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Sedimentary Facies and Architecture of a Gigantic Gravelly Submarine Channel System in a Cretaceous Foredeep Trough (the Magallanes Basin, Southern Chile)

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Abstract : The Lago Sofia conglomerate in southern Chile is a deep-marine gravelly deposit, which is hundreds of meters thick and kilometers wide and extends laterally for more than 100 km, filling the foredeep trough of the Cretaceous Magallanes Basin. For understanding the depositional processes and environments of this gigantic deep-sea conglomerate, detailed analyses on sedimentary facies, architecture and paleoflow patterns were carried out, highlighting the differences between the northern (Lago Pehoe and Lago Goic areas) and southern (Lago Sofia area) parts of the study area. The conglomerate bodies in the northern part occur as relatively thin (< 100 m thick), multiple units intervened by thick mudstone-dominated sequences. They show paleoflows toward ENE and S to SW, displaying a converging drainage pattern. In the southern part, the conglomerate bodies are vertically interconnected and form a thick (> 400 m thick) conglomerate sequence with rare intervening fine-grained deposits. Paleoflows are toward SW. The north-to-south variations are also distinct in sedimentary facies. The conglomerate bodies in the southern part are mainly composed of clast-supported conglomerate with sandy matrix, which is interpreted to be deposited from highly concentrated bedload layers under turbidity currents. Those in the northern part are dominated by matrix- to clast-supported conglomerate with muddy matrix, which is interpreted as the products of composite mass flows comprising a turbidity current, a gravelly hyperconcentrated flow and a mud-rich debris flow. All these characteristics suggest that the Lago Sofia conglomerate was formed in centripetally converging submarine channels, not in centrifugally diverging channels of submarine fans. The tributaries in the north were dominated by mass flows, probably affected by channel-bank failures or basin-marginal slope instability processes. In contrast, the trunk channel in the south was mostly filled by tractive processes, which resulted in the vertical and lateral accretion of gravel bars, deposition of gravel dunes and filling of scours and channels, similar to deposits of terrestrial gravel-bed rivers. The trunk channel developed along the axis of foredeep trough and its confinement within the trough is probably responsible for the thick, interconnected channel fills. The large-scale architecture of the trunk-channel fills shows an eastward offset stacking pattern, suggesting that the channel migrated eastwards most likely due to the uplift of the Andean Cordillera.

Key words : submarine channel, foredeep, deep-sea conglomerate, architectural elements

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1. Introduction

Submarine channels are the major routes of sediment transport on the ocean floor and an integral part of submarine fans, which make up the most prolific hydrocarbon reservoirs among a variety of deep-marine depositional systems (Clark and Pickering 1996a; 1996b). Oceanographic surveys on modern submarine channels reveal that they comprise a number of fluvial features, apparently similar to those of terrestrial rivers, including high to low channel sinuosity, meander belts, point bars, braided channels, and crevasse splays (Hagen et al. 1994; Damuth et al. 1995; Klaucke and Hesse 1996; Klaucke et al. 1998), although there can be significant differences in channel morphology, evolution, and depositional processes between the subaerial and submarine varieties (Peakall et al. 2000). The dimension and planform geometry of channels and their downslope changes are also as varied as those of terrestrial fluvial systems (Flood and Damuth 1987; Clark et al. 1992; Clark and Pickering 1996b). Hesse (1989) suggested, for example, that there may be at least two submarine drainage patterns: one of centrifugally diverging distributaries on submarine fans and the other of centripetally converging tributaries that join a major trunk channel.

Recognizing the channel characteristics is crucial for understanding the nature and morphological evolution of ancient channel systems and predicting the spatial variation of reservoir characteristics (e.g., Wonham et al. 2000). These characteristics cannot, however, be measured

or inferred reliably from ancient strata in most cases because of limited extent and occurrence of outcrops. This situation led workers on ancient channels, either submarine or terrestrial, to rely on architectural element analysis in addition to conventional lithofacies analysis to infer the channel characteristics (Miall 1989; Clark and Pickering 1996a). In spite of these efforts, there has been a large gap in the scale of observations between modern and ancient systems, resulting in the lack of common dataset for comparing modern and ancient channels (Mutti and Normark 1987; Clark and Pickering 1996b). It is therefore of great concern to fill the gap between the different datasets and link the planform characteristics with the cross-sectional characteristics of submarine channels.

The Lago Sofia conglomerate (abbreviated as LSC) in the Cretaceous Cerro Toro Formation, southern Chile (Fig. 1), is deep-marine gravelly deposits, which are hundreds of meters thick, kilometers wide, and extend laterally for up to 100 km (Scott 1966). The LSC has been formerly interpreted as channel-levee complexes developed upon a submarine fan (Winn and Dott 1979). Recent studies debate on the nature of the channels whether they represent leveed-channel complexes (DeVries and Lindholm 1994; Beaubouef et al. 1996; Beaubouef 2004) or backfilled erosional channel complexes without levees (Coleman 2000; Crane and Lowe 2001). The authors believe that an understanding of the nature of the overall LSC depositional system is necessary before an in-depth examination and debate on the characteristics and nature of the channel-fill units in the LSC depositional system.

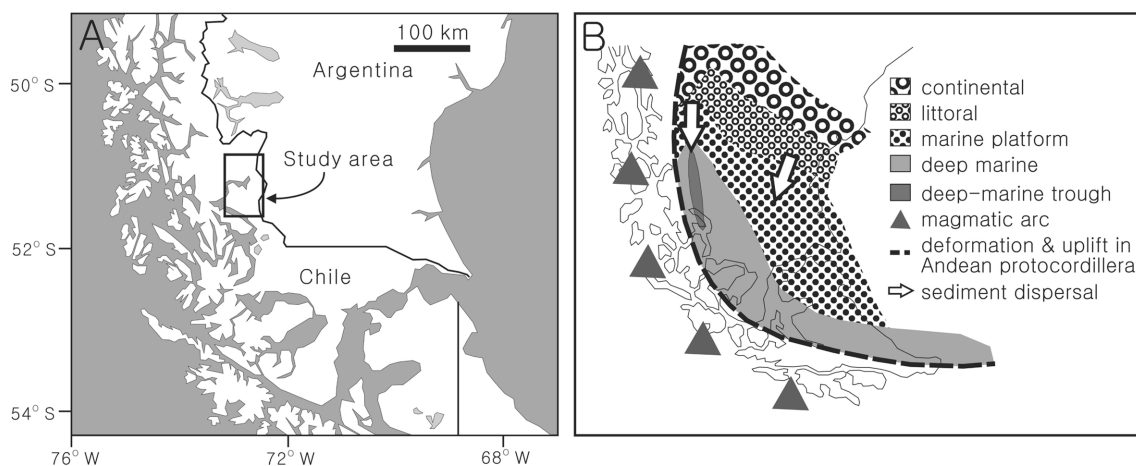


Fig. 1. (A) Location map of the study area. (B) Depositional setting of the Magallanes Basin during the middle to late Cretaceous, consisting of a deep, N-S-trending foredeep trough adjacent to the western margin and a gently sloping foreland ramp in its central and eastern parts. The Magallanes Basin was formed by flexural subsidence due to thrust loading to the east of the uplifted Andean proto-cordillera (Biddle et al. 1986; Wilson 1991)

The primary objective of this paper is to document the overall lithofacies characteristics of the LSC and their north-to-south (proximal-distal) variations along the LSC depositional system in order to provide an overview of the nature of the LSC submarine channel system. An architectural analysis has also been carried out for an exposure of the presumed axial trunk channel in the downstream reach of the LSC submarine channel system in an attempt to infer the evolution of the LSC submarine channel system.

2. Geological setting

The study area (Fig. 1) is located in the Cretaceous Magallanes Basin along the southwestern margin of the South America and east of the Andes cordillera. The southern South America was subject to crustal extension associated with the breakup of the Gondwana supercontinent during the Middle to Late Jurassic (Dalziel et al. 1987). As a result of the extension, isolated continental rift basins and a back-arc basin (Rocas-Verdes Basin) developed along the Pacific margin (Hathway 2000). During the early Cretaceous, deformation style changed from extension to compression because of the onset of the Andean orogeny, which led to the closure of the back-arc basin and partial obduction of the basin floor onto the craton margin (Dalziel and Brown 1989). The flexural subsidence due to the thrust loading together with compression in the adjacent orogenic belt resulted in the development of a foreland basin (Magallanes Basin) to the east of the eastward vergent Andean fold-thrust belt (Biddle et al. 1986; Wilson 1991).

The Magallanes Basin consisted of a deep, N-S-trending foredeep trough adjacent to the western margin and a gently sloping foreland ramp in its central and eastern parts (Biddle et al. 1986; Wilson 1991) (Fig. 1B). Throughout the late Cretaceous, arc- and cordillera-derived clastic sediments, volcanic, plutonic, and metamorphic in origin, were dispersed axially along the foredeep trough, resulting in deposition of a thick (6.5–7.5 km) succession of deep-marine strata, including the Cerro Toro Formation (Cecioni 1957; Katz 1963; Scott 1966; Winn and Dott 1979). In the eastern part of the basin, shallow marine and slope environments persisted, which were relatively sediment-starved and prograded slowly to the southwest (Biddle et al. 1986). The geometry and depositional regime of the basin persisted for about 30 Ma until the latest Cretaceous. During the Maastrichtian, deformation in the Patagonian fold-thrust belt began to migrate eastward,

producing substantial changes in basin geometry and sediment dispersal patterns (Biddle et al. 1986; Wilson 1991). Clastic material was shed eastward from the rising cordillera, and the basin depocenter shifted eastward and widened to encompass the former foreland ramp.

