ABSTRACT: Cross-sectional asymmetry is characteristic of sinuous channels in both fluvial and submarine settings. Less well documented are the facies distributions of asymmetric channels, particularly in submarine settings. Exposures of the axial submarine channel-belt in the Magallanes retro-arc foreland basin on Sierra del Toro represent the fill of a 3.5 km wide, 300 m thick channel complex, here termed the “Wildcat,” that displays an asymmetric cross section and facies distribution. Measured sections and mapping demonstrate that facies proportion, degree of amalgamation, and margin architecture vary laterally from east to west across the Wildcat channel complex. The eastern side is characterized by thick-bedded, amalgamated sandstone and clast- and matrix-supported conglomerate that onlap a steep, simple margin adjacent to sandy overbank deposits. The western side contains thin-bedded, sandy and muddy strata that onlap a shallow composite margin adjacent to mud-rich out-of-channel strata.

The observed asymmetry is likely due to centrifugal flow forces and was caused by a low-sinuosity right-hand meander bend of the Cerro Toro axial channel-belt. The facies and architecture of the opposing margins indicate that the eastern and western sides constitute the outer and inner bends of the Wildcat channel complex, respectively. The modest cross-sectional asymmetry of the Wildcat complex is likely a product of the low channel-belt sinuosity. The absence of lateral accretion surfaces and deposits suggests that the channel did not migrate during filling. Flows depositing the uppermost channel fill were only weakly confined, resulting in flow divergence and overbank deposition.

A depositional model that incorporates the asymmetric facies distributions and the contrasting outer-bend and inner-bend architecture of the Wildcat channel complex is also presented. Similar facies distributions exist in other low-sinuosity submarine channels, and even more extreme facies and cross-sectional asymmetry probably characterize more highly sinuous channels. Data on facies distributions presented here represents a useful resource for constraining numerical and experimental models of the evolution of sinuous submarine channels as well as reservoir models of sinuous submarine channels.

INTRODUCTION

Channel asymmetry can be defined both by the cross-sectional shape of the channel, or architectural asymmetry, and by the across-channel variation in infilling grain size and facies, or facies asymmetry (Pyles et al. 2010). Generally, sinuosity and asymmetry are highly correlated (Melton 1936). Leopold and Wolman (1960) provide a thorough review of this bifold asymmetry for meandering fluvial systems, and more recent studies include Nanson (1980), LaPointe and Carson (1986), Johanneson and Parker (1989), Miall (1996), and Dodov and Foufoula-Georgiou (2004). Architectural asymmetry is caused by enhanced erosion of the outer bank of a channel due to differential boundary shear stress generated as a flow negotiates a meander bend. Higher sinuosities, therefore, generate a steep outer bank and a shallow inner bank at bend apices, whereas channels with lower sinuosities tend to be only slightly asymmetric at bend apices. At inflection points between bends or at straight reaches of channels, symmetric cross-sections are expected (Pyles et al. 2010). Facies asymmetry is caused by flow-velocity gradients as well as helical flow patterns redistributing sediment across the channel (see Leopold and Wolman 1960 and references therein).

Architecturally asymmetric submarine channels were not identified until high-resolution bathymetric data became available. First recognized were the higher outer-bank levees (Buffington 1952; Flood and Damuth 1987) caused by flow superelevation (Imran et al. 1999), Coriolis forces (Menard 1955; Klaucke et al. 1998) or fold-belt development (Clark and Cartwright 2009). Seismic-reflection (Kolla et al. 2001), outcrop (Satur et al. 2005; Pyles et al. 2010), and modern-seafloor studies (Hay 1987a, 1987b; Babonneau et al. 2002; Antobreh and Krastel 2006; Lamb et al. 2008) confirm the widespread architectural asymmetry of sinuous submarine channels.

Facies asymmetry has been more widely recognized in submarine channels due to outcrop access and the focus of the petroleum industry on intrachannel reservoir communication. Seismic-reflection studies commonly describe facies asymmetry in submarine channels, both with (Stelting et al. 1985a; Stelting et al. 1985b; De Ruig and Hubbard 2006) and without (Abreu et al. 2003; Deftuck et al. 2003; Kolla et al. 2007) lithologic calibration. Outcrop studies also describe submarine channel-fill exhibiting facies asymmetry (Campion et al. 2000; Hickson and Lowe 2002; Abreu et al. 2003; Satur et al. 2005; Crane and Lowe 2008; Pyles et
al. 2010). At least two sinuous modern submarine channels have been cored that demonstrate facies asymmetry (Hay et al. 1983a, 1983b; Johnson et al. 2009). These numerous examples of architectural and facies asymmetry, however, are rarely considered when making reservoir models (Labourdette 2007; Sweet and Sumpter 2007). Many flume studies also reproduce facies asymmetry in sinuous channels (Keevil et al. 2006; Keevil et al. 2007; Straub et al. 2008), but these channels are built with symmetric U-shaped cross-sections, questioning their validity.

Outcrops of the Cerro Toro Formation in southern Chile provide both continuous, three-dimensional bed-scale exposure and the larger context of the overall depositional system necessary to construct accurate models of the architecture and evolution of asymmetric submarine channels. This study reports the large (3.5 km wide × 6 km long × 300 m thick), well exposed, very coarse-grained “Wildcat” channel complex on Sierra del Toro, emphasizing the asymmetric facies distribution. The architectural asymmetry is minimal, likely due to the very low sinuosity. A depositional model for sinuous submarine channels is presented, based on observed lateral and downdip variations in facies proportion, degree of amalgamation, paleoflow, and margin architecture. This model is widely applicable and, combined with data from other similar systems, may be used to predict the sinuosity and planform characteristics of asymmetric submarine channels. The quantitative lithologic data, such as amalgamation ratio and facies proportions, can also be used to populate more realistic models of reservoir heterogeneity and constrain numerical and experimental models of submarine channels.

**Magallanes Foreland Basin, Southern Chile**

The Magallanes retro-arc foreland basin (Fig. 1) was created as a result of the inversion of the Rocos Verdes back-arc basin, a rift basin associated with Gondwana breakup (Biddle et al. 1986). Basin inversion was caused by the onset of Andean compressional orogenesis and flexural loading at 92 Ma (Wilson 1991; Fildani et al. 2003; Fildani and Hessler 2005), marked in the Ultima Esperanza district of southern Chile (Fig. 1B) by the deposition of the Punta Barrosa Formation (Fig. 1C). Subsidence rates were high due to the extended crustal underpinnings of the basin (Dalziel et al. 1974) and were intensified by orogenic loading (Fig. 1D; Wilson 1991). Thus, the Magallanes basin remained underfilled and at bathyal water depth (Katz 1963; Natland et al. 1974; Wilson 1991; Fildani and Hessler 2005) during deposition of the Coniacian–Campanian Cerro Toro Formation (Fig. 1C; Katz 1963, Scott 1966). The Cerro Toro Formation consists of more than 2000 m of turbiditic mudstone, but lenses of conglomerate and sandstone up to 400 m thick (the “Lago Sofia” member) are encased within this mudstone (Zeil 1958; Scott 1966; Winn and Dott 1979). These coarse-grained deposits are remnants of a southward-flowing conglomeratic channel-belt that occupied the axis of the elongate foreland basin (Hubbard et al. 2008). Overlying the Cerro Toro Formation is the Tres Pasos Formation, a major slope system (Macellari et al. 1989; Shultz et al. 2005; Hubbard et al. 2010) displaying channelized submarine fans and/or lobes (Romans et al. 2009a), mass-transport deposits (Armitage et al. 2009), and ponded mini-basin fills (Shultz and Hubbard 2005). The Dorotea Formation overlies the Tres Pasos Formation (Macellari et al. 1989) and represents a shelf-edge delta that fed the Tres Pasos slope system (Covault et al. 2009; Hubbard et al. 2010). Extensive reviews of the tectonic and sedimentary evolution of the Magallanes basin are provided by Fildani et al. (2008) and Bernhardt et al. (2008), respectively.

