt dominated by siliciclastic metasediments (Willner 2005). The Western Series represents a paleo-accretionary prism and dominantly consists of HP/LT metasediments with subordinate metabasite intercalations" (see Willner 2005), whereas the Eastern series is a belt of less deformed low-pressure/high-temperature metasediments that represent the retro-wedge (Willner et al. 2005; Glodny et al. 2006).

The transition between the present accretionary prism and the sandwiched paleo-accretionary prism is visible in seismic refraction data (Contreras-Reyes et al. 2008; Scherwath et al. 2009) and as a morphological transition between rough lower slope and more smooth upper slope

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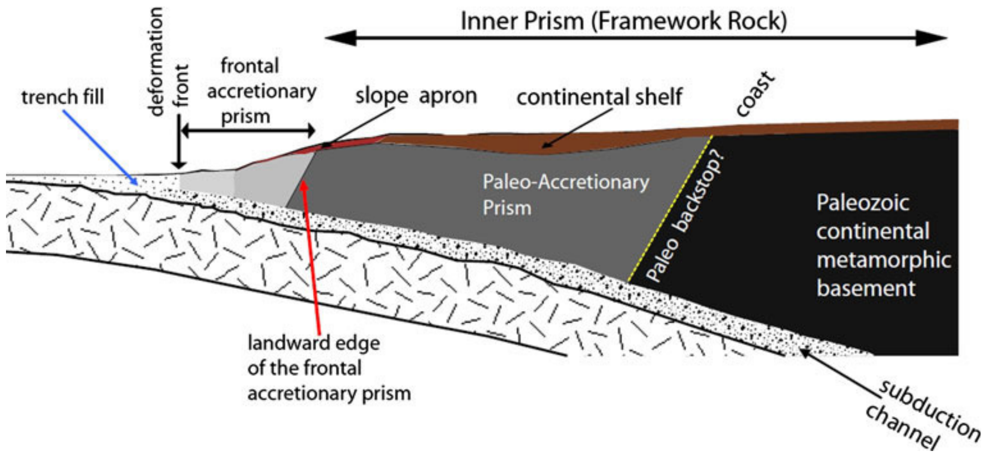

Fig. 8 Typical cross-section of the southern Central Chile convergent margin (after Contreras-Reyes et al. 2010). The frontal accretionary prism is typically 5–40 km wide and abuts against the present backstop, formed by the inner prism that is 50–80 km wide. The inner prism is likely composed of more than one rock unit. Seismic refraction (Contreras-Reyes et al. 2008; Scherwath et al. 2009) and seismological evidence (Haberland et al. 2006; Lange et al. 2007) show the presence of a paleo-backstop structure that separates a paleo-accretionary prism complex from the onshore exposed Paleozoic continental metamorphic basement (Hervé et al. 1988; Glodny et al. 2006)

morphology (Geersen et al. 2011a). The landward backstop of the paleo-accretionary prism against continental metamorphic basement (paleo-backstop) is manifest as velocity gradient suggesting a change in rock type (Contreras-Reyes et al. 2008; Scherwath et al. 2009) as well as by intraplate seismicity (Haberland et al. 2006, 2009; Lange et al. 2007; Dzierma et al. submitted).

Exploratory wells of the Chilean state oil company ENAP are located landward of the paleobackstop, so they do not help in determining the composition and age of the paleo-accretionary complex. The degree of consolidation and lithification of the paleo-accretionary complex is higher than that of the frontal accretionary prism but lower than that of the Palaeozoic continental framework. The remarkably high lateral velocity gradient from 5.5 to >6.0 km/s implies an abrupt change in rock type (Contreras-Reyes et al. 2008), and hence alternation between accretion and erosional phases. The size of the paleo-accretionary complex could have been much larger at the end of the accretion phase, when the complex was formed. Thereafter, an integral part of the accretionary complex was tectonically eroded (Kukowski and Oncken 2006). At present, the width of 50 km of the paleo-accretionary complex represents the remaining material left after the last erosional phase, which took place in the Miocene according to Melnick and Echtler (2006a) and Encinas et al. (2008). Assuming alternation between accretion and erosion phases and based on the age of the oldest shelf sediments (late Cretaceous), the estimated age for the paleo-accretionary complex is Jurassic (Contreras-Reyes et al. 2008).