The Cerro Toro Formation is composed of *ca.* 2000 m

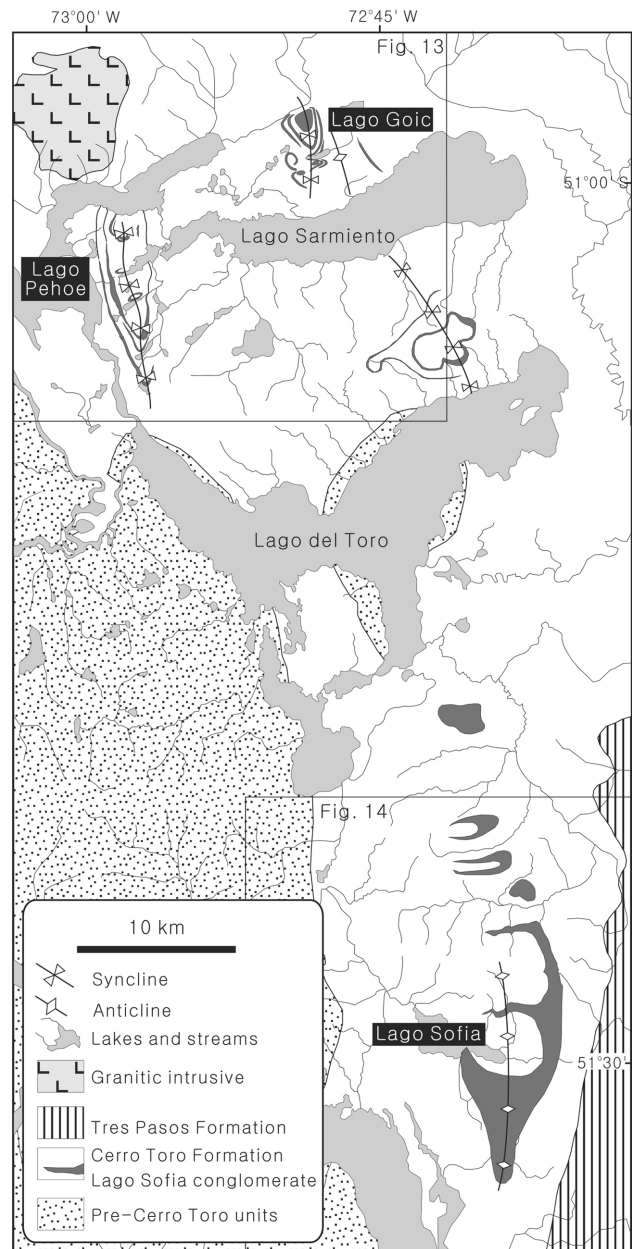


Fig. 2. Geologic map of the study area. The study area largely comprises thick sequences of hemipelagic mudstones and thin-bedded turbidite sandstones (Cerro Toro Formation, late Cretaceous). The Cerro Toro Formation includes a lens of Lago Sofia conglomerate (LSC), which extends for more than 100 km from north to south

of hemipelagic mudstones and thin interbeds of turbidite sandstones deposited during the late Cretaceous (Cenomanian–Campanian) (Cecioni 1957; Katz 1963). The formation is underlain by deep-water clastic sediments of the Punta Barosa Formation (Albian–Cenomanian) and overlain by a shallowing-upward clastic succession of the Tres Pasos Formation (Santonian–Maastrichtian) (Katz 1963; Scott 1966; Winn and Dott 1979; Shultz et al. 2005). A study of foraminiferal assemblages indicates that the water depth in the Magallanes Basin was 1000–2000 m during the deposition of the Punta Barosa and Cerro Toro Formations (Natland et al. 1974).

The strata of the Cerro Toro Formation dip very gently (< a few degrees) toward the south and are gentle- to open-folded with N-S-trending fold axes (Fig. 2), suggestive of mild deformation due to E-W-directed compression. The formation contains a lenticular conglomerate interval, referred to as the Lago Sofia Member (Katz 1963) or the Lago Sofia Lens (Scott 1966), outcropping for about 100 km from Torres del Paine National Park in the north

to Lago Sofia in the south (Fig. 2). The Lago Sofia conglomerate (LSC) is several tens to hundreds of meters thick and kilometers wide and encased by dark gray hemipelagic mudstones and thin-bedded turbidites. A group of workers (Scott 1966; DeVries and Lindholm 1994; Beaubouef et al. 1996; Beaubouef 2004) presented a leveed-channel model to explain the stratigraphic relations of the LSC relative to the surrounding fine-grained deposits, whereas another group of workers (Coleman 2000; Crane and Lowe 2001) suggested that the channels of the LSC are simple, erosional features cutting into the fine-grained deposits.

3. Channel-fill lithofacies

Facies A: Clast-supported conglomerates with sandy matrix

Description

This facies includes all the clast-supported conglomerates with sand matrix that are massive or very crudely

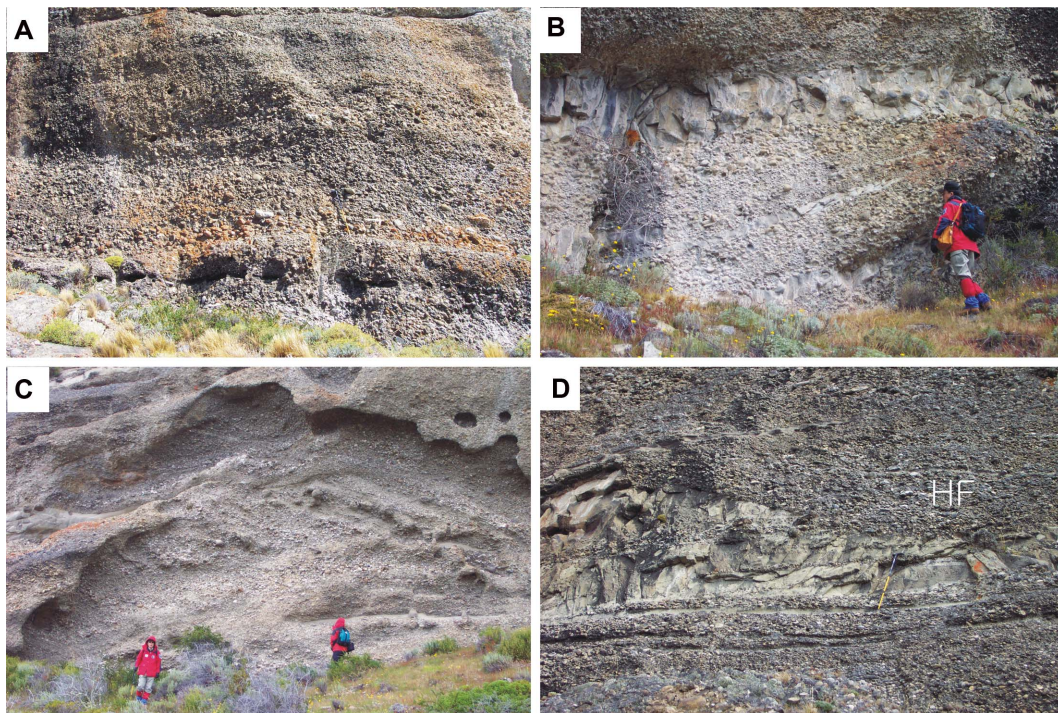


Fig. 3. Characteristics of Facies A conglomerate. (A) Stacked sheets of clast-supported conglomerate (Element S). Note the parallel to subparallel strata. Lago Goic area. (B) Laterally-inclined strata (Element LIS) in the Lago Sofia section (the lower part of the photograph). The conglomerate strata are discerned by grain-size variations and thin sandstone interbeds, and are inclined with respect to the upper boundary. The dip direction of the strata is highly oblique to the paleocurrent direction measured from clast imbrication. (C) A set of foreset strata (Element FS) in the Lago Sofia area. The height of the cross strata is ca. 3 m. (D) A hollow-fill unit (Element HF) in the Lago Sofia section. Note the concave-up, erosional surface cutting into the underlying sandstone beds. A stick for scale is 95 cm long

stratified, planar-stratified, low-angle inclined-stratified or high-angle cross-stratified (Fig. 3). They consist mostly of pebble- to cobble-grade gravels with rare boulders. The gravel clasts are generally well-rounded to subrounded and commonly long-axis-parallel [a(p)a(i)] imbricated. The matrix consists of moderately sorted fine-to-medium sand. Massive or very crudely stratified conglomerates occur commonly as several meter-thick, lenticular units with prominent scours at the base. They pass gradationally into stratified conglomerates either vertically or laterally. Individual strata of the stratified conglomerates are generally decimeters thick, massive and ungraded. Inversely or normally graded strata are rare. The stratification is identified by the contrasts in clast size, content, and fabric between adjacent strata and rarely by thin sandstone lenses. In low-angle inclined-stratified conglomerates (Fig. 3B), the dip of the strata is commonly perpendicular to imbrication direction of the gravel clasts. High-angle cross-stratified conglomerates rarely form dune-like bedforms composed of meter-thick cross-bedded sets (Fig. 3C).

Interpretation

The clast-supported texture with sand matrix and the imbrication of gravel clasts suggest that the conglomerates were deposited from the gravelly bedload or underflow of turbidity currents, which underwent various degrees of tractive or near-bed movement on the bed (Walker 1975; Winn and Dott 1977; Lowe 1982; Nemec 1990). The massive or very crudely stratified conglomerates are interpreted to have resulted from rapid deposition of gravelly dispersion at the base of a highly competent turbidity current, whereas the other conglomerates with a variety of stratifications suggest prolonged tractive transport of gravel on the bed. The predominance of the a(p)a(i) imbrication rather than a(t)b(i) imbrication suggests that the gravel was deposited from highly concentrated bedload layers (Todd 1996; Jo et al. 1997). The tightly clast-supported texture and the general lack of sandstone interbeds suggest that the turbidity currents deposited mostly the population-1 grains of Lowe (1982) and transported the majority of finer-grained materials further downcurrent. Marked contrasts in clast size, clast content, and fabric between adjacent strata in some conglomerates with sandstone lenses suggest that they are amalgamated beds of multiple turbidity-current events, whereas the others may have been deposited from sustained turbidity currents, furnished continuously with coarse-grained sediment. The meter-thick sets of cross-

stratified conglomerates (Fig. 3C), for example, suggest that the turbidity currents experienced the conditions for dune development for a long period so that the dunes could attain quasi-equilibrium with the turbidity currents (Allen 1970).

Facies B: Matrix- to clast-supported conglomerates with muddy matrix

Description

This facies includes the matrix- or partly clast-supported conglomerates with muddy matrix. They are mostly very thick-bedded, commonly in excess of 10 m in thickness, and pinch out gradually on large exposures. They are easily distinguished from the Facies A conglomerates by the total lack of internal stratifications and the muddy and dark-colored nature of the matrix (Fig. 4A). They show a variety of grading patterns, but are most commonly inverse-to-normally graded (Fig. 4B). When the inversely graded division is thin and/or the normal grading is indistinct, the conglomerates appear to be massive and chaotic (Fig. 4A,C). In general, the conglomerates can be divided into two divisions with transitional contacts. The lower division is composed of clast-supported pebbles and cobbles, showing upcurrent-dipping [a(p)a(i)] imbrication and well-developed basal inverse grading (Fig. 4B). The lower contact is generally erosional (Fig. 4A,C), occasionally showing flute or groove casts. The upper division is disorganized or normally graded and composed of loosely clast-supported or matrix-supported pebbles. The upper division characteristically contains abundant intraformational clasts, ranging from fine pebble-size mudstone chips to several meter-long sandstone or mudstone blocks (Fig. 4B,C). The matrix is composed of poorly sorted muddy sand, containing about 30 vol.% sand. The conglomerates of this facies are in some cases capped by decimeter-thick layers of abundant mudstone chips set in a mudstone or sandy mudstone matrix.