**Axial Channel-Belt of the Cerro Toro Formation**

First mapped in the early twentieth century (Hauthal 1907), the conglomeratic lenses of the Cerro Toro Formation represent the deposits of an axial channel-belt that was more than 100 km in length and ~ 8 km wide (Hubbard et al. 2008). Scott (1966) first described the conglomerate units as deep-water units deposited by southward-flowing currents. Winn and Dott (1977, 1979) interpreted the formation as a leveed-channel system deposited by southward-moving turbidity flows on an elongate submarine fan. The most recent interpretation (Hubbard et al. 2008) is that the ~ 400-m-thick Lago Sofia member represents an axial channel-belt partially confined by levees and partially by the foredeep margin. This channel belt displayed very low (1.06) sinuosity and likely had multiple tributary conduits (Fig. 1: Crane and Lowe 2008; Hubbard et al. 2008). Provenance of the channel-belt fill is interpreted to be the Andean arc and fold-and-thrust belt; sandstone plots in the transitional arc QFL domain and conglomerate clasts consist predominantly of rhyolites, granitoids, and metasedimentary rocks (Zeil 1958; Scott 1966; Crane 2004; Valenzuela 2006). Romans et al. (2009b) provides a comprehensive provenance analysis of the axial channel-belt and the rest of the Magallanes basin.

**Paleogeography of the Axial Channel-Belt**

A paleogeographic reconstruction of the Magallanes basin during deposition of the Cerro Toro axial channel-belt is shown in Figure 1A. The coarse, up to boulder, grain size and amalgamated facies relationships of the channel-belt deposits suggest that the source area had high sediment supply, a steep gradient, and a narrow shelf. Coeval shallow-marine deposits identified about 50 km north of the study area are thought to represent a coeval coastal system that fed sediment into the channel belt (Macellari et al. 1989); however, these deposits have not been studied in detail. A modern analog for the Cerro Toro axial channel-belt is the Gaoping submarine canyon and Manila trench submarine channel system in the foreland basin of SW Taiwan, which is a river-fed, high sediment-supply, high-gradient system (Yu et al. 2009). An excellent subsurface analogue is the Puchkirchen axial-channel belt in the Molasse pro-foreland basin of Austria, which displays dimensions, grain size, and architecture similar to the Cerro Toro axial-channel belt (De Ruig and Hubbard 2006; Hubbard et al. 2008; Hubbard et al. 2009). The Cerro Toro axial-channel belt extended for more than 200 km to the south, into Tierra del Fuego (Dott et al. 1982). Proximal parts of the Cerro Toro axial-channel belt are exposed at Sierra del Toro (Fig. 1B), the focus of this study. Downslope exposures to the south include the Cordillera Manuel Señoret and Cerro Rotunda (Hubbard et al. 2008). The Silla Syncline (Fig. 1B), a western locale of proximal Cerro Toro conglomeratic-channel-fill, may represent a tributary channel to the axial channel-belt or the prior location of the belt due to foredeep migration (Crane and Lowe 2008; Bernhardt et al. in press).

**Cordillera Manuel Señoret**

Outcrops of the Cerro Toro Formation in the Cordillera Manuel Señoret area (Fig. 1B) contain highly amalgamated conglomerate and sandstone incised into turbiditic mudstone (Winn and Dott 1979; Hubbard et al. 2008). Winn and Dott (1977) describe dunes with 4 m of relief from this part of the channel belt. Hubbard et al. (2008) undertook a comprehensive study of the area and suggested that confinement was provided both by inner levees and the foredeep margin. Hubbard et al. (2008) presented clear evidence for inner levee development at channel margins on both sides of the channel belt, including overbank diverging paleoflow, bed thinning away from the channel, and slumps associated with levee topography. The narrowing of the outcrop belt and the downdip increase in amalgamation are suggested by Hubbard et al. (2008) to represent a constriction of the foredeep concurrent with deposition caused by differential Andean thrusting.
FIG. 1.—Overview of the Magallanes retro-arc foreland basin, located in southern Chile. A) Paleogeographic map of the Magallanes basin during deposition of the Cerro Toro Formation (Campanian). Inset map shows location of the Magallanes basin in South America. Main transport was basin-axial and directed southward, parallel to the advancing thrust front. Black box denotes location of Part B; D–D denotes the location of Part D. Map modified from Hubbard et al. (2008). B) Landsat image, courtesy of NASA MRSID. Solid red outlines show the modern extent of Cerro Toro conglomeratic channel-fill deposits. Black box denotes the location of Figure 2A. C) Stratigraphy of the Magallanes basin, compiled from Natland et al. (1974), Wilson (1991), Fildani et al. (2003), Romans et al. (2009b). This section does not represent true thickness; the Cerro Toro Formation is ~ 2000 m thick in the northern Magallanes basin. D) Schematic cross section of the Magallanes basin during deposition of the Cerro Toro Formation in the foredeep of the basin, modified from Fildani et al. (2003). Location of cross section is shown in Part A.
FIG. 2.—The location of Sierra del Toro in the northern Magallanes basin. A) The study area of Sierra del Toro, displaying the eastward stacking of channel-fill deposits where flow was directed to the southeast (153°). Inset shows the > 1000 m of stratigraphy exposed on Sierra del Toro. The Wildcat channel complex is 3.5 km wide and exposed for 7 km in the downdip direction. The orange dashed line is the inferred planform of the Wildcat complex. Fifteen sections were measured in the Wildcat complex; their locations and average paleoflow directions are shown on the map. The undifferentiated channel fill lies above the Wildcat complex, but limited
Sierra del Toro

The study area, Sierra del Toro, is a mountain range near the northern, proximal end of the outcrop exposure of the Cerro Toro axial channel-belt (Figs. 1, 2) and is approximately 100 km² in areal extent and 1300 m in relief (Fig. 2). Scott (1966) first noted the presence of conglomerate and south-directed paleocurrents on Sierra del Toro. On the basis of facies relationships and foraminiferal assemblages, Winn and Dott (1979) later interpreted conglomerate packages on Sierra del Toro as part of an elongate, leveed submarine fan–channel system. Hubbard et al. (2008) included Sierra del Toro conglomerate as part of the Magallanes basin axial channel-belt. This study recognizes that outcrops on Sierra del Toro include at least three major conglomeratic units, each of which is interpreted to represent a submarine channel-complex within the axial channel-belt. The thicknesses of these channel complexes range from 20 to 300 m, and the widths range from less than 1 km to greater than 5 km (Fig. 2A, inset). From oldest to youngest, they are named the “Condor,” “Guanaco,” and “Wildcat” complexes (Fig. 2). These channel complexes are composed largely of conglomerate and sandstone and are separated by mudstone. The undifferentiated channel fill that overlies the Wildcat complex (Fig. 2) is also conglomeratic, but recent erosion and scree cover prevent the discrimination of channel morphologies or the genetic association with other complexes.

The Condor complex consists of three westward-migrating, offset stacked submarine channels (Fig. 2) and was named and described by Barton et al. (2007) and O’Byrne et al. (2007). The conglomeratic channel-fill commonly contains dune and bar forms (O’Byrne et al. 2007). J obe et al. (2009a) showed that paleocurrents were directed to the southeast and the orientation of the eastern margin of the Condor complex is 165° (Fig. 2). The Guanaco complex (Figs. 2A, B) contains at least five individual channels, each 5–70 m thick and 0.1–1 km wide. These channel stacks quasi-aggradationally, centered above the eastern margin of the Condor complex and underneath the western margin of the Wildcat complex (Fig. 2). The Guanaco complex is exposed only on the north side of Sierra del Toro (Fig. 2). J obe et al. (2009b) speculate that the overlying Wildcat complex may downcut to the south, and amalgamate the two complexes, thereby rendering them indistinguishable on the south side of Sierra del Toro.

