Pliocene lahar deposits in the Coastal Cordillera of central Chile: Implications for uplift, avalanche deposits, and porphyry copper systems in the Main Andean Cordillera

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Abstract

Lahar deposits occur within a shallow marine sedimentary succession of the Pliocene La Cueva Formation in the Coastal Cordillera of central Chile (33°40′–34°15′S). Provenance studies of the abundant volcanic material in the lahar deposits suggest that they derive from denudation by mass wasting of Oligocene–Miocene volcanic rocks on the western slopes of the Main Andean Cordillera at the same latitude. Pliocene rock debris deposits preserved in the region of El Teniente (~34°S) and scattered along the westernmost part of the Andes of central Chile indicate catastrophic erosive events related to the rapid uplift of the cordilleran block. This rock debris was deposited by avalanches and transformed further downslope into lahars by dilution with stream water. Lahars were channeled along the ancient drainage system that reached a shallow Pliocene sea at the site of the present Coastal Cordillera. The exceedingly rapid exhumation of active porphyry systems during the Early Pliocene in this part of the Andes may have played a role in affecting hydrothermal processes, brecciation, and diatreme formation at the porphyry systems of El Teniente and Río Blanco–Los Bronces.

Keywords: Andes; Lahar; Avalanche; Pliocene; Mass wasting; Porphyry copper

1. Geological setting and study objective

Four main N–S-trending physiographic units can be recognized in central Chile (Fig. 1). From west to east, they are as follows: (1) the Coastal Cordillera, about 50 km wide, with most summits varying from 1000 to 2000 m above sea level (a.s.l.); (2) the Intermediate Depression, a 50 km wide alluvial plain that slopes westward from about 700 to 400 m a.s.l.; (3) the Main Andean Cordillera, varying from 2000 to almost 7000 m a.s.l., the highest peaks of which are formed by volcanoes of the currently active southern volcanic zone; and (4) a Miocene–Pliocene fold-and-thrust belt that extends farther east into Argentina (Ramos, 1988; Giambiagi et al., 2001).

Between 33°40′ and 34°15′S, the Coastal Cordillera is largely formed by extensive Mesozoic granitoid batholiths, as well as Paleozoic metamorphic and plutonic rocks (Gana et al., 1996; Wall et al., 1996). Cretaceous and scarce Eocene marine deposits are exposed only in coastal cliffs west of Litueche (34°07′S) and at Algarrobo (33°22′S), whereas Neogene marine deposits, known as the Navidad and La Cueva formations (Tavera, 1979; Brüggen, 1950), are widely distributed in this part of the Coastal Cordillera.

At this latitude, Oligocene–Miocene volcanic rocks form most of the western flank of the Main Andean Cordillera. The 1300–1900 m thick lower part of these volcanics, Oligocene–Early Miocene in age, has been mapped as the Coya–Machalí Formation or the equivalent Abanico Formation north of 34°S (Klohn, 1960; Aguirre, 1960; Thiele, 1980; Charrier et al., 2002). The overlying, unconformable, subhorizontal volcanic rocks, 1300–3000 m thick, are considered part of the Farellones Formation (Charrier et al., 2002). K–Ar ages for both units overlap between about 21 and 16 Ma, which suggests that the unconformity is diachronic.