Interpretation

The conglomerates of this facies, previously termed the diamictites by Winn and Dott (1979), are interpreted to have resulted from composite mass-flow events, comprising a turbidity current, a gravelly hyperconcentrated flow, and a mud-rich debris flow (Sohn et al. 2002). The erosional lower contact with well-developed flute and groove casts indicates an initial erosional event caused by a turbulent flow. The erosion was immediately followed by deposition from a gravelly hyperconcentrated flow, involving high rates of shear strain and active clast collisions, resulting in

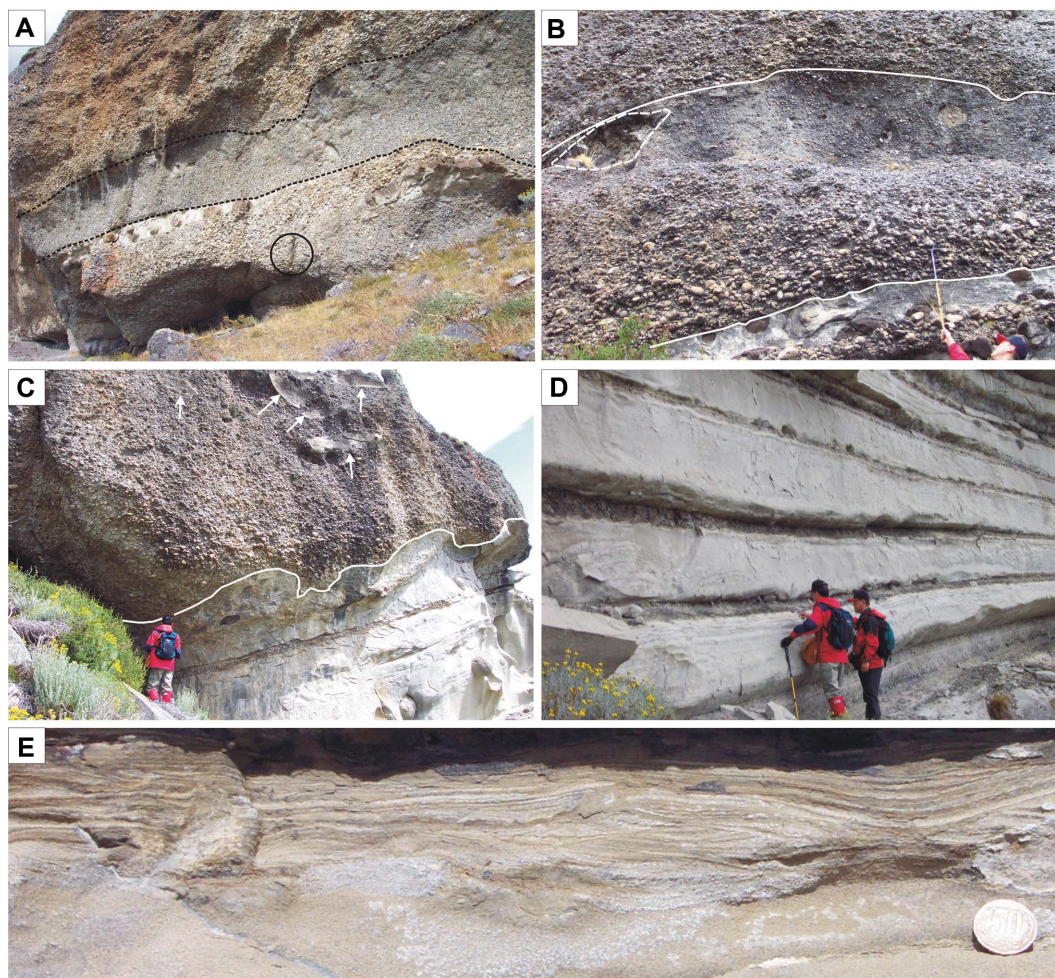


Fig. 4. Characteristics of Facies B conglomerate and Facies C sandstone. (A) A diamicnite bed (Facies B, middle part of the photograph) in the Lago Sofia section, showing irregular sheet-like geometry and slightly erosional base. A stick for scale (circled), 95 cm long. (B) Inverse-to-normally graded conglomerate (Facies B) with intraformational megaclasts in the uppermost part of the bed, Lago Sofia section. (C) Disorganized conglomerate (Facies B) with intraformational megaclasts (arrowed) in the Lago Sofia section. (D) Thick-bedded massive sandstones (Facies C) in the Lago Sofia section. (E) Ripple cross-laminated topmost of thick-bedded massive sandstones in the Lago Sofia section

basal inverse grading and well-developed imbrication of gravel clasts. The upper division is generally indicative of cohesive debris flows that have undergone a very low rate of laminar shearing possibly with a rigid plug (Johnson 1984; Shultz 1984). The development of normal grading in the upper division of some units is most likely due to incremental aggradation from a debris flow that was progressively finer-grained toward the rear part (Vallance and Scott 1997; Sohn et al. 1999). Sohn et al. (2002) interpreted that the composite mass flows resulted from progressive dilution of gravelly but cohesive debris flows that were generated by the failure of nearby channel banks or slopes flanking the channel system and experienced a

full-scale dilution of the debris flows because of hydroplaning of the flow fronts.

Facies C: Medium- to thick-bedded sandstones *Description*

This facies includes thick- to very thick-bedded sandstones. They occur as discontinuous interbeds between the conglomerate facies (Fig. 3D), as tens to hundreds of meters-thick packets either above or beneath the conglomerate sequences (Fig. 4C,D), and as lateral equivalents of the conglomerate sequences. Individual sandstone beds are decimeters to more than a meter thick, composed of fine-to-medium sand, and mostly massive and ungraded.

Some beds have planar- or ripple cross-laminated divisions at the topmost parts, a few cm to 10 cm thick (Fig. 4E). Flute and groove casts are common at the base. Most sandstone beds are laterally continuous without noticeable variations in bed thickness. Basal scours are rare and, if present, very shallow.

Interpretation

This facies is interpreted to have been deposited by rapid suspension fallout of sand from turbidity currents (Lowe 1982; Pickering et al. 1986; Johansson et al. 1998). The generally massive and ungraded nature of the sandstones with scarce erosion surfaces at base suggests that the turbidity currents were highly depositional and overloaded with suspended sediment (Lowe 1988).

4. Occurrence of channel-fill lithofacies

Lago Pehoe area

Within the Torres del Paine National Park, several conglomerate packages are exposed along the limbs of an open-folded syncline with a north-south-oriented axis, named the Cerro Silla syncline, east of Lago Pehoe (Figs. 2 and 5). The conglomerate packages in this area were designated as channel-complex sets (CCS) 1 to 4 from base to top in a recent paper by Beaubouef (2004). The channel-complex sets consist of a number of channel fills and channel complexes, which are several tens of meters thick, 0.5–1.5 km wide, and variably amalgamated, making up conglomerate bodies that are as thick as 250 meters and extend laterally for more than several

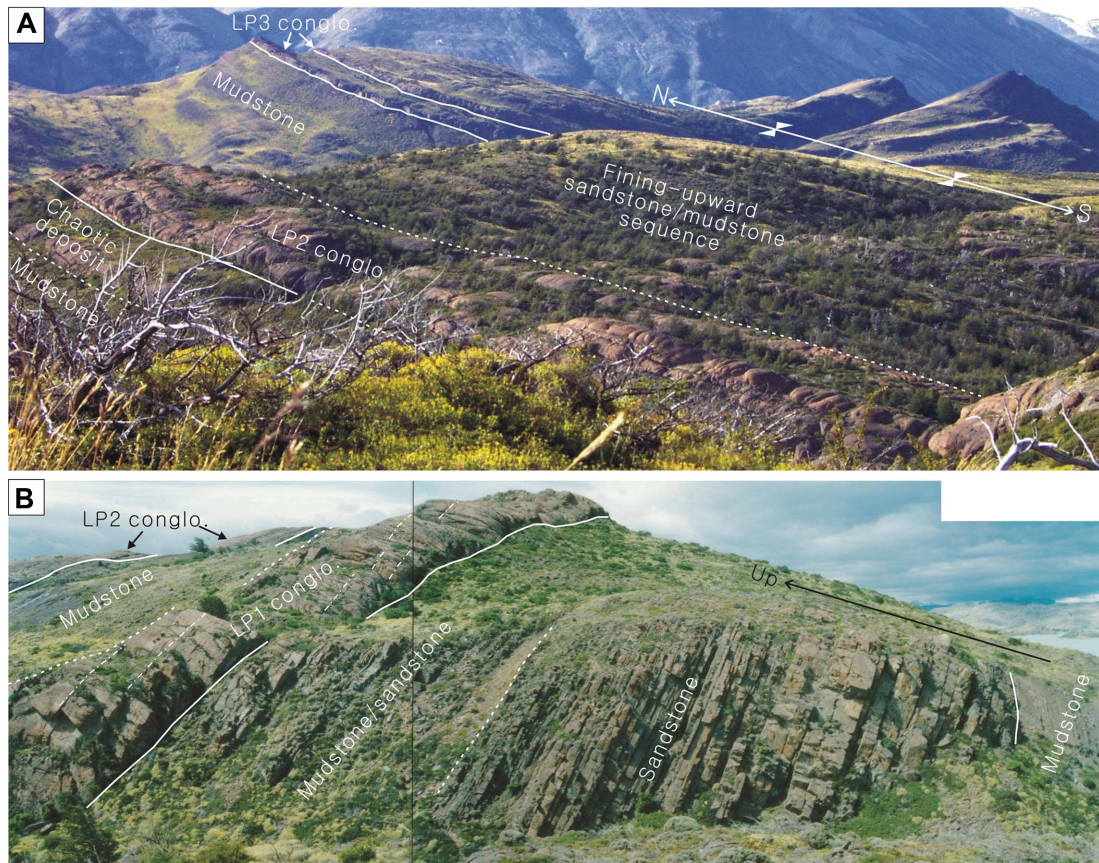


Fig. 5. Overview of the gentle- or open-folded strata of the Cerro Toro Formation in the Lago Pehoe area. (A) The middle conglomerate (LP2; CCS 3 of Beaubouef 2004) in the foreground is underlain by a chaotic deposit, which is about 20 m thick and composed of disorganized pebbly mudstone (CCS 2 of Beaubouef 2004). The LP2 conglomerate passes upward into a thinning- and fining-upward sequence of alternating conglomerate, sandstone, and mudstone beds. The LP3 conglomerate (CCS 4 of Beaubouef 2004) in the background overlies a thick (>100 m) succession of dark gray mudstone and consists of two very thick-bedded conglomerate units (base outlined). They abruptly pinch out near the trough of the syncline (not shown). (B) LP1 conglomerate (CCS 1 of Beaubouef 2004) and adjacent strata, consisting of hemipelagic mudstones and a thick sequence of massive sandstones

kilometers (Beaubouef 2004). These channel-complex sets are separated by several tens to hundreds of meter thick hemipelagic mudstones, of which the thickness varies depending on the degree of vertical amalgamation of channel fills. In general, vertical amalgamation decreases toward channel margins.

The lowermost conglomerate package (LP 1) in the Lago Pehoe area (Fig. 5B), corresponding to part of CCS 1 of Beaubouef (2004), is up to about 50 m thick and extends laterally for about 10 km with meager variations in thickness, although it eventually pinches out toward the north and the south (Fig. 2). Gigantic (more than several decimeters wide and meters long) flute and groove casts are commonly observed at the base of the conglomerate package. It consists mainly of Facies B conglomerates that are ungraded or inverse-to-normally graded and subordinately of stratified conglomerates (Facies A) (Fig. 6). The grading patterns in the conglomerates are difficult to discern in many cases because of amalgamation of the conglomerate beds. Thin and discontinuous lenses of massive or stratified sandstones and laminated mudstones are common along the scoured and amalgamated boundaries of the conglomerate beds. The gravels in the conglomerates are generally clast-supported and imbricated. The conglomerates commonly contain intraclasts of sandstones and mudstones in the upper parts of the beds.