Wildcat Channel Complex.—The uppermost channel complex on Sierra del Toro is named the “Wildcat channel complex” because of the rare wildcat Oncifelis geofforyi (“gato montés” in Chilean Spanish) that resides among the conglomeratic outcrops. This complex forms the caprock of Sierra del Toro (Fig. 2) and exhibits average and maximum thicknesses of 143 and 294 m, respectively. The Wildcat complex is 3.5 km wide and is exposed for 6 km downstream; with the average thickness of 143 m, there are ~ 3 km³ of Wildcat channel-fill on Sierra del Toro. Paleocurrent indicators from the Wildcat complex indicate average (mean ± 1σ) paleoflow to the southeast (153 ± 40°; Fig. 2A at upper right), consistent with map trends of the channel margins (Fig. 2A). Previous work on the Wildcat channel complex is limited to two studies. Hubbard et al. (2007) described the “Sarmiento Vista” (SV) locale on the northern face of Sierra del Toro (Fig. 2B), where amalgamated, conglomeratic channel-fill overlies the eastern margin. J obe et al. (2009c) incorporated the Sarmiento Vista locale into an examination of the entire eastern margin of the Wildcat complex.

Dataset and Methods.—A total of 18 measured sections logged at 10 cm resolution, totaling over 2000 m, provide the basis for correlation and analysis of the Wildcat complex. These are supplemented by 975 paleocurrent measurements, facies mapping, and photopanel interpretation. Facies proportions were calculated by dividing the thickness of each facies in a measured section by the total thickness of that section, normalized for covered intervals. Amalgamation ratio (AR), defined as the number of amalgamation surfaces divided by the total number of sedimentation units (Manzocchi et al. 2007; Romans et al. 2009a), was also calculated for each measured section. In order to measure the erosive power of turbidity currents, only conglomerate, sandstone, and mudstone units were used to compute AR; debris flows and slurry flows were not incorporated because they represent either hybrid flows or nonturbulent flows. Five ash beds were sampled from below, within, and above the Wildcat complex, and their locations are marked on subsequent figures; these ashes are being dated by A. Bernhardt (unpublished data).

Lithofacies of the Wildcat Channel Complex

Lithofacies of the Wildcat channel complex generally display evidence of rapid deposition by energetic sediment gravity flows. Table 1 provides specific descriptive characteristics of each lithofacies. Hubbard et al. (2008) provide a thorough description and motivation for the use of the lithofacies scheme for the Cerro Toro Formation (Fig. 3 and Table 1 in Hubbard et al. 2008), and this study adapts their terminology with some modifications germane to the Wildcat complex. Lithofacies continuity from Sierra del Toro to the Cordillera Manuel Sexoret, more than 50 km downstream, suggests that the Cerro Toro axial channel-belt was an immense and continuous depositional system. The term “mudstone” is used throughout this study as a generic term describing a sedimentary rock composed of silt and clay where specific amounts of each constituent are not specified and no process of sedimentation is implied (adapted from Bates and Jackson 1984).

IIIscg—Clast-Supported Conglomerate

IIIscg consists of clast-supported, normally graded and imbricated, sand-matrix cobble conglomerate (Fig. 3A). Basal contacts with IIIm commonly show large “canoe” flutes (Fig. 3B). Where IIIscg overlies IIIhs, large (~1–2 m high) flame structures are frequently developed.

IIIIf—Slurry-Flow Conglomerate

IIIIf sedimentation units can be up to 40 m thick, but are commonly 4–11 m thick and display an upward transformation from a basal clast-supported conglomerate to an upper conglomeratic mudstone (Fig. 3C). The clast-supported basal divisions typically occupy < 25% of the total unit thickness, and the transition can be gradual or abrupt. Basal contacts often display flute casts and load structures (Fig. 3C). Extrabasinal clasts range in size from sand to boulders (Fig. 3D), but cobbles are predominant. Units of IIIIf show normal grading of extrabasinal clasts (Fig. 3D), while large (up to 6 m) intrabasinal clasts (i.e., raft blocks) are concentrated near the top of the upper matrix-supported division.
### Table 1.—Characterization of lithofacies in the Wildcat channel complex, Cerro Toro Formation, exposed on Sierra del Toro.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Characteristic grain size</th>
<th>Sedimentary structures and depositional processes (R &amp; S divisions from Lowe 1982; T divisions from Bouma 1962)</th>
<th>Average / maximum sedimentation unit thickness</th>
<th>Average amalgamation ratio (AR)</th>
<th>Secondary and notable features</th>
<th>Percentage (by thickness) of Wildcat channel fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIIscg</td>
<td>Cobble: 12 × 6 cm average 40 × 25 cm max</td>
<td>Normally graded (R₁), imbricated and/or crudely planar laminated (R₃); high-density turbidity currents (Lowe 1982)</td>
<td>1.7 m / 6 m</td>
<td>0.95</td>
<td>Intrabasinal clasts; flute casts; cross bedding; sand-filled scours; large (~ 1 m) flame structures</td>
<td>41%</td>
</tr>
<tr>
<td>Clast-supported</td>
<td>Medium sand matrix</td>
<td>Local IIIss lenses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>conglomerate</td>
<td>IIIsf</td>
<td>Basal division: clast-supported cobbles with sandy and muddy matrix; normally graded (both clasts and matrix); flame structures; Large (&gt; 5 m) intrabasinal raft blocks common in upper divisions</td>
<td>4–11 m / 40 m</td>
<td>0.85</td>
<td>Flute casts and flame structures; Large (&gt; 5 m) intrabasinal raft blocks common in upper divisions</td>
<td>14%</td>
</tr>
<tr>
<td>Slurry-flow</td>
<td>Upper division: poorly sorted muddy matrix with sand, gravel, and raft blocks</td>
<td>Normally graded; “slurry flows” (Lowe and Guy 2000) or “hybrid sediment gravity flows” (Haughton et al. 2009)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>conglomerate</td>
<td>IIIdf</td>
<td>Mudstone matrix with sand and gravel clasts; random grain dispersion and orientation; debris flow (Hampton, 1975)</td>
<td>2–4 m / 14 m</td>
<td>7%</td>
<td>Dispersed intrabalinal raft blocks</td>
<td>N/A</td>
</tr>
<tr>
<td>Debris-flow</td>
<td>IIIss</td>
<td>Medium-grained (66%) to coarse-grained (28%) sand; common gravel lags and IIIscg lenses</td>
<td>0.5–1 m / 5 m</td>
<td>0.80</td>
<td>Fe-bearing concretions up to 1 m diameter; flute casts; traction-structured tops (Tₚ); cross-stratification (Sₗ, Tₗ) rare</td>
<td>24%</td>
</tr>
<tr>
<td>conglomerate</td>
<td>IIIsm</td>
<td>Fine-grained sand interbedded with mudstone, gravel lags and conglomerate lenses are rarely developed</td>
<td>Planar-laminated (Tₘ) and ripple-laminated (Tₚ); low-density turbidity currents (Bouma, 1962)</td>
<td>30 cm / 100 cm sandstone</td>
<td>Flute casts; bioturbation by <em>Skolithos</em> and <em>Zoophycus</em> khonofacies; convolute lamination and water-escape structures;</td>
<td>12%</td>
</tr>
<tr>
<td>Interbedded sandstone and</td>
<td></td>
<td>Planar-laminated mud (Tₗₘ) and ripple-laminated sand (Tₚ); low-density turbidity currents (Bouma, 1962)</td>
<td>5 cm / 25 cm mudstone</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mudstone</td>
<td>IIIm</td>
<td>Mudstone sil + clay; fine-to medium-grained sandstone</td>
<td>Planar-laminated mud (Tₗₘ) and ripple-laminated sand (Tₚ); low-density turbidity currents (Bouma, 1962)</td>
<td>2 cm avg mudstone</td>
<td>Bioturbation by <em>Skolithos</em> khonofacies; Fe-bearing carbonate concretions in both mud and sand; <em>Inoceramus</em> body fossils</td>
<td>2%</td>
</tr>
<tr>
<td>Mudstone with thin sandstone interbeds</td>
<td></td>
<td>Planar-laminated mud (Tₗₘ) and ripple-laminated sand (Tₚ); low-density turbidity currents (Bouma, 1962)</td>
<td>5 / 50 cm sandstone</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(Fig. 3C). Deep burrows of the *Glossifungites* ichnofacies have also been recognized in IIIsf (Hubbard and Shultz 2008).