Present shelf and slope sedimentation

The young sediment cover of the shelf and slope was sampled over the last 20 years by coring campaigns along depth transects (Table 1). ODP Leg 202 Sites 1233, 1234 and 1235 were drilled in slope basins of the upper and middle slope in water depths of 838, 1,015 and 489 m, respectively (Figs. 3, 5). Sediment-echosounder data were obtained along cruise tracks of RV SONNE cruise SO161 and SO210 on the continental slope. These latter data are presented here for the first time to image sedimentary structures on the shelf.

The ODP coring had the goal to obtain an undisturbed millennium-scale sediment core record of paleoclimatic changes. Consequently, small slope basins with thick sediment fill, where turbidites were expected to be channelled away by surrounding canyons, were selected for drilling (Mix et al. 2003). In this setting, thick and rapidly accumulating hemipelagic sequences were cored, which are characterized by extremely high bulk sedimentation rates of 90 cm/ka (site 1234), 70 cm/ka (site 1235) and >100 cm/ka (site 1233) over the cored intervals. The lithology is described as homogeneous silty clay and clay with varying, but generally low biogenic content and few thin silt and volcanic ash layers. The low biogenic component in spite of persistent highly productive upwelling cells in the Concepción area (sites 1234 and 1235) was explained by dilution due to the overwhelmingly high fluvial input of siliciclastic material (Mix et al. 2003).

Surface sediment samples (grab samples, gravity cores and multicorer samples) of shelf and upper slope were

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described by Lamy et al. (1998, 1999, 2001), Hebbeln et al. (2000), Muñoz et al. (2004), Raitzsch et al. (2007) and Stuut et al. (2007). Sediment composition of the described samples is dominated by terrigenous input which generally increases to the south in relation to the climatically controlled southward increase in denudation rates of the hinterland. Offshore mid-latitude Chile (33°S) samples provide a record of temporal variations in the terrigenous sediment supply that reflect changes in weathering conditions related to shifts of the latitudinal position of the Southern Westerlies (Lamy et al. 1999, 2001). Lamy et al. (1998) showed that regional variations in silt size and bulk mineralogy of terrigenous silts are governed by the source-rock composition of the different geological terranes and the relative source-rock contribution of the Coastal Cordillera and the Andes as controlled by the river networks. These trends are also reflected in the bulk chemistry (Stuut et al. 2007).

The biogenic sediment input shows a close relation to the environmental conditions in the Peru–Chile Current, as the accumulation rate of organic carbon in the sediments fits well with the present-day productivity patterns that are related to cells of coastal upwelling known from satellite data (Hebbeln et al. 2000). The carbonate content along the slope varies mainly between 0 and 20 % (Hebbeln et al. 2000). For the continental slope offshore Concepción, sedimentation rates were determined over the past ~100 years for two sites at 1,294 and 2,065 m water depth (Muñoz et al. 2004). The very high values of 180 ± 20 cm/ka were explained by the vicinity of the BioBío Canyon.

Seismic reflection data (Contardo et al. 2008; Geersen et al. 2011b), bathymetric data (Völker et al. 2011a, b) and the PARASOUND sediment-echosounder data shown here demonstrate that mass-wasting is a common effect on the slope that affects many of the slope basins and that focusing of sedimentation leading to extreme sedimentation rates in sheltered slope basins is contrasted by winnowing and sediment starved zones on the shelf. PARASOUND sediment echo-sounder data of the shelf break and uppermost slope around 36°S show a thin sediment cover that unconformably overlies deformed and tilted older strata (Fig. 9a, b). Locally, the older strata pinch out to form hard ground basement highs lacking a young sedimentary cover. Further south around 38°S, the relatively thin young sediment cover is affected by bottom current erosion as can be seen from v-shaped incisions (Fig. 9c). Deformation of the topmost sediment cover due to mass wasting is common (Fig. 9d). The overall impression of the sediment-echosounder data is of a bottom-current-dominated high energetic depositional regime where young sediments fill sheltered basins and pockets while elevated areas are practically swept free from young sediments and/or subject to bottom current erosion. Probably a large fraction of the shelf sedimentation is exported to shelf basins or eventually funnelled to the Peru–Chile Trench via submarine canyons. On the shelf, offshore Punta Lugurne (~36°S, Fig. 3) on the other hand, undisturbed and well-stratified sediments of 50-ms two-way-travel time were observed on RV SONNE cruise SO210 (Linke 2011).