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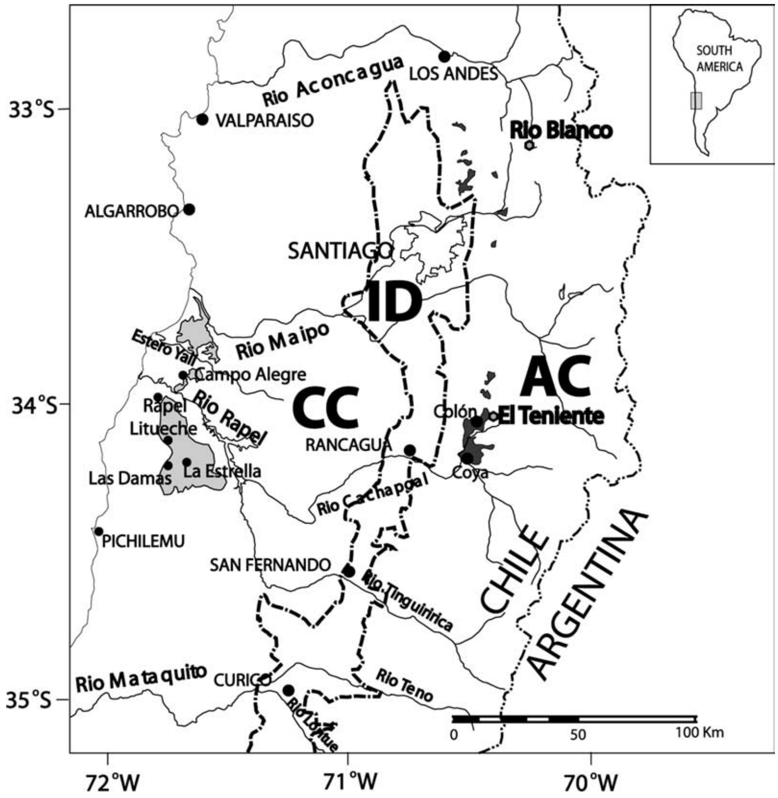

Fig. 1. Location map, showing localities cited in the text and the outline of the outcrops of the Colón–Coya (dark gray) and La Cueva (light gray) formations. CC, Coastal Cordillera; ID, Intermediate Depresión; AC, Main Andean Cordillera.

Miocene plutons are scattered throughout the Main Andean Cordillera (e.g. Kurtz et al., 1997; Maksaev et al., 2003a), where supergiant late Miocene–Pliocene porphyry Cu–Mo ore bodies, such as Rio Blanco–Los Bronces and El Teniente, occur within hydrothermal alteration zones related to multiphase porphyritic stocks (6.46–4.37 Ma; Deckart et al., 2003; Maksaev et al., 2003b, 2004) (Fig. 1). The host rocks are Upper Miocene basaltic and andesitic volcanics, diabase sills, and gabbros at El Teniente (Skewes et al., 2002; Maksaev et al., 2004), as well as Miocene andesites and a middle Miocene granodioritic batholith at Río Blanco–Los Bronces (Serrano et al., 1996). The El Teniente and Río Blanco–Los Bronces ore bodies are associated with breccia pipes and typical diatreme structures (Sillitoe, 1985).

In this part of the Andes, Neogene relief growth was related to a combination of active arc volcanism and compressive tectonics (Godoy et al., 1999; Charrier et al., 2002, 2005). Erosion of the Andean orogen was accompanied by Neogene marine sedimentation along the westernmost section of the present Coastal Cordillera (Brüggen, 1950). Subduction-related volcanism first developed during the Eocene–Oligocene under an extensional regime, followed by basin inversion and uplift of the Main Andean Cordillera as a result of Miocene–Pliocene compressive pulses with continued volcanic activity (Charrier et al., 2002, 2005).

This article describes the sedimentary characteristics of lahar deposits occurring in the Pliocene sedimentary successions of the Coastal Cordillera. Because time-equivalent volcanic rock debris (Colón–Coya Formation) is also present on the western slopes of the Main Andean Cordillera (Cuadra, 1986), we associate their development with these lahar deposits. These relationships have important implications for Andean uplift, erosion, and unroofing of late Miocene–Early Pliocene porphyry systems.