The sedimentation mechanics of these units remain poorly understood, even after extensive study (Scott 1966; Winn and Dott 1979; Sohn et al. 2002; Crane 2004; Hubbard et al. 2008). flute casts indicate turbulent flow behavior, whereas matrix-supported divisions indicate cohesive debris-flow-like behavior. Consequently, these rheologically complex flows are best termed slurry flows (sensu Lowe and Guy 2000; Crane 2004), where both cohesive and turbulent forces are active during deposition and complex temporal and/or spatial (head to tail) changes in rheology are likely (Fisher 1983; Sohn et al. 2002). A synonymous term for slurry flow is “hybrid sediment gravity flow” (Haughton et al. 2009). These conglomeratic slurry flow units, although common in the Cerro Toro Formation, seem to be quite rare in the rock record; the closest analog seems to be units from the Proterozoic of Ontario that are interpreted by Miall (1985) as submarine “clast-rich debris flows.”

With much focus on flow rheology, plausible triggering mechanisms for IIIsf have not been fully discussed. Two possible scenarios are envisioned here: the first, which Hubbard et al. (2008) prefer, is a conglomeratic turbidity current (i.e., IIIscg) that erodes and incorporates enough muddy intrabasinal material during downslope movement to change its rheology. Alternatively, IIIsf could be created by large-scale submarine slope failures, where interbedded conglomerate, sandstone, and mudstone are mixed and variably disaggregated during downslope movement. We prefer this mechanism since the high initial sediment concentration in a flow generated by slope failure facilitates the incorporation of large intrabasinal clasts into the flow rather than the flow having to erode the clasts piecemeal. Furthermore, intrabasinal clasts are rare in IIIscg, suggesting that they are not frequently eroded.

**IIIsf—Debris-Flow Conglomerate**

IIIdf deposits, unlike IIIsf, do not have clast supported bases; rather, IIIdf is composed completely of matrix-supported conglomeratic mudstone. Individual sedimentation units are commonly 2-4 m thick and contain randomly dispersed extrabasinal and intrabasinal clasts (cf. upper division in Fig. 3C). IIIdf are much more common in the western part of the Wildcat complex.

**IIIss—hick-Bedded, Amalgamated Sandstone**

IIIss consists predominantly of structureless (Fig. 3E) or dish-structured (Fig. 3F) medium-grained sandstone that is often amalgamated. Granule and pebble lags (Fig. 3F) are commonly found at amalgamation surfaces, suggesting that a significant amount of sediment bypassed this proximal part of the axial channel-belt.

**IIIm—Interbedded Sandstone and Mudstone**

IIIm units are commonly ~ 1 m thick, consisting of interbedded traction-structured sandstone (Fig. 3G) and moderately bioturbated mudstone (Fig. 3G). IIIm can also contain thin beds of conglomerate, usually as local lenses. IIIm in the channel fill is more common in the western part of the Wildcat complex, and out-of-channel IIIm exists in notable quantity adjacent to the eastern margin.

**IIIm—Mudstone with Thin Sandstone Interbeds**

These layered, rhythmic, laminated to thin-bedded mudstone units make up the bulk of the Cerro Toro Formation (Fig. 3H), but make up only 2% (in thickness) of the Wildcat channel fill. Thin-bedded sandstone is sparse, composing about 10–20% of IIIm (Fig. 3H).

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**ASYMMETRY OF THE WILDCAT CHANNEL COMPLEX**

**Units 1, 2, 3, 4, and 5 and Their Lateral Facies Changes**

Vertical changes in lithofacies stacking patterns and accompanying stratigraphic surfaces were used to package the Wildcat channel complex into the five units mapped in the outcrops. Each unit is distinct in terms of facies and architecture, and each records a discrete phase in channel evolution. These units, from oldest to youngest, are (Fig. 4A, B): Unit 1, Unit 2, Unit 3, Unit 4, and Unit 5. These units are hierarchically similar to the fourth-order packaging of Hubbard et al. (2008) and probably
represent individual channels within the Wildcat complex. These units are equivalent in hierarchy to the “channel elements” of Pyles et al. (2010). Each unit in the Wildcat channel complex displays an across-channel westward decrease in amalgamation ratio and the proportion of conglomeratic and amalgamated facies (Figs. 4A, B, 5). Bed-thickness plots do not show any lateral trends that are statistically significant, signifying that amalgamation and facies proportions are the distinguishing characteristics of the Wildcat facies asymmetry. The eastern side of the Wildcat complex consists of highly amalgamated lithofacies onlapping an architecturally simple, steep (averaging 9.4°) margin. The character of the Wildcat channel fill drastically changes westward (Fig. 4A) and is characterized by: (1) the westward decrease in proportion of IIIscg, IIIss, and IIIsf (Figs. 4, 5); (2) the westward increase in proportion of IIIsm and IIIIdf (Figs. 4, 5); and (3) the westward decrease in AR (Fig. 4 inset graphs). The western margin of the Wildcat complex is shallow (averaging 7.1°), heterolithic, and composite, with many internal surfaces and drapes (Fig. 4). These changes are enumerated below for both the north-side and south-side exposures on Sierra del Toro.

**North-Side Exposures of the Wildcat Channel Complex**

**Eastern Margin: North-Side Exposure.**—Nine measured sections (Table 2) document the complete eastern margin of the Wildcat channel complex on the north side of Sierra del Toro (Fig. 4A). Over an across-channel distance of 1.2 km, more than 200 m of channel fill onlaps and pinches out against the margin, resulting in a margin slope of 9.4°. Figure 6 shows the Sarmiento Vista locale, where 100 m of highly amalgamated (AR = 0.93; Fig. 4A inset), predominantly conglomeratic
channel fill onlap the margin surface that is cut into IIIm (Fig. 4A). About 50 m of the onlap occurs between the measured sections SV2 and SV1, where the lowest IIIdf and Unit 1, composed of IIIsf and IIIss, pinch out (Fig. 6). The lowest IIIdf may be a localized slump near the stepped channel margin (Figs. 4A, 6). Unit 2, composed predominantly of IIIsf and about 45 m thick, pinches out abruptly just east of SV1 (Figs. 4A, 6A). Near the eastern margin, Unit 3 consists of IIIsf and IIIss whereas Unit 4 consists of IIIss (Fig. 6). At the Flame section, Units 3 and 4 pinch out against the margin (Figs. 3C, 4A, 7A). Unit 5, composed of IIIsf and local IIIss, pinches out just east of the WC section (Figs. 4A, 7C), and the abandonment of the channel is marked by onlapping IIIsm documented in the CZM sections (Figs. 4A, 7B). The average slope of the eastern margin surface is 9.4° (Fig. 4A), although it is uneven and locally exceeds 15° (Figs. 4A, 6A). This margin resembles the southwestern margin of the Paine complex in the Silla Syncline (Crane and Lowe 2008) as well as the western margin of the axial channel-belt farther south at Cerro Mocho (Hubbard et al. 2008).

A 40-m-thick accumulation of IIIsm is present outside the channel adjacent to Unit 5 at the uppermost eastern margin (section CZM1 in Figs. 4A, 7B). This accumulation may represent a levee deposited by flows overbanking the channel at its eastern margin and flowing down the regional southeast slope. Deposition of the surrounding IIIm would elevate the IIIsm overbank accumulation above the conglomeratic channel fill even more, supporting a levee interpretation. However, lateral exposure is limited and therefore no unambiguous conclusions about the genetic relationship between the IIIsm overbank accumulation and the Wildcat channel fill are possible.