Gas and fluid seepage

The presence of solid gas hydrates is indicated by the observation of a bottom simulating reflector (BSR) in seismic reflection data, while the seepage of gas-charged fluids at the seafloor is manifest by the occurrence of chemosynthetic bio-communities as well as by the acoustic detection of gas bubbles in the water column (acoustic flares in sediment-echosounder data). Here, we report on the present-day knowledge on the distribution of seepage-related fauna. At other convergent continental margins, such as of Central America and New Zealand, active seepage of (methane-rich) fluids is a common phenomenon, often located within a trench-parallel belt of the middle continental slope. In those places, a variety of active seeps appear to be long-standing structures, related to faults that connect the plate interface with the seafloor and form conduits (e.g. Sahling et al. 2008; Barnes et al. 2010). The presence of fluid seepage can therefore bear information on the hydraulic properties of the forearc, its tectonic situation and internal structure.

Seismic profiles show bottom simulating reflectors (BSR), commonly associated with the occurrence of gas hydrates on the continental slope of southern Central Chile below a water depth of 650 m (Brown et al. 1996; Díaz-Naveas 1999; Grevemeyer et al. 2003; Morales 2003; Rodrigo et al. 2009). At some places, the BSR intercepts the seafloor below the shelf break (Rodrigo et al. 2009). Typical members of chemosynthetic bio-communities indicative for methane seepage (e.g. clams of the family *Vesicomyidae* and tubeworms of the genus *Lamellibrachia*) are known by now from many places at the Chile margin. The first indication of seep communities was the description of *Calyptogena australis*, from the vicinities of Mocha Island (~38°S) at 1,400 m water depth (Stuardo and Valdovinos 1988, Fig. 4). This first report was followed by others from offshore Concepción Bay (Sellanes and Krylova 2005; Oliver and Sellanes 2005; Sellanes et al. 2008; Quiroga and Sellanes 2009), a region that was termed the Concepción methane seep area (CMSA, Sellanes et al. 2004, Fig. 3). Three other bathyal seep sites were discovered recently, located off the Limari River (at ~30°S) at 1,000 m depth, off El Quisco (~33°S) at 350 m depth, and the most recent one, off the Taitao Peninsula