2. Description of sedimentary deposits

2.1. Coastal Cordillera

The La Cueva Formation occurs mostly between Litueche and La Estrella (Fig. 1), where it overlies the Paleozoic granitic basement, and east of Rapel Village, where it overlies the uppermost Rapel member of the Navidad Formation. The maximum thickness calculated for this formation is 100 m, though most sections usually do not reach more than 30 m thickness because of erosion. The contact with the Navidad Formation consists of a firmground with abundant burrows (Buatois and Encinas, in press), covered by a 1 m thick conglomerate with small rounded clasts (Fig. 2). This conglomerate is overlain by sandstone and siltstone with abundant, generally articulated gastropods and bivalves. The rare siltstones contain fossil and plant fragments. Medium and coarse sandstone with planar, trough, and herringbone cross-bedding, as well as abundant *Ophiomorpha* and *Thalassinoides* traces, overlie these beds (Figs. 3 and 4), constituting the most typical and widespread facies of the La Cueva Formation.

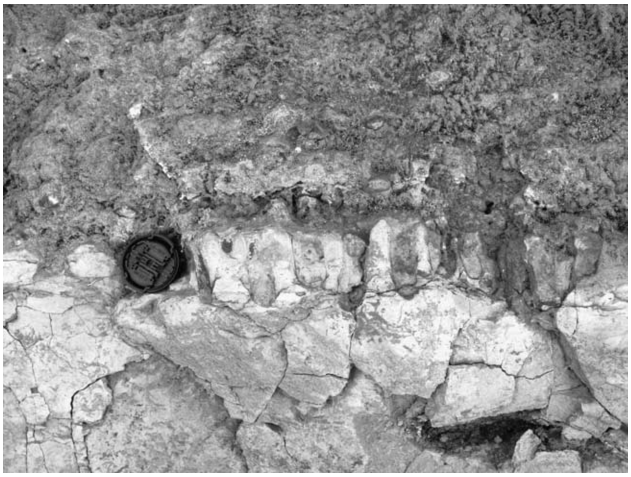

Fig. 2. Contact between the uppermost member of the Navidad Formation (bottom) and La Cueva Formation (top) marked by camera lens cap. A firmground with abundant burrows occurs on top of the Navidad Formation (Rapel member), which is covered by a basal transgressive conglomerate of the La Cueva Formation, indicating a relative sea level rise.

Locally, sandstones contain abundant bivalves, gastropods, shark teeth, ray plates, and whale bones. These facies are particularly well exposed in a sand quarry 1 km north of Litueche (Fig. 1), where paleocurrent directions obtained from planar cross-bedding show rather constant trends of 102° and 011°, consistent with measurements obtained elsewhere in this formation (Fig. 5). At some localities north of the Yali River and in Campo Alegre, these sandstones contain rounded pumice clasts and show trough and planar cross-bedding with abundant reactivation surfaces and escape fossil traces (Fig. 6). The mean paleocurrent direction given by planar cross-bedding within these pumice-bearing beds is 344° in the Yali River, whereas trough cross-beds at Campo Alegre trend toward 039° (Fig. 5). Near La Estrella, sandstones are interbedded with conglomerates. The sandstones are either massive with common floating clasts or show planar cross-bedding with current bipolarity. Both facies are thoroughly bioturbated by *Ophiomorpha* and *Thalassinoides*. Conglomerate beds are formed by centimeter- to decimeter-scale, volcanic,

Fig. 3. Planar lamination (below hammer) and herringbone cross-bedding (above hammer) generated by tidal reworking in sandstones of the La Cueva Formation.