The middle conglomerate package (LP 2) comprises a more than 100 m-thick [about 250 m thick based on Beaubouef's (2004) estimation] sequence of conglomerates (CCS 3 of Beaubouef 2004) and overlies a tens-of-meter thick unit of chaotic or disorganized pebbly mudstone (CCS 2 of Beaubouef 2004) (Fig. 5A). The CCS 3 conglomerates have lithofacies characteristics that are overall similar to those of the CCS 1 conglomerates (Fig. 7A), but is more lenticular in geometry, laterally pinching out more rapidly (Fig. 8A). It consists mainly of ungraded to inverse-to-normally graded conglomerates (Facies B), which pass laterally into medium- to thick-bedded T_{ab} sandstones (Facies C) (Fig. 8B), reflecting an axis-to-margin facies change in a submarine channel (Beaubouef 2004). The overall geometry and orientation of the CCS 3 conglomerate suggest that it represents a segment of a channel fill, several kilometers wide and trending southeastward (Fig. 8A). Beaubouef (2004) suggests that the CCS 3 conglomerate consists of at least five leveed-channel complexes that are 30–60 m thick, 1–1.5 km wide, and migrated southward.

The uppermost conglomerate package (LP 3; CCS 4 of Beaubouef 2004) consists of two distinct units of

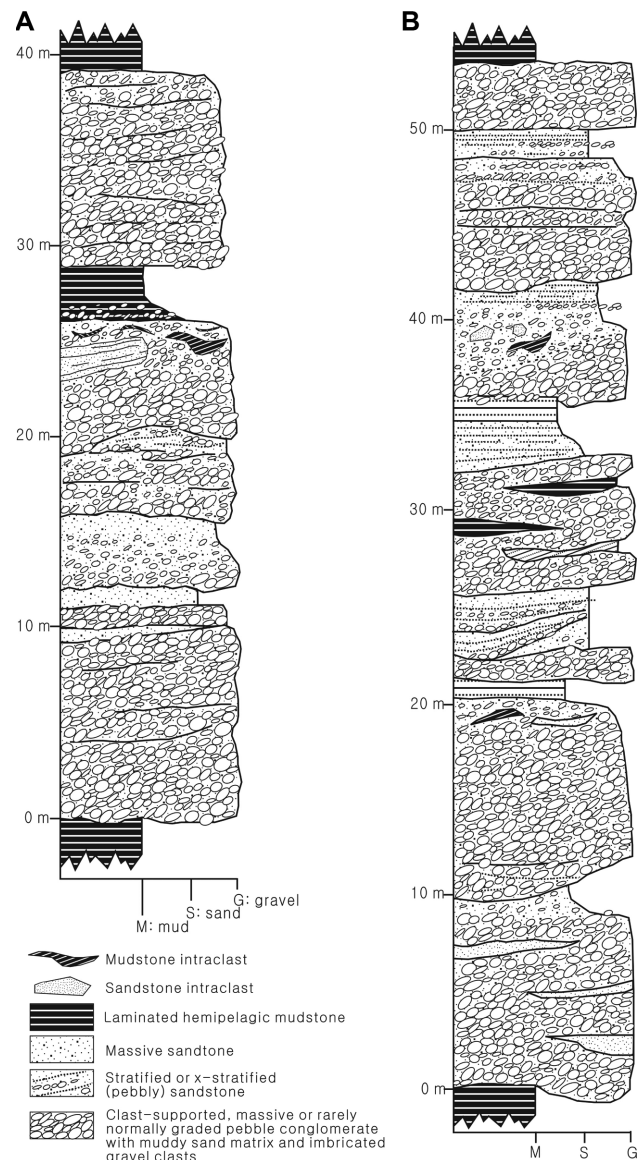


Fig. 6. Columnar logs of the lowermost conglomerate (LP1; CCS 1 of Beaubouef 2004) at the Lago Pehoe area

conglomerate (Fig. 5A). The lower one comprises a single very thick (about 15 m thick) conglomerate bed, consisting of a lower division of clast-supported and imbricated pebble conglomerate and an upper division of matrix-supported and disorganized pebbly mudstone, containing abundant meter-long blocks of sandstones and mudstones (Fig. 7B). The upper one is composed of disorganized conglomerate as well as stratified conglomerates (Facies A) and massive sandstones (Facies C) (Fig. 7C). Both conglomerate units pinch out abruptly toward the northeast (Fig. 8A).

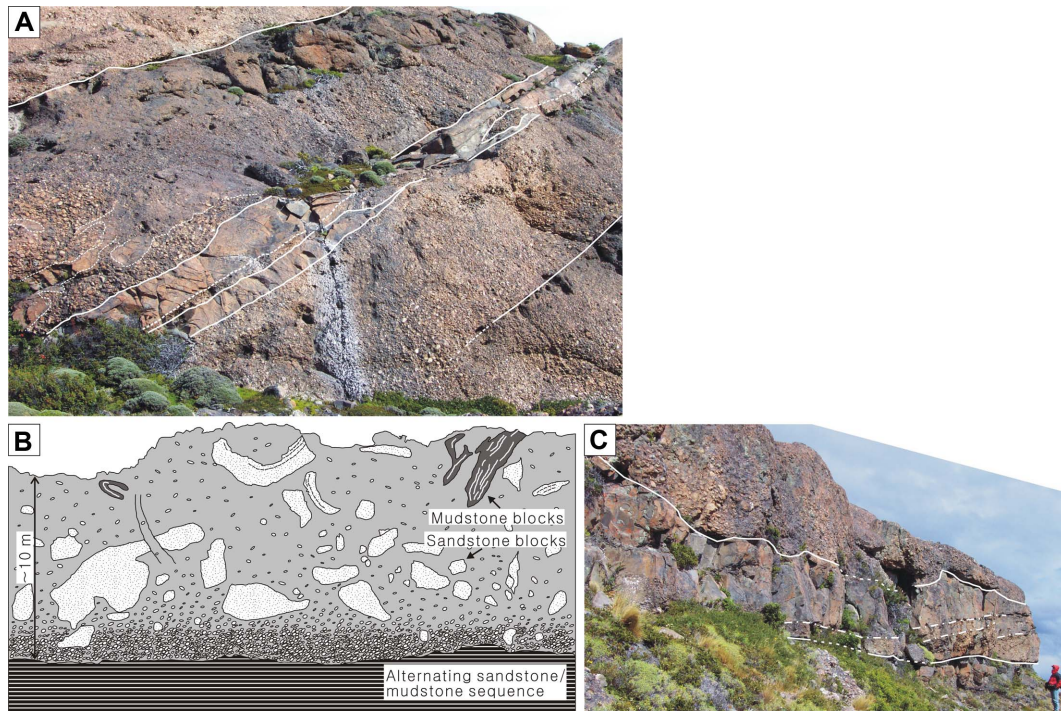


Fig. 7. (A) Sedimentary characteristics of the middle conglomerate unit (LP2; CCS 3 of Beaubouef, 2004) in the Lago Pehoe area. (B) A very thick diamictite bed (Facies B) in the upper conglomerate unit (LP3; CCS 4 of Beaubouef 2004), which is chaotic or disorganized and contains abundant intraformational megaclasts. (C) Thick-bedded sandstones (Facies C) and overlying conglomerate (Facies B) in the upper conglomerate unit (LP3) in the Lago Pehoe area

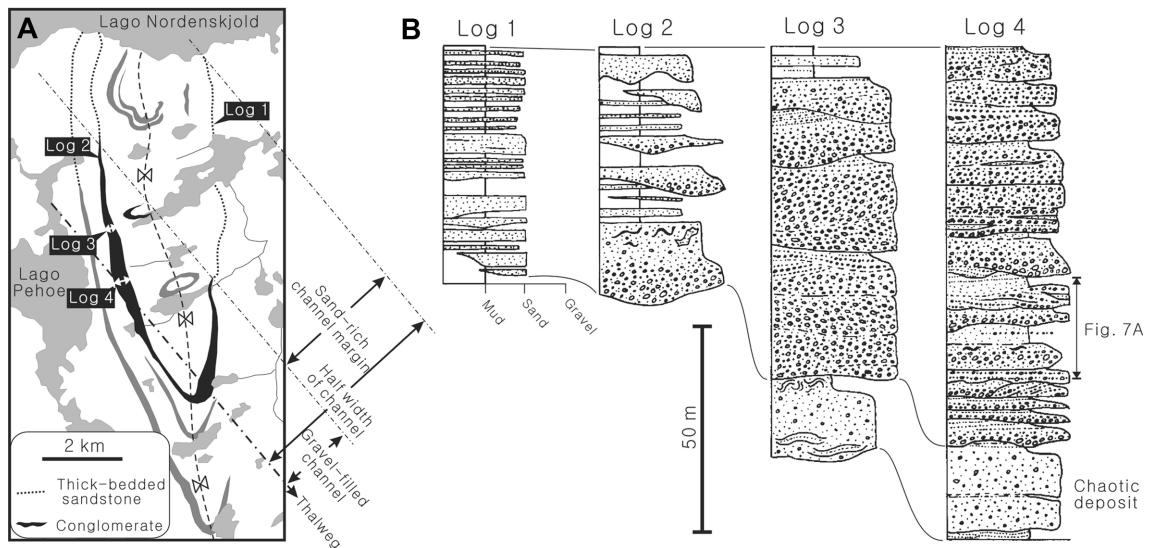


Fig. 8. (A) Detailed geological map of the Lago Pehoe area (from Scott 1966), showing inferred channel orientation of the LP2 conglomerate. (B) Columnar logs from the LP2 conglomerate

Lago Goic area

Several packages of conglomerates are exposed along the limbs of a north-south-oriented, gently folded syncline in the Lago Goic area (Fig. 9A). These conglomerate

packages are separated by relatively thin (less than a few tens of meters thick) sequences of hemipelagic mudstones compared with those of the Lago Pehoe area. Only the lower two of these conglomerate packages, which are