**Wildcat Facies Transition: North-Side Exposure.**—The westward facies changes on the north side of Sierra del Toro are shown in Figure 8, where amalgamated IIIscg, IIIss, and IIIscg/ss at Sarmiento Vista and ETF pass westward into bedded IIIsm and IIIdf at the WTF section. Amalgamation ratio (AR) along this transect decreases from 0.93 to 0.62 (Fig. 4A inset), representing the addition of interbedded mudstone as IIIsm becomes the dominant facies. Each of the units making up the Wildcat complex demonstrate these facies changes (Fig. 5). Unit 1 shows a distinct change from IIIscg and IIIss to IIIsm (Figs. 5, 8). In Unit 2, IIIsf decreases sharply in proportion and is replaced by IIIdf and IIIsm (Figs. 4A, 5, 8). Unit 3 thickens to the west due to the addition of IIIsm at the expense of IIIscg and IIIss (Figs. 4A, 5, 8). Unit 4, IIIss in the east, becomes much less amalgamated and more heterolithic to the west (Figs. 4A inset, 5). Unit 5 is well exposed in the CC section, where it is much less amalgamated (Fig. 4A inset) than in eastern sections. This westward change is manifested in Figure 5 by the sharp drop in the percentage of IIIscg and IIIsf as well as a 35% increase in IIIsm. The eastern margin of the underlying Guanaco channel complex is also exposed in this locale (Fig. 8) and consists of many individual channel fills, composed predominantly of IIIscg and IIIsf, onlapping out-of-channel IIIm. The Guanaco complex can be traced to the south into the CC section (Figs. 2, 9).

**Western Margin: North-Side Exposure.**—Outcrops of the western margin are well exposed at two locations on the north side of Sierra del Toro (Figs. 8, 9). Just west of the WTF section, more than 30 m of Unit 1 onlaps the western margin (Fig. 8). At WTF, Unit 1 is not amalgamated (AR = 0.62; inset of Fig. 4A) and consists of almost 50% IIIsm (Fig. 5). The western margin is also exposed 2.2 km downdip of WTF at the CC section (Figs. 2A, 9), where Units 1–5 are bedded, laterally discontinuous, and exhibit an AR of 0.70 (Fig. 4A inset). Units 1, 2, and 3, constituting over 85 m of heterolithic, non-amalgamated channel fill, lap out onto at least three internal surfaces that collectively form the composite western margin of the Wildcat channel complex (Fig. 9A). A predominance of IIIsm and IIIdf in Units 2 and 3 attests to the muddy, fine-grained nature of the margin (Fig. 5). Scree cover and a post-depositional thrust fault (Figs. 2, 9) preclude the exposure of the onlap of Units 4 and 5 onto the western margin. However, these units are clearly exposed on the south side (see below). The Wildcat western margin closely resembles the northern margin of the Paine complex in the Silla Syncline (Crane and Lowe 2008). The underlying Guanaco channel complex shows margin architecture similar to the Wildcat near the CC section (Fig. 9B), where IIIscg, IIIsm, and IIIsf display multiple pinchout surfaces against the western margin (Fig. 9B).

**South-Side Exposures of the Wildcat Channel Complex**

Units 1–5 are traceable from the north-side exposures to the south side of Sierra del Toro and allow the three-dimensional (3D) characterization of the Wildcat channel complex. Due to cliffy exposures, only three measured sections document the Wildcat complex on the south side (Fig. 4B). However, outcrop photomosaics demonstrate that, as on the north side, the south-side exposures of the Wildcat channel complex display marked lateral changes in amalgamation ratio (inset of Fig. 4B) and facies proportions (Fig. 5), and the eastern and western margin architectures considerably differ.

**Eastern Margin: South-Side Exposure.**—The south-side exposure of the eastern margin records the onlap of 110 m of channel fill over a distance of 680 m, resulting in a margin slope of 9.1°, similar to that in the northern exposure. The AR of the south-side exposure of the eastern Wildcat channel fill is quite high (0.90; Fig 4B inset) and Units 3–5 appear massive and conglomeratic in outcrop (Fig. 7D). Units 1 and 2, near the eastern margin, are poorly exposed (Figs. 2C, 7D), but probably onlap the eastern margin just west of the H2O section. Unit 3, composed
Fig. 4.—Depositional-strike correlation panels of the Wildcat channel complex (see Fig. 2 for location). Paleoflow is into the page for both panels. A) North-side correlation panel, displaying 12 measured sections across 3.5 km of channel fill that document the evolution of Units 1–5. The eastern margin is steep (9.4°) and overlapped by amalgamated, conglomeratic facies. A facies change occurs to the west, and the western Wildcat consists of thin-bedded, less amalgamated facies such as IIIsm and IIIdf. B) South-side correlation panel, displaying three measured sections across 3.5 km of channel fill. The eastern and western margins of the Wildcat are exposed on the south side (Figs. 2, 7, 12), and the facies change is drastic from east to west.
FIG. 4.—Continued.

FACIES AND ARCHITECTURAL ASYMMETRY OF A SUBMARINE CHANNEL FILL, CERRO TORO FM, CHILE

For detail, see Figs. 10-11
of IIIscg and IIIss, and Unit 4, composed of IIIss, pinch out progressively onto the eastern margin just east of the H2O section (Figs. 4B, 7D). Unit 5, composed of IIIscg, continues to the east, pinching out east of the SSM section (Figs. 2C, 4B).

Wildcat Facies Transition: South-Side Exposure.—The westward facies changes in the Wildcat complex are also well exposed on the south side of Sierra del Toro at the “Rocas” locale (Fig. 10). The Rocas section (Fig. 4B) represents a point midway in this transition, where facies proportions are similar to the ETF section on the north side of Sierra del Toro (Figs. 2, 4A, 5). Just northwest of the Rocas section, Unit 1 changes from IIIscg and IIIss to IIIsm and Unit 2 changes from IIIsf to IIIsm and IIIdf (Figs. 4B, 10). The IIIscg and IIIss of Unit 3 and the IIIss of Unit 4 also show the facies transition westward into IIIsm (Figs. 4B, 10). These facies changes are characterized at the bed scale by the progressive thinning and loss of IIIscg into IIIss, which is replaced by IIIsm (inset of Fig. 10). Unit 5 remains conglomeratic at this locale (Fig. 10), but eventually thins and fines to the west (Fig. 11). The lowest IIIsf unit (Figs. 4B, 10, 11) may be part of the Guanaco complex, but exact correlation from the north side is not possible due to scree cover.

Western Margin: South-Side Exposure.—The final pinchout of the western margin of the Wildcat channel complex is fully exposed on the south side of Sierra del Toro (Fig. 11). Unlike the eastern margin, the western margin is not a steep, amalgamated, single surface. Rather, the western margin is composite and consists of multiple erosional surfaces, some of which are draped. The onlap of 200 m of channel fill over 1.6 km results in a non-decompacted margin angle of 7.1°, which is shallower than that of the eastern margin. Not all beds terminate against the basal margin surface (Figs. 4B, 11): Units 1 and 2 seem to onlap the basal margin surface, whereas Units 3–5 pinch out onto multiple internal surfaces. The last occurrence of IIIscg on the western side is about 400 m from the final pinchout, and IIIsm continues until the final pinchout of the western margin (Fig. 11). This contrasts the eastern margin, where IIIscg directly abuts IIIm at the final pinchout (Fig. 7). Beneath and adjacent to the western-margin surface, the out-of-channel mudstone, IIIm, contains no overbank IIIsm accumulation similar to that at the eastern margin (cf. Fig. 7).

DISCUSSION

Meander-Bend Architecture of the Cerro Toro Axial Channel-Belt

The axial channel-belt of the Cerro Toro Formation displays very low (1.06) sinuosity (Fig. 1; Hubbard et al. 2008). The exposure at Sierra del Toro allows for the detailed analysis of a single right-hand meander bend in the axial channel-belt (orange dashed line in Fig. 2A). Evidence in the Wildcat channel complex for this low-sinuosity meander bend includes: (1) the facies asymmetry and distribution; (2) the modest architectural asymmetry; (3) the contrasting morphology and stratigraphic architecture of the margins; and (4) the sandy overbank accumulation that is found adjacent to the amalgamated and steep (eastern) margin. The amalgamated, thick-bedded, conglomeratic facies and the steep, simple margin in the eastern Wildcat form the outer bank of the meander bend, complete with a sandy (IIIsm) overbank accumulation adjacent to Unit 5 (Figs. 4A, 5, 6, 7). In the western Wildcat, the thin-bedded, non-amalgamated, fine-grained facies (Figs. 4, 5), the shallow, composite margin with many internal onlap surfaces (Figs. 9, 11), and the absence of sandy overbank facies (Figs. 9, 11) are most consistent with deposition on the inner bend of a meandering channel. The Puchkirchen axial channel-belt in the Molasse basin of Austria forms a notable analog for the very low sinuosity and channel architecture seen in the Wildcat (cf. Hubbard et al. 2009).