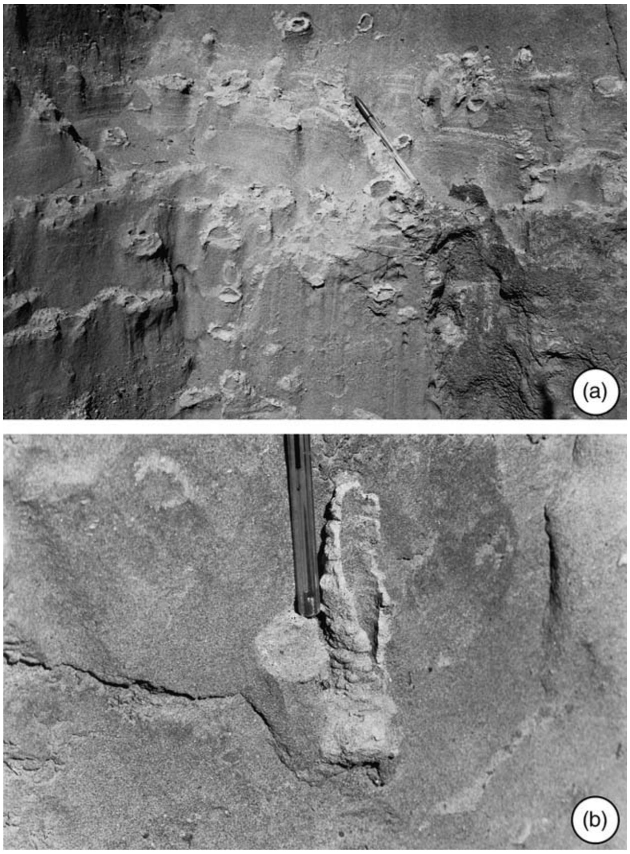

Fig. 4. (a) *Ophiomorpha* in sandstone beds of the La Cueva Formation; (b) detailed view.

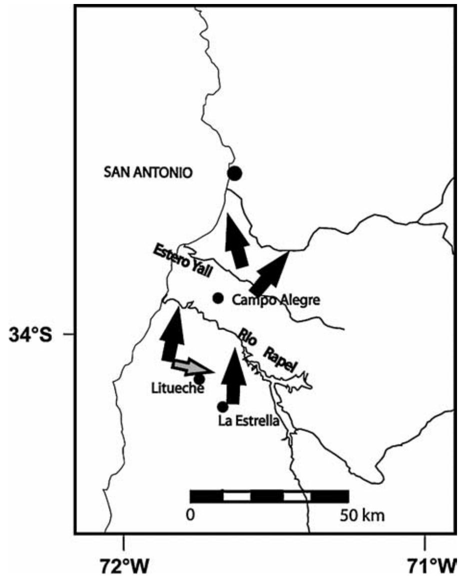

Fig. 5. Paleocurrent directions in the La Cueva Formation. Black arrows correspond to paleocurrent directions obtained from planar cross-bedding in sandstones at Litueche and pumice-rich sandstones at Estero Yali, as well as trough cross-bedding in pumice-rich sandstones at Campo Alegre and imbricated clasts at La Estrella (see Fig. 1). These paleocurrent directions are interpreted as having been generated by fluvial processes. Gray arrow corresponds to paleocurrent directions obtained from planar cross-bedding in sandstones at Litueche, interpreted as having been generated by marine and tidal processes.

Fig. 6. Escape fossil trace (*Fugichnia*) in pumice-rich sandstone beds of the La Cueva Formation. The pumice is thought to have been deposited in the basin by pyroclastic flows that were channeled along the drainage system and suddenly increased the sedimentation rates, leading to escape traces.

well-rounded clasts, which in some places are imbricated, indicating paleocurrents toward 002°. Both sandstone and conglomerate beds show erosive contacts, which in some parts indicate underscouring in cohesive sediments (Fig. 7).

At the type locality of the La Cueva Formation, in the hills surrounding the village of Las Damas, the succession is formed by cross-bedded, fossiliferous sandstone overlain by massive sandstone with abundant angular, millimeter- and centimeter-scale, floating, volcanic clasts (Figs. 8 and 9a). A matrix- to clast-supported conglomerate with an erosive to transitional basal contact caps the section (Fig. 8). Its angular to rounded clasts, dominated by volcanics, are generally of decimeter-scale but also include some conspicuous granitoid blocks up to several meters in diameter (Fig. 9b–d). This unit locally consists of two conglomerate beds separated by sandstone with parallel lamination and low-angle planar cross-bedding. (Fig. 9e and f).