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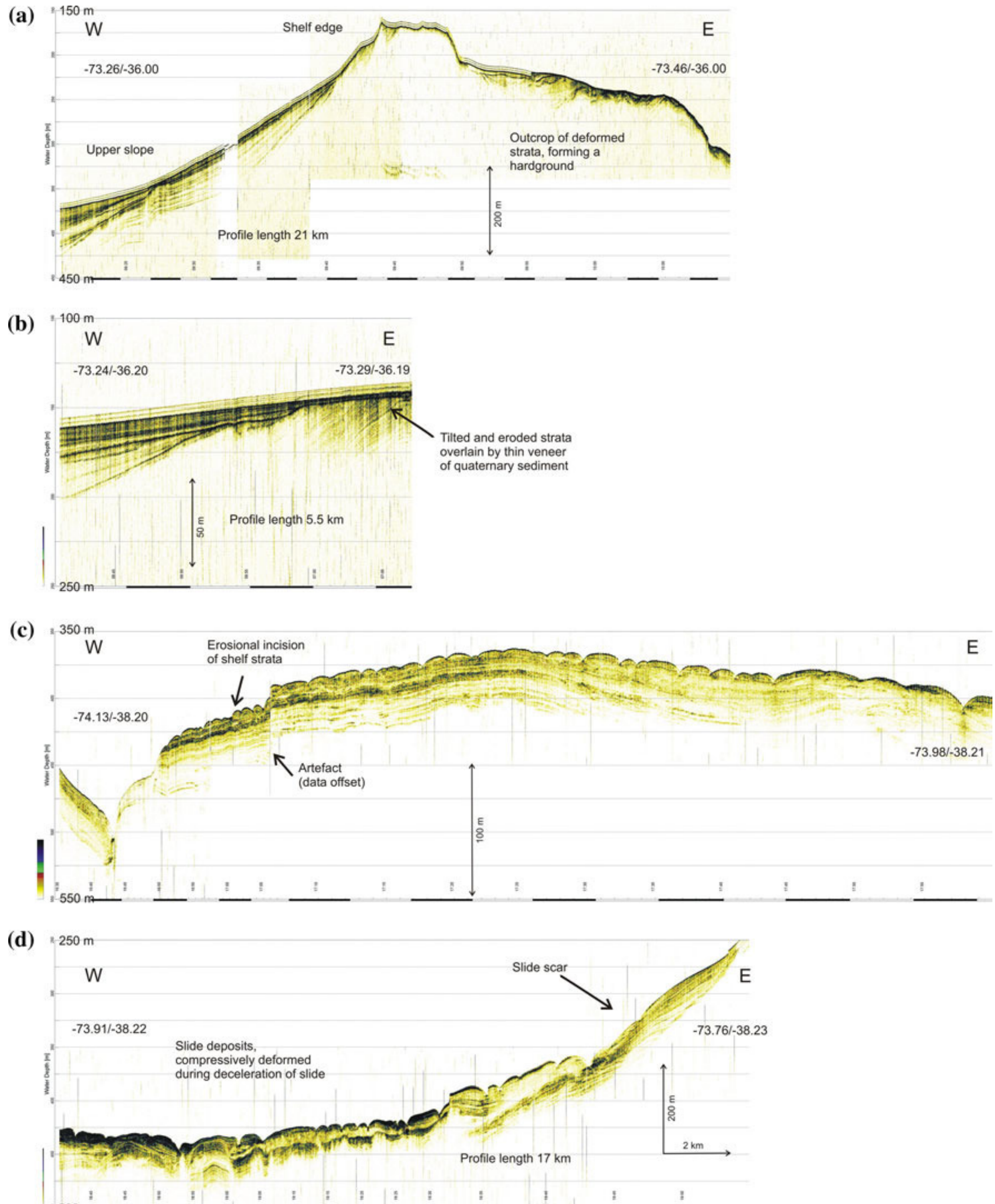

Fig. 9 Sample PARASOUND sediment-echosounder profiles from the shelf and upper slope of southern Central Chile, each representing seismic facies types. **a** Outcrop of lithified sediments at the shelf edge; **b** angular unconformity of tilted lithified strata against thin cover of young sediments; **c** subparallel strata, incised by parallel grooves; **d** small landslide at the shelf edge. Location of PARASOUND profiles **a** and **b** is indicated in Fig. 3, of profiles c and d in Fig. 4

(~46°S) at 600 m depth (J. Sellanes, unpublished data), all of them indicated by the presence of typical seep communities. Fluid seepage-related features of the seafloor (patches of high acoustic backscatter, possibly representing authigenic carbonates) as well as acoustic anomalies in the water column (gas flares) were detected on the upper to middle slope in 1,500 m water depth (Flueh and Bialas 2008) offshore Concepción Bay (CMSA, Fig. 3). While authigenic carbonates that probably formed as the result of methane-rich fluid expulsion form extensive pavements in

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two distinct areas of the middle slope (north of BioBio Canyon and around Itata Canyon), acoustic anomalies in the water were described rarely (Klaucke et al. 2012). According to Klaucke et al. (2012), the apparent misfit between indications of present fluid seepage and the size of authigenic carbonate patches and chemoherms indicates that fluid venting must have been more intense over some period of the past.

Chloride content of the pore waters of gravity cores from the continental slope is meaningful for the detection of subduction-related diagenetic processes, as a number of these processes consume (alteration of volcanic ash to smectite, Martin et al. 1995) or release (transformation of smectite to illite, Kastner et al. 1991) fresh water when trench fill is being subducted along with the down-going plate (e.g. Hensen et al. 2004). Offshore Central Chile, pore water geochemical measurements from gravity cores obtained on RV SONNE cruise SO210 (Linke 2011) were conducted by Scholz et al. (submitted). They show that pore fluids in cores of the accretionary prism show a higher chlorinity than seawater and relate this finding to the sequestration of water through formation of hydrous minerals (alteration of volcanic ash to smectite). In contrast, cores from the upper slope have a lower chlorinity than seawater which most likely is due to clay mineral dehydration, for example the alteration of smectite to illite. Thermal constraints from heat flow modelling let Scholz et al. (submitted) suggest that these low-salinity fluids are generated in the upper plate, whereas the dehydration of underthrust sediments must take place further seaward.