Differing Margin Architecture and Facies of the Wildcat Channel Complex.—Although locally exceeding 15°, the outer (eastern) bank of the Wildcat channel complex has an average angle of 9.4°, whereas that of the inner (western) bank is 7.1°. The modest architectural asymmetry is attributed in part to the low sinuosity of the axial channel-belt, inasmuch as higher sinuosity submarine channels have been shown to have greater architectural asymmetry (Pirmez and Flood 1995; Babonneau et al. 2002; Antobreh and Krastel 2006; Pyles et al 2010).
Table 2.—Characterization and AR (amalgamation ratio) of the 19 stratigraphic sections measured at Sierra del Toro.

<table>
<thead>
<tr>
<th>Section abbrev.</th>
<th>Measured section name</th>
<th>Side of Sierra del Toro</th>
<th>Thickness (m)</th>
<th>Wildcat channel-fill thickness (m)</th>
<th>Average thickness of IIIscg / IIIss</th>
<th>Average thickness of IIIsm / IIIm</th>
<th>Amalgamation Ratio (AR)</th>
<th>Average flow direction / of indicators</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZM1</td>
<td>Chorrillo Zapata Margin 1</td>
<td>North</td>
<td>29</td>
<td>0</td>
<td>N/A</td>
<td>210 / 24 cm</td>
<td>0.48</td>
<td>167° / 16</td>
<td>Overbank IIIsm accumulation at E margin</td>
</tr>
<tr>
<td>CZM2</td>
<td>Chorrillo Zapata Margin 2</td>
<td>North</td>
<td>12</td>
<td>0</td>
<td>N/A</td>
<td>120 30</td>
<td>0.50</td>
<td>106° / 8</td>
<td>Channel abandonment IIIsm facies at E margin</td>
</tr>
<tr>
<td>CZM3</td>
<td>Chorrillo Zapata Margin 3</td>
<td>North</td>
<td>16</td>
<td>0</td>
<td>N/A</td>
<td>78 29</td>
<td>0.45</td>
<td>–</td>
<td>Channel abandonment IIIsm facies at E margin</td>
</tr>
<tr>
<td>CZM4</td>
<td>Chorrillo Zapata Margin 4</td>
<td>North</td>
<td>26</td>
<td>0</td>
<td>N/A</td>
<td>86 21</td>
<td>0.47</td>
<td>162° / 12</td>
<td>Channel abandonment IIIsm facies at E margin</td>
</tr>
<tr>
<td>CZM5</td>
<td>Chorrillo Zapata Margin 5</td>
<td>North</td>
<td>40</td>
<td>3</td>
<td>2 m / 40 cm</td>
<td>140 29</td>
<td>0.52</td>
<td>168° / 45</td>
<td>Channel abandonment IIIsm facies at E margin</td>
</tr>
<tr>
<td>WC</td>
<td>Wildcat Thrust</td>
<td>North</td>
<td>70</td>
<td>32</td>
<td>88 / 90 cm</td>
<td>1.2 / 0.25 m</td>
<td>0.73</td>
<td>–</td>
<td>Channel fill &amp; abandonment IIIsm facies at E margin</td>
</tr>
<tr>
<td>Flame</td>
<td>Flame</td>
<td>North</td>
<td>105</td>
<td>105</td>
<td>3.2 m / 94 cm</td>
<td>63 13</td>
<td>0.76</td>
<td>086° / 66</td>
<td>Amalgamated eastern side of the Wildcat</td>
</tr>
<tr>
<td>SV1</td>
<td>Sarmiento Vista 1</td>
<td>North</td>
<td>147</td>
<td>147</td>
<td>170 / 90 cm</td>
<td>N/A / 43</td>
<td>0.93</td>
<td>127° / 54</td>
<td>Amalgamated eastern side of the Wildcat</td>
</tr>
<tr>
<td>SV2</td>
<td>Sarmiento Vista 2</td>
<td>North</td>
<td>197</td>
<td>197</td>
<td>95 / 118 cm</td>
<td>N/A / 18</td>
<td>0.88</td>
<td>172° / 193</td>
<td>Amalgamated eastern side of the Wildcat</td>
</tr>
<tr>
<td>ETF</td>
<td>Eastern Thrust Fault</td>
<td>North</td>
<td>252</td>
<td>184</td>
<td>150 / 61 cm</td>
<td>44 9</td>
<td>0.80</td>
<td>164° / 127</td>
<td>Transitional central zone of the Wildcat</td>
</tr>
<tr>
<td>WTF</td>
<td>Western Thrust Fault</td>
<td>North</td>
<td>224</td>
<td>181</td>
<td>120 / 78 cm</td>
<td>2.6 36</td>
<td>0.62</td>
<td>128° / 106</td>
<td>Western bedded side of the Wildcat</td>
</tr>
<tr>
<td>CC</td>
<td>Central Canyon</td>
<td>Central</td>
<td>330</td>
<td>294</td>
<td>2 m / 97 cm</td>
<td>2.4 14</td>
<td>0.70</td>
<td>157° / 189</td>
<td>Full thickness of the Wildcat</td>
</tr>
<tr>
<td>SSM</td>
<td>South Side Margin</td>
<td>South</td>
<td>63</td>
<td>23</td>
<td>N/A / 74 cm</td>
<td>1.7 32</td>
<td>0.59</td>
<td>164° / 42</td>
<td>Channel fill &amp; abandonment IIIsm facies at E margin</td>
</tr>
<tr>
<td>H2O</td>
<td>Waterfall</td>
<td>South</td>
<td>95</td>
<td>95</td>
<td>1.6 / 1.1 m</td>
<td>N/A / 17 cm</td>
<td>0.90</td>
<td>157° / 31</td>
<td>Amalgamated eastern side of the Wildcat</td>
</tr>
<tr>
<td>Rocas</td>
<td>Rocas dip face</td>
<td>South</td>
<td>315</td>
<td>315</td>
<td>1.9 / 1.2 m</td>
<td>3.2 / 0.5 m</td>
<td>0.95</td>
<td>177° / 88</td>
<td>Full preserved thickness of the Wildcat</td>
</tr>
<tr>
<td>SC</td>
<td>Snowy Cliff</td>
<td>South</td>
<td>65</td>
<td>0</td>
<td>3.8 / 1.3 m</td>
<td>50 / 20 cm</td>
<td>0.83</td>
<td>197° / 29</td>
<td>Undifferentiated channel fill above the Wildcat</td>
</tr>
<tr>
<td>DC1</td>
<td>Downcutting 1</td>
<td>South</td>
<td>92</td>
<td>0</td>
<td>100 / 57 cm</td>
<td>118 / 7 cm</td>
<td>0.68</td>
<td>165° / 91</td>
<td>Undifferentiated channel fill above the Wildcat</td>
</tr>
<tr>
<td>DC2</td>
<td>Downcutting 2</td>
<td>South</td>
<td>18</td>
<td>0</td>
<td>96 / 49 cm</td>
<td>200 / 7 cm</td>
<td>0.76</td>
<td>117° / 4</td>
<td>Undifferentiated channel fill above the Wildcat</td>
</tr>
<tr>
<td>SW</td>
<td>Slurry Wall</td>
<td>North</td>
<td>69</td>
<td>0</td>
<td>1.6 / 1 m</td>
<td>320 / 11 cm</td>
<td>0.81</td>
<td>–</td>
<td>Undifferentiated channel fill above the Wildcat</td>
</tr>
</tbody>
</table>
FIG. 6.—The eastern, amalgamated side of the Wildcat channel complex (north-side exposure). White and red dashed lines indicate the margin surface and the unit boundaries, respectively.

A) Outcrop photo of the eastern side, demonstrating the onlap of more than 100 m of channel fill (white dashed line is the margin surface). Paleoflow is into the page and obliquely to the right. In the background of the photo, the rest of the channel fill onlaps the margin surface (see Fig. 7). Arrows at upper left denote the perspective of photos in Figure 7.