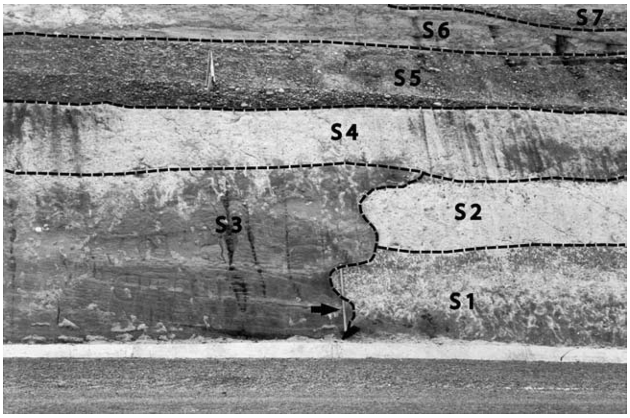

Fig. 7. Alternation of sandstone and conglomerate beds of the La Cueva Formation forming different successions (S1–S7) at La Estrella. Contacts between these successions are marked with stippled lines. Successions show contacts with complicated patterns in S3; S5 and S7 are clast-supported conglomerate horizons, and the rest are sandstone beds. S3 has planar cross-bedding, and S1, S2, S4, and S6 are massive beds, probably due to thorough bioturbation that indicates long periods between floods. Hoe for scale is marked with an arrow and is approximately 1.20 m long.

Petrographic analysis of cobbles from this conglomerate shows two groups of volcanic clasts: (1) amphibole-bearing andesites (Fig. 10a); and (2) ortho- and clinopyroxene-bearing andesites (Fig. 10b). Both groups contain sodic plagioclase.

The petrography of the conglomerate matrix indicates that it is composed of (1) angular to subangular andesitic grains (ca. 65%); (2) subhedral to euhedral crystals (10%) of plagioclase and minor ortho-/clinopyroxene, amphibole, and magnetite; and (3) interstitial, glassy volcanic material (25%) (Fig. 10c). Lithic and monomineralic grains in the matrix are similar to the conglomerate cobbles. Heavy mineral analysis shows an association that comprises ortho- and clinopyroxene crystals with magnetite inclusions, almandine garnet, hematite, and rutile as the dominant minerals, with minor amphibole, epidote, and zircon (Fig. 10d).

2.2. Main Andean Cordillera

The Colón–Coya Formation was defined by Cuadra (1986) at the localities with the same name and is equivalent to the Alto Colón ‘complex’ first described by Camus (1977). Gómez (2001) also used the term ‘complex’, though this term normally refers to areas with a high structural complexity, which is not the case in our study area. We therefore prefer to keep the name Colón–Coya Formation. This unit was initially regarded as part of the Farellones Formation (Klohn, 1960), but subsequent studies showed it unconformably overlies the Coya–Machalí and Farellones formations (Cuadra, 1986; Gómez, 2001). These deposits cover an area of approximately 200 km^2 between Colón and Coya (Fig. 1), where their present volume has been estimated at 7.3 km^3 (Gómez, 2001). In addition, similar deposits occur scattered along the westernmost section of the Main Andean Cordillera between 33° and 34°S (SERNAGEOMIN, 2002) and within sections of the Intermediate Depression (Marangunic et al., 1979). This unit is mainly formed by rock debris with local andesitic lavas, volcanic ash flows, and conglomerate (Godoy et al., 1994; Gómez, 2001). The largest part is formed by chaotic, unconsolidated rock debris with a matrix-supported fabric and variable thicknesses reaching up to 300 m (Cuadra, 1986; Gómez, 2001) (Fig. 11). Rock fragments are angular and poorly sorted, ranging from a few millimeters to 25 m in diameter (Gómez, 2001). Clasts are coarser and more chaotic in the northeastern outcrops along the headwaters of the Coya River, where they are exposed at up to 2550 m a.s.l. In contrast, relatively finer and better sorted facies occur downstream to the southwest, extending down to 900 m a.s.l. at the confluence of the Coya and Cachapoal rivers (Gómez, 2001). Most clasts are grey, pyroxene-bearing andesite and fluidal dacite, similar in age and composition to rocks of the Farellones Formation exposed in the El Teniente district (Godoy et al., 1994). The abundant unconsolidated matrix is composed of crushed rocks, clays, and volcanic ash. Petrographically, it consists of subrounded to angular lithic fragments of pyroxene-bearing dacite tuff, plagioclase, and pyroxene crystals, as well as minor glass shards.