The occurrence of gas seeps is also known at many intertidal and shallow subtidal places at the W side of Mocha Island off southern Central Chile (~38°S, Fig. 4). At this locality, two possible sources have been ascribed for it: (a) subsurface thermogenic hydrocarbon accumulations that are trapped within the Cretaceous rock sequence (Comisión Nacional de Energía Chile, 2002; Sánchez 2004) and (b) coal-bed methane, coming from coal-bearing sediments of the Trihueco Formation in the Arauco Basin in the continental shelf (Mordojovic 1981). Recent measurements indicate that emanations contain 70 % methane, and the estimated methane fluxes emitted directly to the atmosphere amount to 815 ta^{-1} when considering the five subtidal and intertidal seeps detected at the Island (Jessen et al. 2011). The C stable isotope compositions of methane from the intertidal seeps averaged at −43.8 ± 0.4 ‰ (with respect to PeeDee Belemnite) and are suggestive of a substantial fraction derived from thermogenic sources. While stable carbon isotopic compositions of marine benthic organisms indicate a dominant photosynthesis-based food web, $\delta^{13}C$ of some hard-substrate invertebrates were in the range −36.8 to −48.8 ‰, suggesting assimilation of methane-derived carbon by some selected taxa (Jessen et al. 2011).

Summary and conclusion

Our compilation of older and recently published data, cruise reports, scientific theses and previously unpublished geological and geophysical data on the shelf and upper slope of Central Chile allows drawing the following conclusions:

1. The presence of fourteen deeply incised submarine canyon systems, their extension onto the shelf, as well as their direct connection to river systems on land impacts severely on shelf sedimentation, as the bulk of fluvial transported sediment is likely funnelled downslope instead of being stored on the shelf. High sedimentation rates are observed on shelf and upper slope in spite of this deprivation of fluvial transported material due to local zones of constant or seasonal upwelling and due to the sheer amount of fluvial input. Sediment-echosounder profiles show both patches of undisturbed and well-stratified sediments on the shelf and eroded sedimentary structures closer to the shelf edge. The local lack of young sedimentary cover is attributed to the Gunther Current that flows vigorously poleward close to the shelf edge.
2. The sedimentary basins that underlie the shelf platform and the upper continental slope consist of Oligocene to Quaternary infill in structural basins of the Paleozoic metamorphic basement. The thickness of the individual units varies significantly both within Arauco and Valdivia Basin as well as from basin to basin. Reflectors of the sedimentary fill of those basins are offset by six fault zones that form the continuations of large crustal fault systems known on land such as the Morgüilla Fault and the Mocha-Villarica Fault Zone. The continuity of these SE-NW trending crustal faults into the submarine forearc has been postulated but never clearly documented before. Five of the six fault systems appear to have been active over the evolution of the basin from late Cretaceous to the present, while for one fault system activity appears to have ceased in Pleistocene. Some of these faults zones—notably the MVFZ (Haberland et al. 2006, offshore Arauco peninsula; Dzierma et al. submitted, cluster G), a nameless fault NW of Valdivia (Dzierma et al. submitted, cluster F) and side branches near the LOFZ (Dzierma et al. submitted, cluster H)—show clusters of seismicity that extend downwards into the lower crust, Moho and uppermost mantle. The clusters indicate that the marine forearc is getting sheared in NW–SE direction in addition to the overall background compression, a tectonic regime that is due to the transpressional docking of the Chiloé Microplate to the South American Plate.

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3. The structure of the upper continental margin beneath the shelf basins is marked by a prominent transition from a former accretionary prism that was tectonically eroded in parts to the newly forming accretionary prism. This transition marks the shift from a phase of tectonic erosion to the present phase of accretion that is supposed to have occurred about 4 Ma ago. The transition is further expressed in the surface morphology as a shift from smooth, gently sloping upper continental slope to a more complex and steeper slope below 2,000 m water depth.
4. Seepage of gas-charged fluids is observed both indirectly and directly, clustered to a few locations on the shelf and upper slope. This seepage appears to be of shallow origin and not related to the release of fluids from the subducting Nazca Plate by deeply connecting conduits as was observed, for example off Costa Rica (Sahling et al. 2008).

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