B) Outcrop photo of the amalgamated facies (AR = 0.90) of the eastern side of the Wildcat. Inset shows geologist for scale; more than 200 m of channel fill are exposed on this outcrop face. Fourth-order Units 1, 2, 3, 4, and 5 are discussed throughout the text. Units 3, 4, and 5 can be correlated to those seen in Figure 7C, D.

FIG. 7.—Eastern margin of the Wildcat channel complex on Sierra del Toro (north-side and south-side exposures). A) View to south that shows the rapid thinning of over 100 m of channel fill (foreground) onto the margin surface. Paleoflow is obliquely to the right and into the page. Dashed box shows location of Part B; see Part C for perspective location. B) The easternmost channel-fill and overbank deposits of the Wildcat complex; location provided in Part A. Unit 5 (IIIscg) pinches out just east of CZM5, and the IIIsm abandonment fill pinches out just to the east. Note the IIIsm overbank accumulation measured in CZM1 that lies adjacent to Unit 5, the uppermost channel fill. C) Looking onto the northern exposure of the eastern margin, where Units 4 and 5 onlap. Note the perspective location of Part A and the location of Fig. 6 around the corner. D) The southern exposure of the eastern margin, where Units 3, 4, and 5 onlap the margin from left to right (i.e., west to east). Note the highly amalgamated nature of this exposure.
The packaging of the Wildcat complex into Units 1–5 suggests multiple episodes of channel incision and filling, but the morphology and preservation of the resultant surfaces and internal margins differs significantly at the eastern and western margins. It is likely that due to centrifugal effects and elevated shear stress, currents preferentially eroded the eastern outer bank and deposited amalgamated coarse-grained facies, leading to its steep, conglomeratic, amalgamated nature (Figs. 4, 6, 7). The stepped nature of the eastern margin (Fig. 6) probably represents margins of individual units; however, severe amalgamation has rendered these multiple surfaces into a single, steep, stepped outer bank. The IIIsm overbank sandstone accumulation adjacent to the outer bend of the Wildcat complex (Figs. 4A, 7) likely represents the deposits of turbidity currents that experienced flow stripping (sensu Piper and Normark 1983) around the outer bend of the Wildcat channel complex. Although a levee accumulation is expected in the overbank of the outer bend (cf. Posamentier 2003) and levees have been identified elsewhere in the axial channel-belt (Hubbard et al. 2008), no definitive levee geometries are apparent on Sierra del Toro (Fig. 7).

Flows interacted differently with the inner bend, where lower shear stress resulted in the fine-grained and non-amalgamated nature of the western margin (Figs. 4, 5). The lack of large-scale erosion and amalgamation during the multiple incision and fill episodes of Units 1–5 led to the preservation of each unit’s margin, resulting in a heterolithic, complicated, composite western margin (Figs. 4, 9, 11). This style of

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**FIG. 8.—** Facies transition in the central Wildcat (north-side exposure). Inset shows location of photo on the north side of Sierra del Toro. From measured section ETF to WTF, amalgamation decreases from 0.80 to 0.62 and the proportion of IIIss and IIIscg decreases by 22% (Fig. 5). This lateral facies change is also expressed by a decrease in clifffy exposures. The Guanaco channel complex is also present in this locale, and it pinches out to the east and west. Thrust faulting is focused at this locale, probably due to loss of structural rigidity caused by the facies transition.

**FIG. 9.—** Western margin of the Wildcat complex (north-side exposure). A) The complicated margin architecture that characterizes the western margin as well as the westward bed thinning and loss of conglomerate. Units 1, 2, and 3 transition here into IIIsm and then into out of channel mudstone (IIIm). Unfortunately, a fault and scree obscures the pinchout of Units 4 and 5; however, those are clearly exposed on the south side (see Fig. 12). Inset shows location of Part B. B) Close-up view of the western margin; see Part A for location of photo. Note the geologist for scale. The complicated margin architecture is demonstrated by both the Wildcat and Guanaco complexes.
inner-bank architecture has also been documented in modern sinuous submarine channels (Antobreh and Krastel 2006). The conglomeratic basal region of flows did not reach the western margin, resulting in the in-channel deposition of IIIsm near the margin. Since these IIIsm deposits occur within the confines of the channel fill, they may represent inner-levee deposits (cf. Hubbard et al. 2008).

**Lack of Lateral Accretion Deposits.**—The architectural and facies asymmetry in the Wildcat channel complex agree with models of normal helical circulation within sinuous submarine channels (Johannesson and Parker 1989; Abreu et al. 2003; Pirmez and Imran 2003; Straub et al. 2008); “reverse” helical flow (Keevil et al. 2006; Keevil et al. 2007; Peakall et al. 2007) is not supported by the observed facies data in this study. Lateral accretion deposits (Abreu et al. 2003; Arnott 2007; Dykstra and Kneller 2009; Pyles et al. 2010) are expected in sinuous submarine channels with normal helical flow. However, no lateral accretion deposits are observed in the Wildcat channel complex, suggesting that there was no migration of the channel or erosion of the banks during deposition. The IIIIm that composes the banks may have been compacted and cohesive, resisting major bank erosion and lateral migration. Alternatively, the Wildcat complex may have been entrenched and aggradational due to levee growth, a commonly documented stage in the evolution of submarine channels (Clark and Pickering 1996; Peakall et al. 2000; Kolla et al. 2007). In the Magallanes basin, levee confinement may have been a factor, but the higher-order confinement of the axial channel-belt by the foredeep probably was the driving factor for preventing the development of sinuosity and lateral accretion (cf. Hubbard et al. 2005; Hubbard et al. 2008; Hubbard et al. 2009). The structurally-induced prevention of sinuosity has also been documented on the modern seafloor (Clark and Cartwright 2009). The Wildcat channelform was probably cut by highly erosive flows, setting up the very low-sinuosity meandering profile. The channelform was then filled in an aggradational manner, with multiple episodes of incision and filling (Units 1–5 in Figs. 4, 9, 11) without significant lateral migration of the channel. The abandonment phase is represented in the Wildcat complex by the thin IIIsm package that overlies the conglomeratic channel fill (Figs. 4A, 7B).

**Paleoflow Patterns in the Wildcat Channel Complex: Loss of Confinement and Consequent Overbank Deposition**

The dominant paleoflow direction in the Cerro Toro axial channel-belt is to the south-southeast (Scott 1966; Winn and Dott 1979; Hubbard et al. 2008). The Guanaco complex and thin-bedded turbidites beneath the Wildcat complex also display south-southeast-directed paleoflow patterns, down the inferred regional slope of the axial channel-belt (Fig. 2A). In the Wildcat complex, south-southeastward paleoflow patterns are consistent across the channelform in Units 1 (155° ± 20° in the format mean ± 1σ), 2 (157° ± 17°), and 3 (164° ± 15°) (Fig. 12). In Units 4 and 5, however, paleoflow directions are not unidirectional, but exhibit divergence across the channel. In Unit 4, paleoflow was 162° ± 42° in the east and 225° ± 10° in the west (Fig. 12). In Unit 5, paleoflow was 121° ± 23° in the east and 230° ± 7° in the west (Fig. 12).

Consistent south-southeastward paleoflow in Units 1–3 indicate that the flows were fully confined within the channel. This inference is...
supported by the lack of sandy overbank accumulations adjacent to Units 1, 2, and 3 (Fig. 4). Diverging paleoflow directions in Units 4 and 5 of the Wildcat channel fill are thought to reflect the gradual loss of confinement as the channel filled and flows were able to overtop the banks. Currents flowing through the Wildcat channel complex during deposition of Units 4 and 5 were not fully confined and consequently spread out within the channel and spilled out of the channel along the outer bank (Fig. 12). The sandy overbank accumulation on the outer bank adjacent to Unit 5 (Figs. 4A, 7B) displays southeast paleoflow directions (Fig. 12), indicating that the flows, once outside the channel, moved down the regional basin slope. The undifferentiated channel fill lying above and to the west of the Wildcat complex shows southwestward paleoflow (Fig. 2A) and may represent the continuation of this spillover that eventually resulted in channel avulsion. However, exposure is limited in the undifferentiated unit (Fig. 2A), and no unambiguous conclusions about the genetic relationship between it and the Wildcat complex are possible.