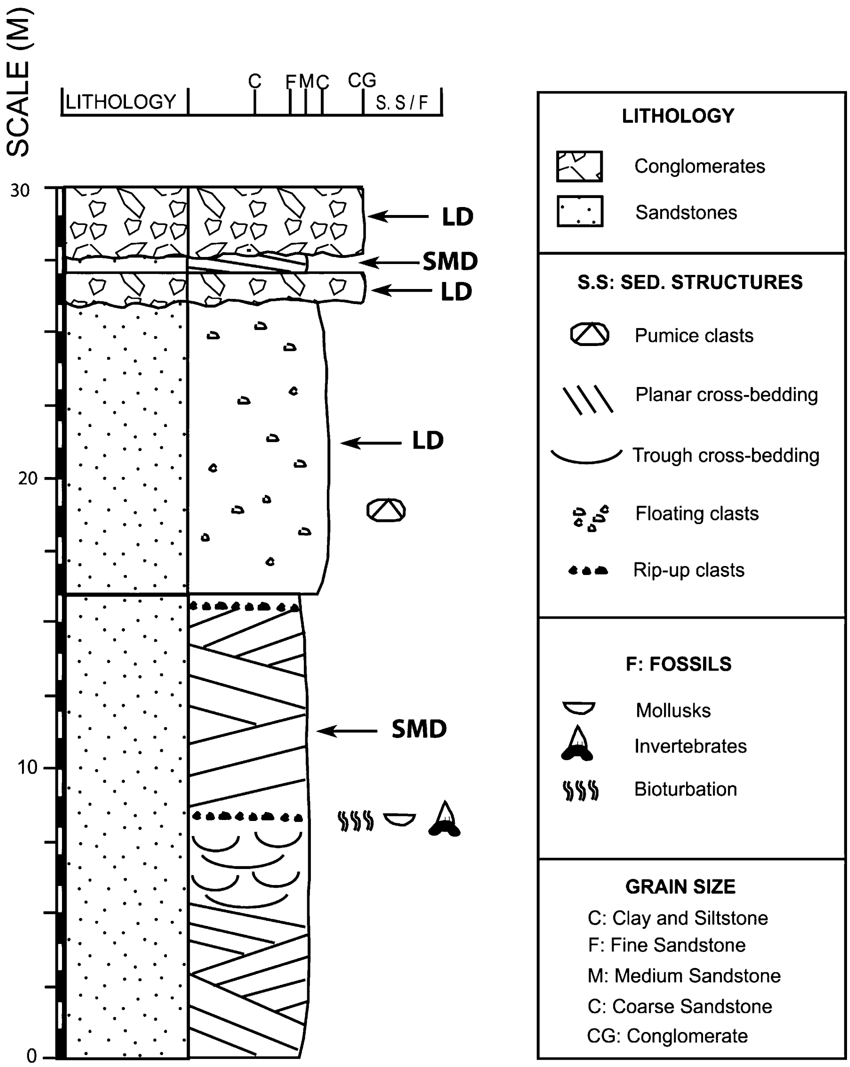

Fig. 8. Stratigraphic column of the La Cueva Formation, representative of the area surrounding Las Damas Village. Upper massive sandstone and conglomerate beds are interpreted as generated by lahar flows. Sandstone beds with planar and trough cross-bedding are interpreted as generated by marine reworking of sand deposited in a shallow marine environment. LD, lahar deposits; SMD, shallow marine deposits.

3. Age

3.1. Coastal deposits

On the basis of a comparison of bivalves and gastropods from the La Cueva Formation with fossils from the Coquimbo Formation, as well as modern mollusks, Brüggen (1950) ascribes a late Pliocene age to the La Cueva Formation. A subsequent study of the marine fossils by Herm (1969) supports this age. Yet the wide age range represented by the fossil species allows only a general Pliocene age assignment for this formation. This age is supported by the abundant presence of teeth of the great white shark *Carcharodon carcharias*, which first appeared in the late Miocene but only became abundant since the Pliocene (Encinas et al., 2003a; Suárez et al., 2003).