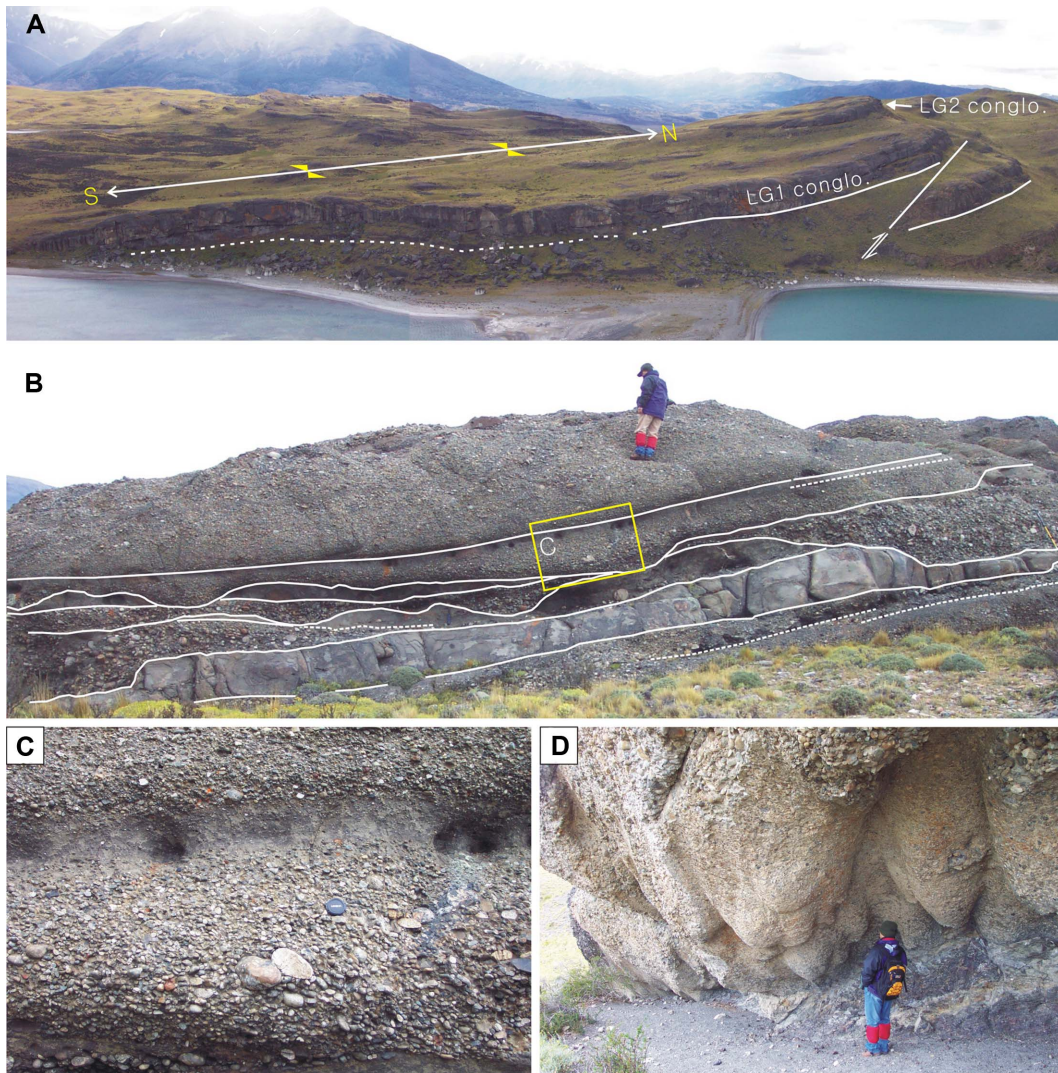


Fig. 9. Sedimentary characteristics of the LSC in the Lago Goic area. (A) The LSC here is gently folded with a N-S-trending fold axis. (B) The LSC is composed of subequal proportions of facies A and B conglomerates with common erosional hollows. (C) Inverse-to-normally graded conglomerate with imbricated gravel clasts. (D) Gigantic flute casts at the base of LG1 conglomerate

several tens of meters thick and extend laterally for several kilometers, could be properly mapped. The overlying conglomerate packages could not be further differentiated and mapped because of poor exposure. Lateral pinching-out of the conglomerate packages, as seen in the Lago Pehoe area, could not be identified because of the small areal extent of the overall LSC exposures.

The conglomerates in the Lago Goic area mainly belong to Facies B, consisting of ungraded or inverse-to-normally graded conglomerates with common clast imbrication (Fig. 9B,C). Crudely to thinly stratified conglomerates with clast imbrication and scoured bases (Facies A; Fig.

9B) are, however, more abundant than in the Lago Pehoe area. The lowermost conglomerate package with a consistent thickness of about 40 to 50 m has gigantic (more than several decimeters wide and meters long) flute and groove casts at the base (Fig. 9D) similar to the lowermost conglomerate package in the Lago Pehoe area. These gigantic sole marks are observed at almost every outcrop locality where the conglomerate package is exposed to its base, suggesting that the conglomerate package was emplaced upon an extensively fluted and grooved surface. It is inferred that the lowermost conglomerate packages either in the Lago Pehoe or in the Lago Goic areas are lying above the same or laterally

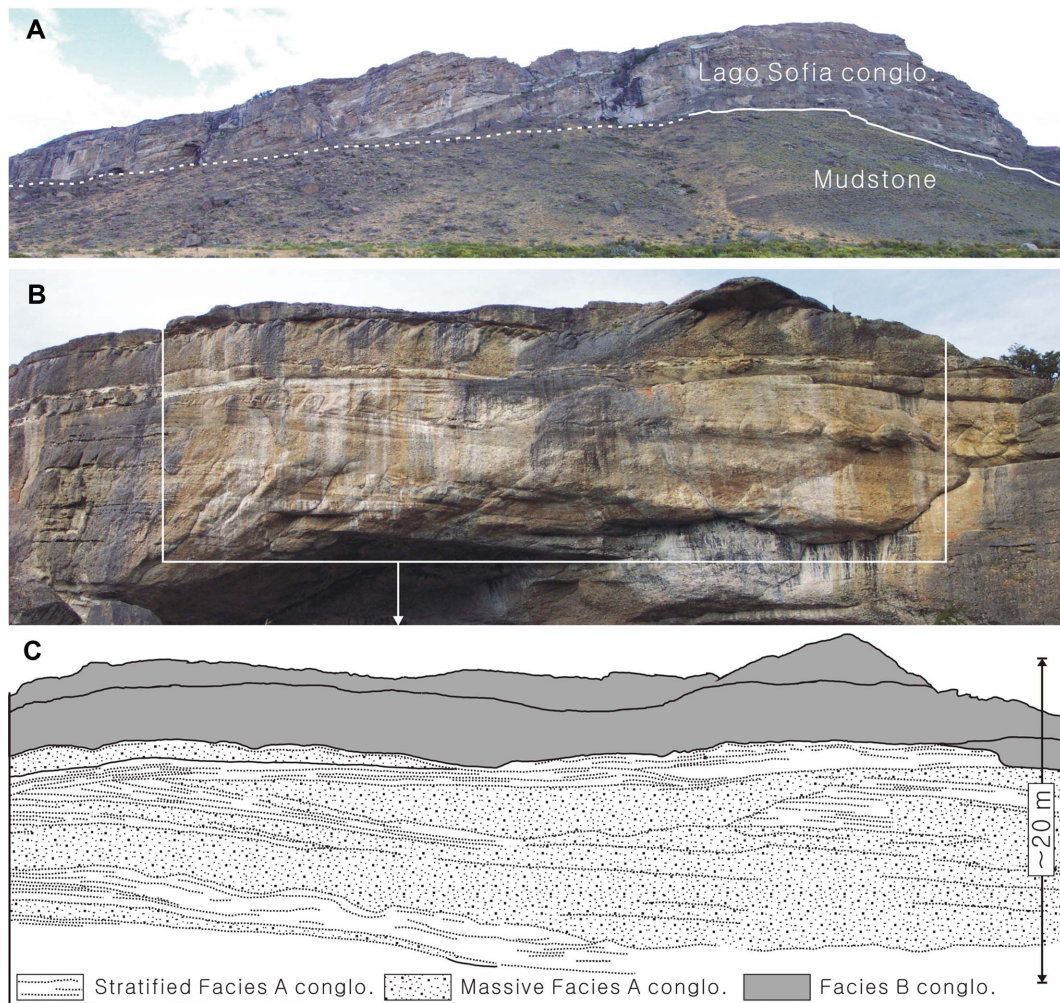


Fig. 10. Sedimentary characteristics of the LSC in the Lago Sofia area. (A) Panoramic view of the LSC at the Lago Sofia section. Solid and dashed lines denote the base of LSC. (B, C) Photograph and sketch of the LSC at the entrance of the Cave of Milodon, consisting dominantly of Facies A conglomerate with subordinate Facies B conglomerate

equivalent erosional surface, defining the base of the LSC.

Lago Sofia area

To the south of Lago del Toro, conglomerates are exposed along the midslope of a series of mounts (Fig. 2). These conglomerates pinch out on the western sides of these mounts, delineating the western limit of the LSC. Excellent transverse section of the conglomerates occurs in the Lago Sofia area where the strata form a gently folded anticline (Fig. 10A). The LSC here consists of about 400-m-thick conglomerates with rare intervening fine-grained facies. The conglomerates are in turn overlain by an about 300-m-thick succession of thick- to very thick-bedded sandstones, which gradually passes upward into a succession of hemipelagic mudstones and thin-



Fig. 11. Gigantic groove casts at base of the LSC in the Lago Sofia section

bedded turbiditic sandstones.

The conglomerates in this area are mainly composed of crudely to thinly stratified and low- to high-angle cross-stratified conglomerates (Facies A) with subordinate intercalations of disorganized to inverse-to-normally graded conglomerates (Facies B; Fig. 10B,C). The basal contact of the LSC here is also characterized by gigantic sole marks (Fig. 11), as are the lowermost conglomerate packages in the Lago Pehoe and Lago Goic areas.

5. Spatial variations of channel-fill characteristics and paleoflow pattern

The most significant north-to-south variation of the LSC in the study area is that the conglomerate packages or the channel-complex sets occur as multiple but thin (generally less than 100 m thick) units in the Lago Pehoe area, intercalated with much thicker fine-grained facies, whereas the conglomerates occur as a thick (about 400 m thick) unit in the Lago Sofia area with rare intervening fine-grained facies (Fig. 12). The relative proportion of the conglomerate facies is also different between the studied areas. In the Lago Pehoe area, the LSC is dominantly composed of the Facies B conglomerates only with thin interbeds of other facies units (e.g. Figs. 6, 7). In the Lago Goic area, the Facies B conglomerates are dominant, but there also occur abundant conglomerate units of Facies A (Fig. 9B). In the Lago Sofia section, Facies A conglomerates are much more abundant than the Facies B conglomerates (Fig. 10). These spatial variations of the conglomerate facies appear to be closely related with the overall paleoflow pattern within the LSC.

Previous studies suggest that the paleoflows in the LSC were directed dominantly toward the south (Scott 1966; Winn and Dott 1979; Beaubouef 2004). Measurement of the paleoflow directions by the authors on the basis of clast imbrication and sole marks reveals, however, that there are considerable variations in paleoflow directions among different facies and different outcrop localities. Above all, fairly consistent paleoflow directions were obtained from the Facies A conglomerates whereas the Facies B conglomerates have highly variable paleoflow directions, commonly at high angles to the overall trend of the presumed LSC channel axes (Sohn et al. 2002). Sohn et al. (2002) interpreted that the mass flows that formed the Facies B conglomerates originated from failure of nearby channel banks or slopes flanking the channel system, and their flow paths were strongly influenced by local topographic relief. On the other hand, the turbidity