Predictive Depositional Model of Sinuous, Asymmetric Submarine Channels

Studies of sinuous submarine channels (e.g., Kneller 1995; Peakall et al. 2000) generally focus on channel morphology and spatial evolution, but relatively few have provided details of internal facies distributions and architecture, which are essential for numerical and experimental models (Zeng and Lowe 1997; Imran et al. 1999; Peakall et al. 2007; Straub et al. 2008). The few studies providing facies data on sinuous submarine channel fill (Campion et al. 2000; Hickson and Lowe 2002) lack the full set of data concerning internal variations in grain size, facies, and amalgamation crucial for input into numerical or more generalized models of channel evolution. This study provides this detailed internal facies data for a very well exposed, large-scale channel complex. Furthermore, the Wildcat complex is a natural system, eliminating problems of scaling common to numerical and experimental models.

Figure 13 is a generalized summary of the Wildcat channel complex that incorporates the observed architectural and facies asymmetry and meander bend architecture discussed above. The schematic model shows a theoretical flow traversing the channel and depositing amalgamated, coarse-grained channel-fill facies and sandy overbank deposits adjacent to a steep erosional margin that forms the outer bend of the channel (Fig. 13). These features contrast with the thinner-bedded, low net-to-gross channel-fill facies and muddy overbank deposits adjacent to a shallow, composite margin along the inner bend (Fig. 13). Due to the very low sinuosity, the channel shows modest architectural asymmetry at the bends (A–A’, C–C’ of Fig. 13), and is probably symmetric in straight reaches and near inflection points (B–B’ of Fig. 13). Hydraulic considerations and the observed differences in channel geometry and internal fill in sinuous fluvial channels (Leopold and Wolman 1960) and submarine channels (Campion et al. 2000; Pyles et al. 2010) suggest that the key elements of this observational model of the Wildcat channel complex have applicability in predicting the general facies distributions and channel geometries in other sinuous submarine channels, especially where exposures are poor or only seismic data is available. For higher-sinuosity channels, the architectural and facies asymmetry should be even more pronounced than for low-sinuosity channels; unfortunately, quantifying the correlation between asymmetry and sinuosity is not possible at this time due to the limited data available. Finally, this model
Three scenarios are possible for the formation of a knickpoint in the axial channel-belt at Sierra del Toro. The first is a deep-seated north–south-trending rift graben inherited from Late Jurassic back-arc extension of the predecessor Rocas Verdes basin (Fig. 1D; Biddle et al. 1986; Fildani and Hessler 2005). Subsurface seismic reflection data indicate the presence of such a graben 20 km downdip (Fosdick et al. 2009) that may extend northward and tip out underneath Sierra del Toro. These grabens potentially were still undergoing thermal subsidence during Cerro Toro deposition and may have caused a steepening downslope gradient under Sierra del Toro. The channel architecture expected by this first scenario may be similar to that shown by Heinio and Davies (2007). The second scenario is a knickpoint caused by the downstream confluence of the axial channel-belt and the Silla Syncline tributary system postulated by Crane and Lowe (2008) and Hubbard et al. (2008). The sediment added to the system at this confluence may have generated enhanced local erosion, leading to the formation of a knickpoint that then migrated upstream in the axial channel-belt to Sierra del Toro. The third scenario is a knickpoint created by a southward-dipping (“down-to-the-basin”) growth-fault system. The presence of southward-dipping growth faults and associated mini-basin fill have been demonstrated in overlying Tres Pasos deposits just 5 km east of Sierra del Toro (Shultz and Hubbard 2005). Furthermore, Figure 14C demonstrates the presence of southward-dipping normal faults on the east side of Sierra del Toro that presumably continue west beneath the Wildcat channel complex. These faults, if syndepositional, would have resulted in the formation of a knickpoint, perhaps similar in geometry to that documented on the modern seafloor (Adeogba et al. 2005).

**Application to Hydrocarbon Exploration**

Facies asymmetry in submarine channels (Stelting et al. 1985a; Stelting et al. 1985b; Campion et al. 2000) can provide significant barriers or baffles to fluid flow in reservoirs within submarine channel fill. Exposures of the Wildcat complex show that across a “reservoir/full field scale” channel fill, significant changes in facies and AR occur within and between Units 1–5 (Figs. 4, 13). These lateral facies changes may severely impact vertical and horizontal permeability across a similar reservoir. Most of these facies variations are small enough to lie below seismic resolution, which would result in poor facies prediction and unexpected borehole results. Furthermore, these facies changes take place over a distance of about 1 km (Figs. 4A, 5), a much smaller distance than typical deep-water well spacing. The differing margin architecture documented here also has implications for reservoir heterogeneity: the amalgamated, steep, outer-bank margin contains many units that provide quality reservoir facies, but the complicated, heterolithic nature of the inner-bank fill not only indicates low-quality reservoir facies but also the presence of severe baffles and barriers for fluid flow in a petroleum reservoir. The data and depositional model presented here can aid in formulating development strategies in reservoirs within sinuous submarine channels. Also, the facies data presented in this study can provide input for more quantitative reservoir models of asymmetric submarine channel fill rather than the simple models currently in use that commonly depict homogeneous channel fill (Labourdette 2007; Sweet and Sumpter 2007).

**Conclusions**

The 3.5 km wide, 300 m thick Wildcat channel complex on Sierra del Toro represents the proximal portion of the axial channel-belt of the Upper Cretaceous Cerro Toro Formation in the Magallanes retro-arc foreland basin, Chile. The Wildcat complex displays strong facies asymmetry and modest cross-sectional, or architectural asymmetry. Paleocurrent patterns within the channel complex and the geometry of
its margins indicate that the axial channel-belt in this locale had a very low sinuosity and was characterized by flows moving to the south-southeast. The Wildcat complex is interpreted to represent part of a gentle right-hand meander bend of the axial channel-belt. Around this bend the channel was characterized by a simple, erosional outer bank and a heterogeneous, composite inner bank. Outer-bend facies are highly amalgamated, conglomeratic, and thick-bedded while inner-bend facies are sandy–muddy, thin-bedded, and not amalgamated. A sandy overbank accumulation exists only adjacent to the outer bend. Turbidity currents flowing through the axial channel-belt responded to the low sinuosity by preferentially depositing coarse sediment in the outer bend as well as in the overbank due to flow momentum and centrifugal forces. The lack of lateral accretion deposits indicates that the channel belt was entrenched and not migrating laterally. The early evolution of the channel fill was characterized by flows that were fully confined by the channel. During the late stage of channel evolution, flow directions became divergent towards the margins, suggesting that flows were beginning to spill outside of the channel, an inference supported by the overbank sandstone accumulation along the outer bend.

The observed facies and cross-sectional asymmetry in the Wildcat complex probably characterize the fill of most sinuous submarine channels, and greater facies and cross-sectional asymmetry is expected with higher sinuosity channels. This asymmetry can result in highly compartmentalized reservoirs and therefore needs to be incorporated into subsurface models. Furthermore, the abundant data concerning channel asymmetry presented here can be used to refine flume experiments and numerical models of sinuous submarine channel evolution.

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FIG. 14.—Correlation panel demonstrating the downdip architectural changes of the Wildcat channel complex, perhaps due to the presence of an intrachannel knickpoint. A) Correlation panel showing the observed downcutting of the undifferentiated channel fill above the Wildcat as well as the inferred downcutting of the base of the Wildcat complex from north to south. These downcutting events are interpreted to be knickpoints in the channel belt responding to a gradient steepening. This steepening is likely due to the presence of N-S rift grabens inherited from the predecessor basin. B) Amalgamation ratio (AR) transect down depositional dip, showing that the increase in both indices corresponds with the presence of the knickpoints. C) Photo of the eastern flank of Sierra del Toro (see inset map in Part A for location) that demonstrates the presence of southward-dipping normal faults that may extend to the west beneath the channel fill. These faults may be syndepositional and related to an intrachannel knickpoint that is responsible for the downdip changes in architecture of the Wildcat channel complex.


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