The volcanic material in the La Cueva Formation was radiometrically dated using pumice clasts within the deposits, which give maximum ages. Analyses were done at the geochronology laboratory of SERNAGEOMIN in Santiago. A whole-rock K–Ar analysis of a scoria clast from a lahar bed of the La Cueva Formation obtained near Las Damas (Fig. 1; Table 1) yields 4.6 ± 0.4 Ma (Early Pliocene).

Biotite from pumice clasts of Estero Yali (Fig. 1), dated by laser-beam step-heating $^{40}Ar/^{39}Ar$ (six steps), reveals a rather disturbed age spectrum (Fig. 12) with a gradient of apparent Pliocene ages from 1.7 ± 0.3 Ma (lowest temperature step) to 5.3 ± 0.5 Ma (highest temperature step; Table 2). The integrated age of all steps is 2.7 ± 0.3 Ma (Fig. 12; Table 2), but this date is only a minimum estimate for the biotite; it is apparent that significant radiogenic Ar loss has affected the mineral, probably due to weathering.

Amphibole crystals collected from pumice clasts at Campo Alegre (Fig. 1) yield a K–Ar age of 7.7 ± 1.0 Ma (Table 1). However, this date should be treated with caution, as it is uncertain whether the different pumice clasts were formed during the same event or different volcanic episodes.

Despite some chronological ambiguity, both paleontological and radiometric records indicate a Pliocene age for this

Fig. 9. Lahar deposits. (a) Massive sandstone beds with angular floating volcanic clasts; (b) massive sandstone beds passing upward to clast- and matrix-supported conglomerate with angular and rounded clasts; (c) top view of a conglomerate horizon showing angular and rounded, mostly andesitic clasts; (d) top view of a conglomerate bed with metric blocks isolated because of differential erosion; (e) two conglomerate beds deposited by lahar events separated by a sandstone layer (indicated by hammer) with planar lamination and low-angle planar cross-bedding, interpreted as formed by marine processes indicating more than one lahar flooded the marine basin; and (f) panoramic view of these beds with sandstone layer indicated by arrow.

marine deposit, as is supported by its stratigraphic position. The La Cueva Formation overlies the late Miocene–Early Pliocene Navidad Formation (Encinas et al., 2005). A maximum Early Pliocene age is therefore ascribed to the La Cueva Formation.

3.2. Main Andean Cordillera deposits

The Colón–Coya Formation initially was regarded as Quaternary lahar breccias, ash flows, and andesite lava flows (Camus, 1977). However, Charrier and Munizaga (1979) obtained whole-rock K–Ar ages of 2.3 ± 0.2 and 1.8 ± 0.2 Ma for andesite lava flows along the Cachapoal River near Coya that indicate a Pliocene–Pleistocene age for this formation. These lava flows were described as covered by lahar deposits from the Colón–Coya Formation (Charrier and Munizaga, 1979), but according to Godoy et al. (1994), the flows actually abut the rock debris, being covered by more recent, reworked material; according to Gómez (2001), they overlie river terraces along the Cachapoal Valley.

Subsequently, Cuadra (1986) obtained an imprecise whole-rock K–Ar age of 1.7 ± 0.7 Ma for a rhyolitic volcanic ash flow deposited over rock debris some 12 km west of the El Teniente mine. Thus, a Pliocene–Pleistocene age was ascribed to this unit (Cuadra, 1986). Furthermore, Godoy et al. (1994) dated oxidized biotites from the same volcanic ash deposit, which also yielded a rather imprecise K–Ar age of 2.9 ± 1.7 Ma.