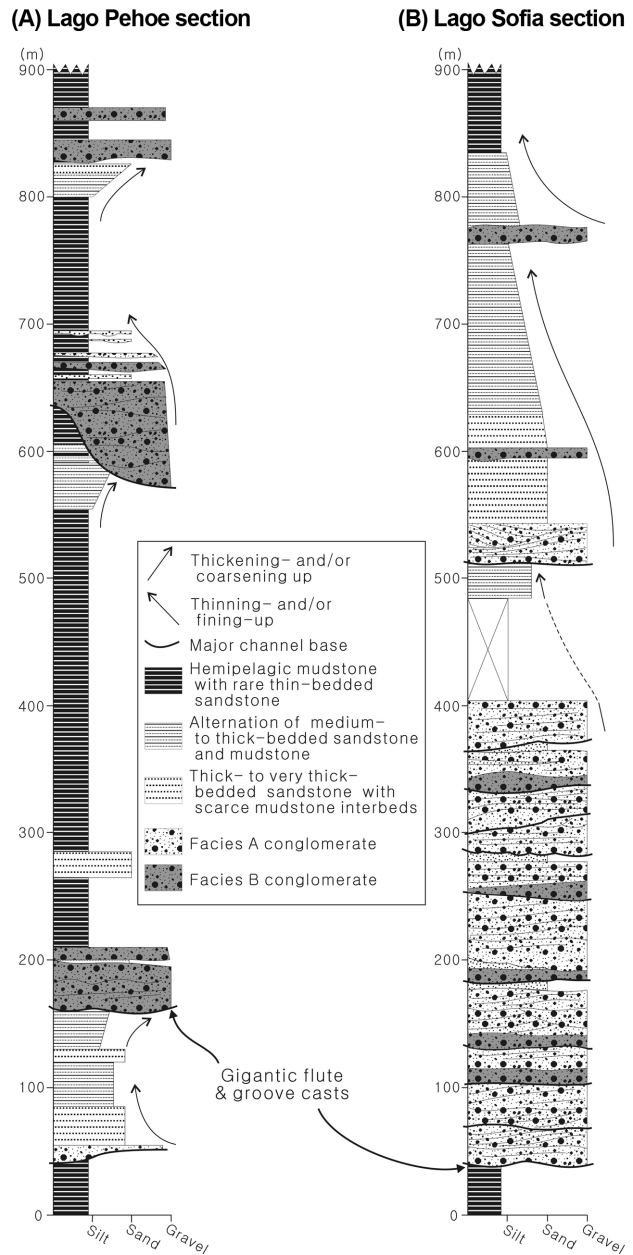


Fig. 12. Columnar logs of Lago Pehoe section in the northern part (A) and Lago Sofia section in the southern part (B). The Lago Pehoe section is characterized by several isolated units of hundred-m-thick conglomerates and abundant intervening fine-grained facies, whereas the Lago Sofia section comprises a much thicker sequence of vertically stacked conglomerates and thick-bedded sandstones

currents that formed the Facies A conglomerates have followed the overall trend of the LSC channel axes.

The overall paleoflow pattern of the LSC reconstructed on the basis of the paleocurrent data obtained from the

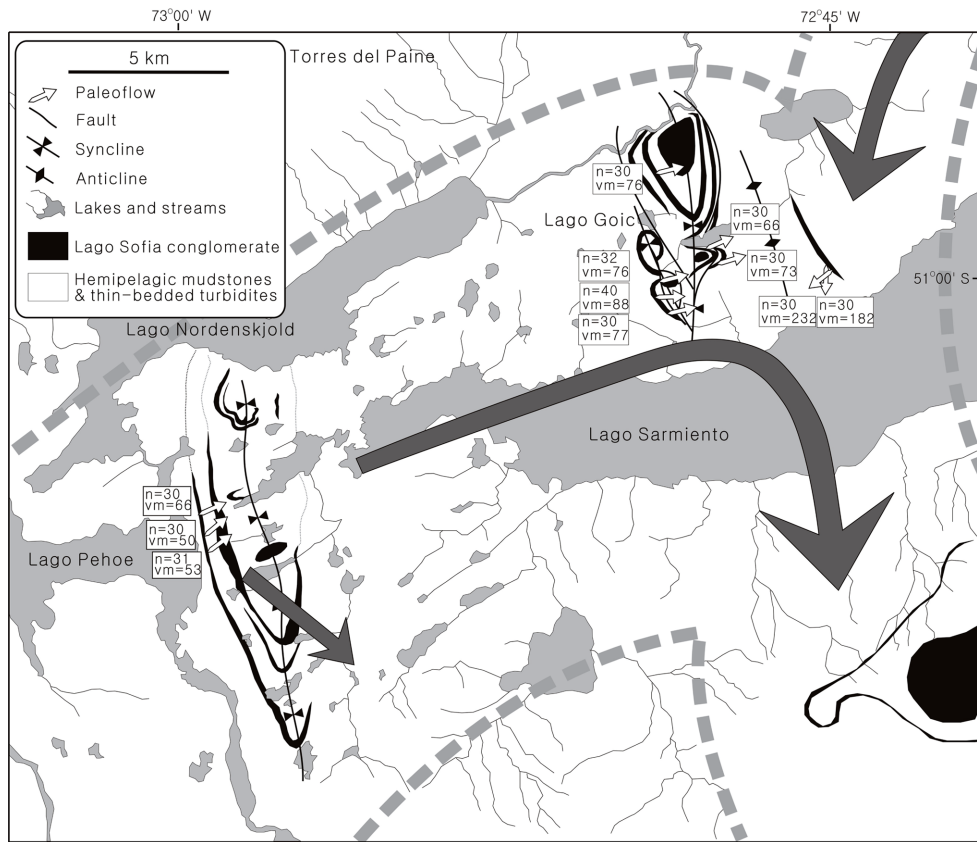


Fig. 13. Distribution of Lago Sofia conglomerates at the Lago Pehoe and Lago Goic sections in the northern part of the study area. Paleocurrent directions, inferred from the clast fabric of Facies A conglomerate, are indicated with possible outlines (thick dashed line) of the channel system

Facies A conglomerates together with the geometry of the conglomerate bodies is shown in Figs. 13 and 14. The dominant paleocurrent vectors in the Lago Pehoe and Lago Goic sections are mostly directed toward the ENE. The paleocurrents in the easternmost exposures are, however, directed toward the south and southwest (Fig. 13), suggesting that the channel didn't extend further eastward but was deflected toward the south. In the Lago Sofia area, the LSC pinches out toward the west in the midslope of a series of mounts, delineating the western limit of the LSC (Fig. 14). In this area, the grooves at base of the LSC (Fig. 11) are trending to south, but the clast imbrication in the Facies A conglomerates indicates consistently southwestward paleoflows (Fig. 14).

It can thus be concluded that the spatial variations of the channel-fill lithofacies are due to proximal-distal changes in the relative proportion of debris-flow and turbidity current processes in a submarine channel system that was directed toward the east and southeast in the north and toward the south and southwest in the south.

6. Architectural elements of the LSC

The LSC shows a number of sedimentary features that are similar to those of terrestrial fluvial deposits. An architectural element analysis, a useful tool for analyzing either submarine or terrestrial channel characteristics (Miall, 1989; Clark and Pickering, 1996a), has been carried out to extract further information on the nature and evolution of the LSC submarine channel. Five architectural elements are classified from the LSC on the basis of large-scale bed geometry and sedimentary facies (Table 1): (1) stacked sheets, (2) laterally-inclined strata, (3) foreset strata, (4) hollow fills, and (5) diamictite (Facies B conglomerate).

Stacked sheets

This element comprises stacked sheet-like beds of clast-supported, pebble to cobble conglomerate, showing a thickness of 3–50 m and extending laterally for hundreds of meters (Fig. 3A; Table 1). Individual conglomerate

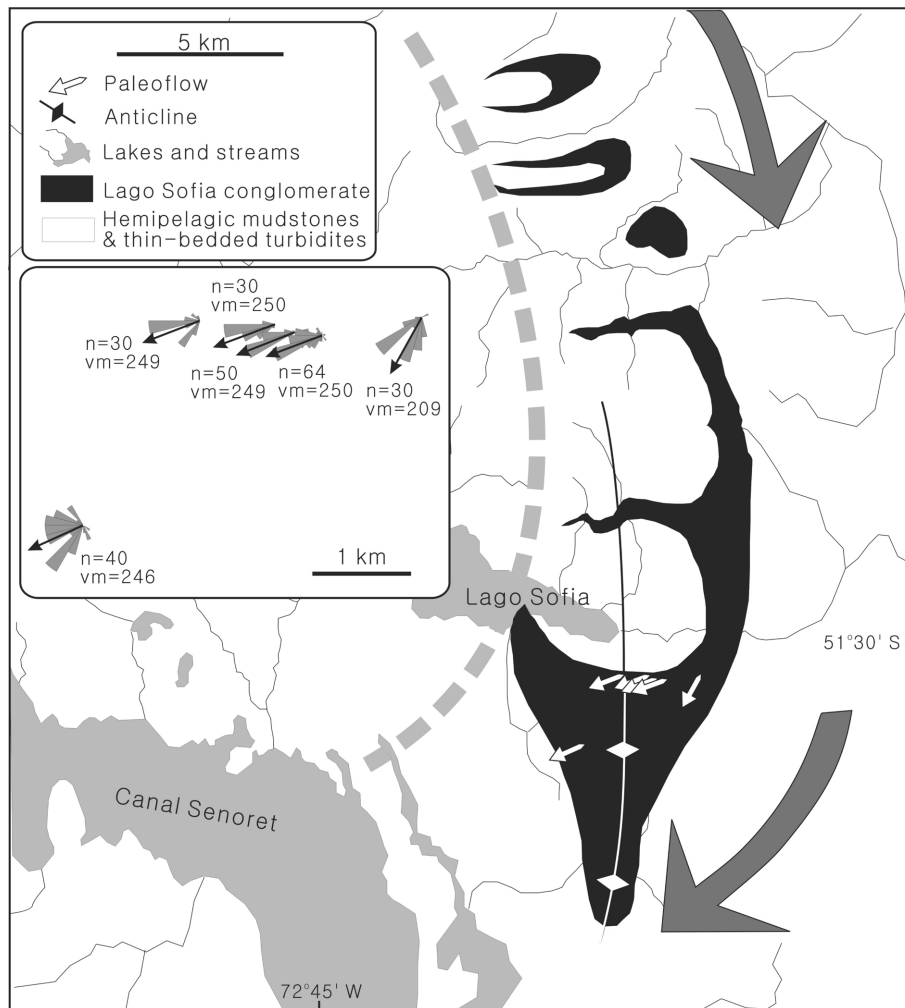


Fig. 14. Distribution of the Lago Sofia conglomerates at the Lago Sofia section in the southern part of the study area. Paleocurrent directions, inferred from the clast fabric of Facies A conglomerate, are indicated with possible outlines (thick dashed line) of the channel system

beds consist of stratified or massive Facies A conglomerates. The beds are decimeters thick and extend laterally for tens of meters, bounded by slightly erosional surfaces. Grain-size difference is commonly discernible between the adjacent beds. Thin lenticular or wedge-shaped sandstone beds are occasionally intercalated.

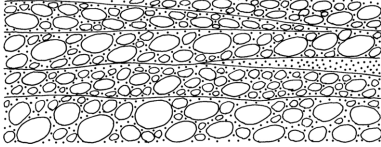
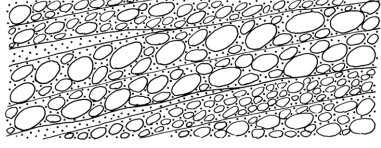
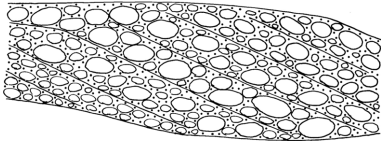
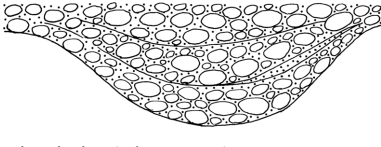
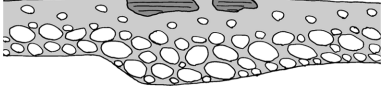
The constituent facies are indicative of bedload deposition by turbidity currents. Sheet-like beds of clast-supported conglomerate are a typical structure of broad gravel bars in terrestrial gravelly braided rivers (Boothroyd and Ashley 1975; Hein and Walker 1977). Such gravel bars are mainly deposited by high-magnitude flood flows, which are similar to subaqueous turbidity currents in high sediment concentration, grain-supporting forces, and the structures of resultant deposits (Todd 1989; Maizels 1993). Although little is known about the gravel bars

formed by turbidity currents, the stacked sheets of Lago Sofia Conglomerate are interpreted to be an analog of the terrestrial sheet-like gravel bars.

Laterally-inclined strata

This element comprises clast-supported, pebble-to-cobble conglomerate of Facies A that are inclined at low angles with respect to the lower and upper bounding surfaces (Fig. 3B; Table 1). The dip direction of the inclined strata is either perpendicular or oblique at high angles to the paleocurrent direction measured from clast imbrication. The element unit is either sheet-like or lens-shaped with a thickness of 7–15 m and a lateral extent of several tens to 200 m. Individual conglomerate strata are decimeters thick and bounded by either non-erosional or slightly erosional surfaces with local scours. Thin

Table 1. Classification and interpretation of architectural elements in the Lago Sofia conglomerates

Elements	Geometry	Description	Interpretation
Stacked sheets (Element S) 	Sheet-like; 3–50 m thick; hundreds of meters in lateral extent	Stacked sheet-like beds of clast-supported, pebble to cobble conglomerate; well-rounded, commonly imbricated clasts; medium-grained sandstone matrix; parallel to subparallel bed geometry; individual beds: decimeters thick, bounded by conformable and slightly erosional surfaces; thin sandstone interbeds	Stacking of bedload gravel sheets and low-relief gravel bars by turbidity currents
Laterally-inclined strata (Element LIS) 	Sheet-like or lenticular; 7–15 m thick; several tens to 200 m in lateral extent	Low-angle inclined strata of clast-supported, pebble to cobble conglomerate; dip of inclined strata, perpendicular to highly oblique to paleocurrents direction; well-rounded, commonly imbricated clasts; medium-grained sandstone matrix; individual beds: decimeters thick, bounded by conformable and slightly erosional surfaces; thin sandstone interbeds, commonly thinning-out updip	Lateral accretion on gravel bars through multiple depositional events (turbidity currents)
Foreset strata (Element FS) 	Lenticular; 2–4 m thick; several meters in lateral extent	Large-scale, planar and tangential cross-stratified, clast-supported, pebble to cobble conglomerate; commonly isolated sets; organized clast fabric	Downstream migration of large gravel dunes
Hollow fills (Element HF) 	Lenticular; 2–12 m thick; a few to 100 m in lateral extent	Lenticular lithosome bounded by concave-up, erosional surfaces; occasionally stepped margin; clast-supported, pebble to cobble conglomerate with occasionally sandstone interbeds; concave-up stratified, massive or crudely stratified	Filling of thalwegs, minor channel forms, and scours
Diamictite (Element D) 	Sheet-like; a few to 30 m thick; hundreds of meters in lateral extent	Sheet-like lithosome of mud-rich conglomerate resting on concave-up, erosional surfaces and flat, conformable surfaces; a single bed or more than one bed; two distinct divisions within individual beds: (1) lower division of clast-supported, imbricated, pebble to cobble conglomerate with common basal inverse grading and (2) upper division of matrix-supported, disorganized, pebble conglomerate or pebbly sandstone with intraformational clasts; highly variable paleocurrents directions, commonly perpendicular to those from stratified conglomerates	Sheet-like or tongue-shaped bodies deposited by debris flows with clast-rich frontal parts, originated from the failure of channel banks or slopes flanking the channel system

sandstone beds are commonly intercalated, thinning out updip.

The laterally-inclined strata are suggestive of lateral accretion with respect to flow direction. Such a lateral accretion is common in terrestrial river bars such as point bars and braided bars, related to spiral flows in curved channel segments around bars (Allen 1983; Miall 1985;

Bridge 1993). It has been recently revealed that deep-sea channels also have lateral accretion deposits as a common feature, although their formative processes are still poorly understood (Abreu et al. 2003; De Ruig and Hubbard 2006). The laterally-inclined strata of Lago Sofia Conglomerate are interpreted to represent lateral accretion of gravel bars in deep-sea channels.

Foreset strata

This element comprises large-scale cross-strata of clast-supported, pebble to cobble conglomerate (Fig. 3C; Table 1). It occurs commonly as a solitary set, which reaches about 3 m in thickness and extends laterally for several meters. Individual cross-strata are decimeters thick and either planar or tangential. The dip direction of the cross-strata is nearly parallel to the paleocurrent direction deduced from clast imbrication. This element is interpreted as the deposits of large gravel dunes that have migrated downstream under turbidity currents (e.g. Clarke et al. 1990).

Hollow fills

This element is a lenticular lithosome resting on a concave-up, erosional base (Fig. 3D; Table 1). It is either massive, horizontally stratified, or concave-up stratified. Individual strata consist of massive and stratified, clast-supported conglomerate (Facies A). Thin sandstone beds are occasionally intercalated between conglomerate strata. The element units are 2–12 m thick and extend laterally for several meters to 100 m. Based on the geometry and the stratal pattern, this element is interpreted as the deposits filling thalwegs, minor channels, and scoured hollows.

Diamictite

This element is a sheet- or wedge-like lithosome consisting of mud-rich conglomerate (Facies B) (Fig. 4; Table 1). It is a few meters to 30 m thick and extends laterally for hundreds of meters. The lower boundaries are generally flat and non-erosional but locally concave-up and erosional. Paleocurrent directions measured from the diamictite units are generally perpendicular or highly oblique to those from stratified conglomerate beds, although they show wide variations.

The constituent facies are indicative of the deposition from mud-rich debris flows (Sohn et al. 2002). The resultant deposits were probably sheet-like or tongue-shaped with a lateral extent of hundreds of meters. The paleocurrent directions perpendicular to main-channel flows deduced from stratified conglomerates suggest that the mud-rich debris flows were originated from the banks or slopes fringing the Lago Sofia deep-sea channel systems.

7. Large-scale architecture of the LSC in the Lago Sofia area

An exposure at the Lago Sofia area is more than 300 m

in stratigraphic thickness and ca. 1.3 km long, showing large-scale architecture of deep-sea channel conglomerate (Fig. 15). The LSC here forms an anticline with an N-S-trending axis (Figs. 10A and 15A). In the western part of the exposure, the erosional base of the LSC is exposed, overlying dark gray mudstones and thin interbedded turbiditic sandstones (Fig. 15B). The erosional base shows prominent groove casts trending N-S (Fig. 11) and is partly stepwise becoming higher to the east. In the middle and eastern parts of the exposure, the base of the LSC is partly exposed, showing either concave-up or stepwise surfaces cutting into the underlying dark gray mudstone beds (Fig. 15C). Together with this, the common occurrence of dark gray mudstone at a few to several meters below the section suggests that the base of the LSC lies nearly horizontal at less than several meters below the section and the conglomerate body is lenticular thinning to the east, as shown in Fig. 15. The lenticular geometry of the LSC is observed on the mountain slope north of Lago Sofia, where the conglomerate body rests on a concave-up base and thins out to the west. The top surface of the conglomerate is inferred to lie also several meters above the section, because of the lack of conglomerate and the occurrence of dark gray mudstone above the exposure. It is thus reasonably supposed that the strata dipping eastwards in the middle and eastern parts of the exposure do not extend updip for long distance, thinning out westwards. Flattening the Lago Sofia strata by eliminating the anticline structure, the base and top of the LSC would become stratigraphically higher eastwards and the strata would show a progressive eastward offset stacking.

The LSC here can be divided into 10 channel complexes bounded by major erosional surfaces (Fig. 15). Since the lower and upper boundaries of the conglomerate body lie just below and above the exposure, respectively, each channel complex appears to terminate at those boundaries. Flattening the LSC strata, the successive channel complexes would show a pattern of eastward offset stacking. Individual channel complexes show various assemblages of architectural elements and sedimentary facies. The complexes 1, 2, 7, 8, and 10 mainly consist of massive and stratified conglomerates of Facies A deposited by turbidity currents. On the other hand, the complexes 3, 4, 5, 6, and 9 comprise similar amounts of turbidite conglomerates (Facies A) and mud-rich conglomerate (Facies B) of debris flows. In general, turbidite conglomerates dominate in this section and mostly form stacked sheets. The stacked sheets, laterally inclined strata, and hollow

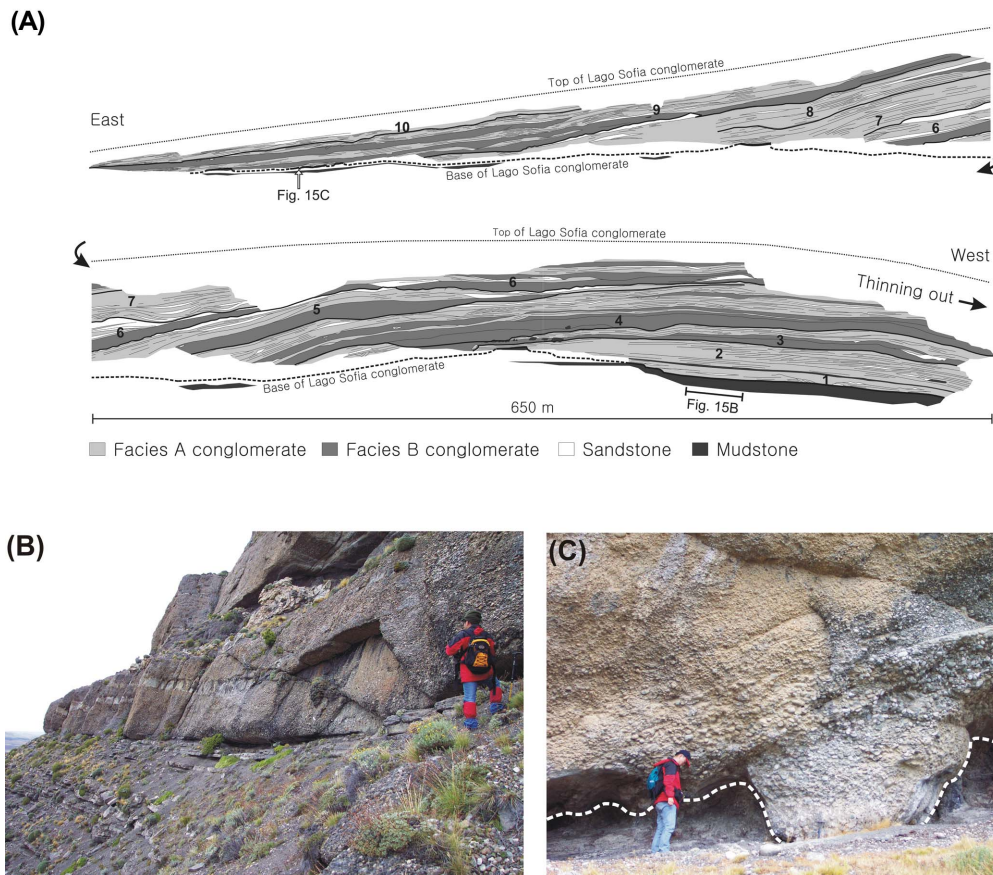


Fig. 15. (A) Sketch of the Lago Sofia section, highlighting the large-scale architecture of deep-sea channel conglomerate. The outcrop consists of stratified conglomerate, diamictite, and sandstone beds formed in an axial trunk channel. The stratified conglomerate is interpreted as the deposits of turbidity currents. Clast imbrication in these conglomerates is indicative of a sediment dispersal to the southwest, reflecting a southwestward-draining trunk channel. Diamictite beds were formed by muddy debris flows. Paleocurrents measured from the diamictite beds are highly oblique to those from stratified conglomerate, suggesting that the debris flows were originated from intermittent failure of channel bank or slope flanking the channel system. Note the progressive eastward shift of channel complexes (numbered) bounded by major down-cutting surfaces (thick lines), which implies a long-term migration of the axial channel to the east. Thick dashed line represents the basal surface of the conglomerate body. (B) The base of LSC in the Lago Sofia section, overlying a sequence of hemipelagic mudstone and turbidite sandstone. (C) A large scour at the base of LSC, cutting into the underlying mudstone

fills are laterally transitional to one another, reflecting juxtaposed geomorphic units of deep-sea channel systems.

8. Depositional model of the LSC submarine channel system

Previous studies interpreted that the LSC was deposited in submarine channels that were developed upon a submarine fan (Winn and Dott 1977; 1979), but a number of sedimentary features contradict with this interpretation. For example, the LSC is encased in a thick succession of

hemipelagic mudstones, and the paleoflow patterns in it are far from radial, negating the possibility of a depositional system with a point source and diverging sediment dispersal pattern. The elongated shape of the LSC in N-S direction also does not support a fan model; it is reminiscent of a channel system. A number of sedimentary features suggest that the LSC was deposited in a submarine channel system, not related to a submarine fan but developed independently along the N-S-trending foredeep trough of the Magallanes Basin (Fig. 16).

A study of the sedimentary strata surrounding the LSC

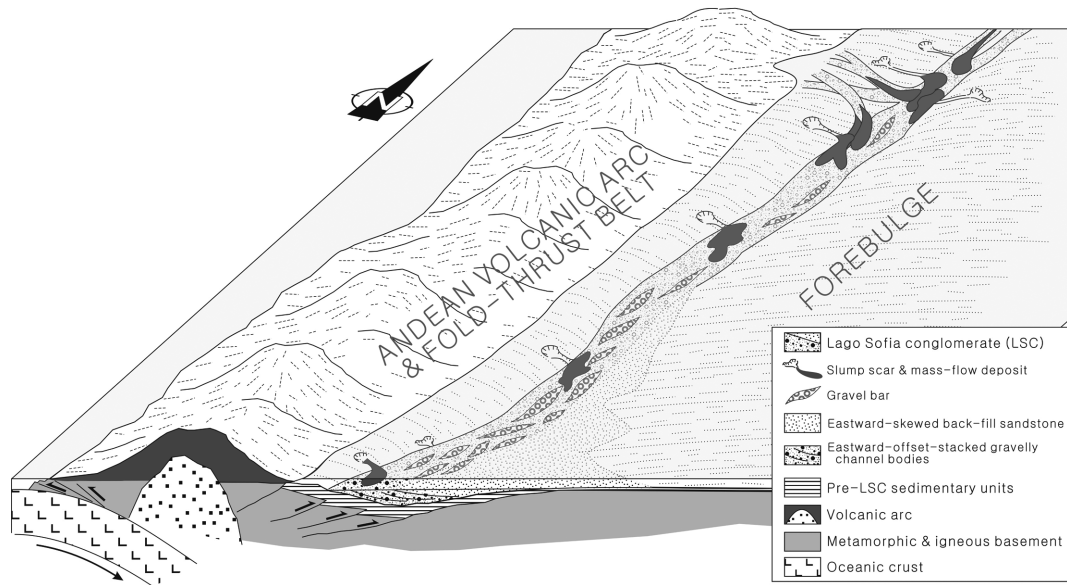


Fig. 16. Depositional model of the LSC and paleogeographic reconstruction of southern Chile during deposition of the LSC

shows that the axes of synsedimentary folds in the hemipelagic mudstones trend north-to-south, indicating that the paleoslope flanking the LSC submarine channel was dipping toward the east (Scott 1966). The sandstone-to-shale ratio and the mean thickness of sandstone beds in these strata also decrease toward the east. Composition of the gravel clasts in the LSC indicates that the clastic sediments were derived mostly from the arc and cordilleran massifs to the west of the basin (Scott 1966). The generally ENE-directed paleocurrent vectors in the Lago Pehoe and Lago Goic sections indicate that the channels here were incised approximately parallel to the dip direction of the paleoslope (Fig. 13), although the channel segment represented by CCS 3 of Beaubouef (2004) is oriented oblique to this general paleoflow direction (Fig. 8). The eastward-directed channels in this area appear to have been bent toward the south at the easternmost part of the LSC exposures, converging to a southward-flowing, main channel (Fig. 13).

The LSC to the south of the Lago del Toro has a lenticular geometry with the long axis trending almost north-to-south and pinching out along the western margin (Fig. 14). The overall geometry of the LSC here together with the south- to southwestward paleocurrent vectors indicates that the conglomerates represent the fill of an N-S-trending channel. The discordance between the overall southward paleoflow pattern in the LSC and the regional eastward-dipping paleoslope inferred from the surrounding strata has been noted by a former study (Scott 1966) but

has remained unanswered. The present authors interpret that this discordance can be resolved by assuming that the LSC submarine channel in the Lago Sofia area was developed along the southward-plunging axis of the foredeep trough rather than on the eastward-dipping slope of the foredeep trough.

The overall sedimentary characteristics of the LSC together with the paleoflow patterns suggest that the LSC was deposited in a submarine channel system, which consisted of several tributaries in the north and a trunk channel in the south (Fig. 16). The channel system is interpreted to be more similar to the drainage developed along a trench (e.g., Lewis 1994; Lewis and Barnes 1999) rather than the centripetally converging submarine-fan channel systems. The overall sedimentary characteristics of the LSC are better explained by this model. The isolated conglomerate bodies of the LSC in the northern sections, separated by hundreds of meter-thick mudstones (Fig. 12A), are interpreted to represent upstream tributaries, each of which were probably active for a relatively short period with a prolonged abandonment. On the other hand, the LSC in the Lago Sofia section (Fig. 12B) is interpreted as the product of amalgamation of multiple channel bodies, which are vertically stacked and interconnected because of the confinement of the trunk channel system within the bottom axis of the foredeep trough.

One of the most interesting features of the LSC is the similarity to terrestrial river deposits in sedimentary facies and architecture, as pointed out by Winn and Dott (1979).

The stratified conglomerate common in the LSC is nearly identical to those of gravel-bed rivers (cf. Boothroyd and Ashley 1975; Hein and Walker 1977). The architectural elements of stacked sheets, laterally-inclined strata, foreset strata, and hollow fills are also common in the deposits of gravelly braided rivers (cf. Boothroyd and Ashley 1975; Karpeta 1993; Nemeč and Postma 1993; Jo et al. 1997). These suggest that the LSC submarine channels were similar in geomorphology to terrestrial, gravelly braided rivers. The morphologic similarity between submarine channels and terrestrial rivers has been increasingly documented from recent deep-sea studies (e.g., Klauke and Hesse 1996; Ercilla et al. 1998; Abreu et al. 2003; Posamentier 2003). Most of the studies are, however, concerned with mud- and sand-rich, sinuous deep-sea channels. The LSC in this study is thought to be a rare example of low-sinuosity, gravelly deep-sea channels, which are similar in morphology, sedimentary facies and architecture to terrestrial gravelly braided rivers.

The main sedimentary processes of the LSC submarine channels are the formation of various gravel bars and the filling of hollows by turbidity currents. The architectural elements of stacked sheets, laterally-inclined strata, foreset strata, and hollow fills represent a range of morphologic units constituting the submarine channels. The gravels might have been transported downstream by a number of turbidity currents over long period, forming various morphologic units, rather than by one turbidity current. Debris flows forming the mud-rich diamictite beds were also one of the principal sedimentary processes operative in the LSC submarine channels. The abundant mud suggests that the debris flows initiated on the levees and/or the slope flanking the channel system (Fig. 16). The sediment failures on the levees and the slope were probably transformed to debris flows in the downstream direction, incorporating gravels from the channel bed. The paleoflows measured from the diamictite beds, which are commonly highly oblique to those of the stratified conglomerate beds (Sohn et al. 2002), also support this interpretation.

The main channel is interpreted to shift progressively eastwards, because the successive channel complexes in the Lago Sofia section show an eastward offset stacking pattern (Fig. 15). The lateral offset stacking of deep-sea channel was documented by De Ruig and Hubbard (2006) for the Oligocene-Miocene Puchkirchen Formation, Austria. The Puchkirchen channel belt was partly highly sinuous and the downstream migration of its meander bends

produced the outer bend-directed offset stacking of channel-belt fills. Such a process, however, does not seem to be responsible for the offset stacking of the Lago Sofia channels, because the Lago Sofia channel is interpreted to be of low sinuosity and any data does not indicate meandering channels. Extrinsic controls are invoked for the most probable cause of the biased movement of the Lago Sofia channel system. During the deposition of LSC, the Andean Cordillera was being uplifted, shedding coarse clastics to the adjacent foredeep trough. The uplift would cause the area east of the Andean Cordillera, including the foredeep trough, to be tilted eastwards, forcing the Lago Sofia channel system to migrate eastwards.

9. Conclusions

The conglomerate bodies of the Cretaceous Lago Sofia Lens in the southern Chile are one of the largest submarine channels filled by gravelly sediments, extending for more than 100 km from north to south. The conglomeratic channel bodies show different stacking patterns, constituent facies and paleoflows in the northern and southern parts of the study area, respectively. The conglomerate bodies in the northern part are isolated and smaller in vertical and lateral dimensions with paleoflows toward ENE and S to SW, whereas they are vertically interconnected and have larger dimensions in the southern part, showing southwestward paleoflows. These features suggest that the channels in the northern part were tributaries that were developed closer to the basin margin and were subject to relatively frequent avulsions. On the other hand, the large channel in the southern part was an axial trunk channel confined along the axis of an elongate foredeep trough. The tributaries were mostly filled with mass-flow deposits, probably affected by channel bank failures or basin-marginal slope instability processes, whereas the trunk channel was dominated by prolonged tractive processes. This difference resulted distinct sets of lithofacies and architectural elements between the tributaries and the trunk channel. The tractive processes dominant in the trunk channel produced various architectural elements representing vertical and lateral accretion of gravel bars, deposition of large gravel dunes and filling of scours and channels, which are nearly identical to those of terrestrial gravel-bed rivers. The Lago Sofia submarine channel probably had a centripetally converging drainage system, contrary to centrifugally diverging submarine fan channels, as previously thought (c.f., Winn and Dott 1979). The

development of such a drainage pattern was probably controlled by the elongate geometry of the foredeep basin, in which the Lago Sofia submarine channel formed. The conglomeratic deposits filling the Lago Sofia channel show an eastward offset stacking pattern indicative of an eastward channel migration, which is most probably due to the uplift of the Andean Cordillera.

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