An attempt to date biotites from the same volcanic ash horizon by step-heating ^{40}Ar/^{39}Ar during this study was unsuccessful because no radiogenic ^{40}Ar was obtained during degasification; the biotites from this volcanic ash appear unsuitable for obtaining an accurate age using the K–Ar

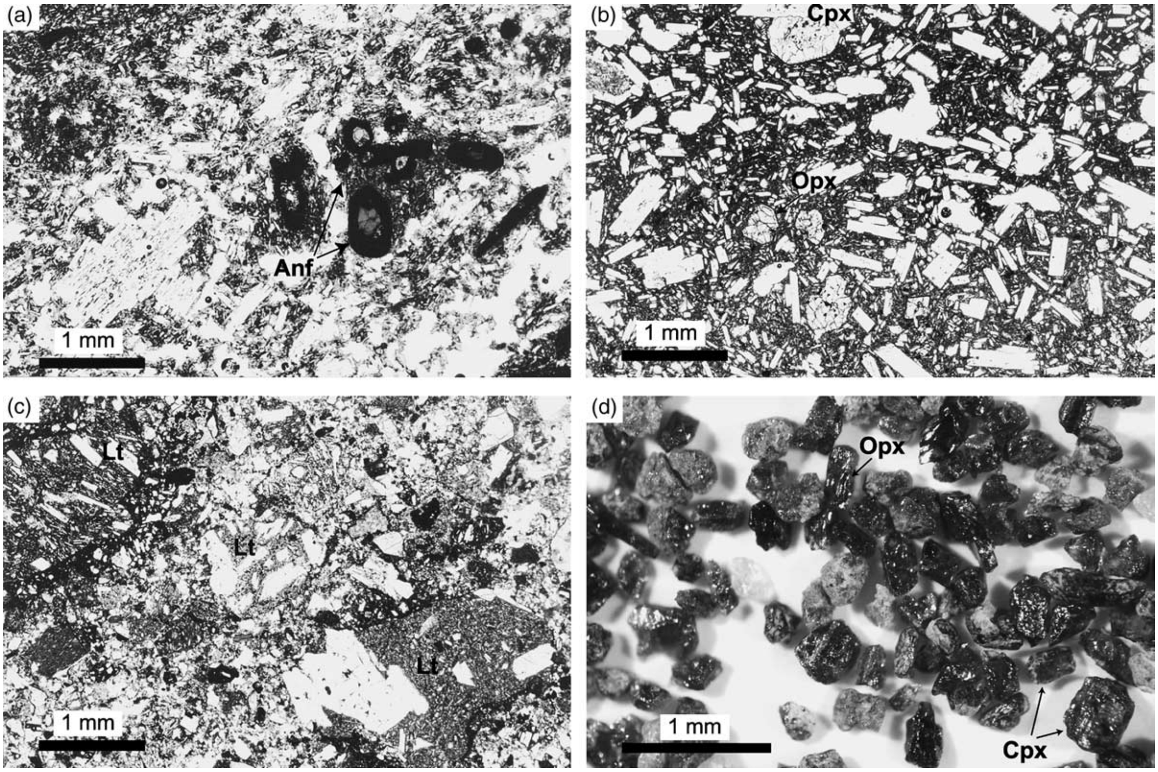

Fig. 10. Microphotographs of thin sections and loose grains from the lahar deposit of La Cueva Formation: (a) amphibole-bearing andesite clast. Note the opacitic border of oxihornblende crystals (Anf); (b) clast of ortho- (Opx) and clinopyroxene- (Cpx) bearing andesite; (c) matrix of the lahar deposit with abundant andesitic lithic grains (Lt); (d) heavy mineral loose grains from the matrix. Note the abundance of ortho- and clinopyroxene.

system, probably due to weathering. However, apatites from the same rhyolitic volcanic ash deposit (TT-111) yield a fission track date of 3.6 ± 3.0 Ma ($\pm 2\sigma$; Table 3a). A separate analysis of apatites from the same sample yields an analogous apatite fission track age of 4.63 ± 2.06 Ma (Table 3a), plus a similar zircon fission track date of 4.97 ± 0.70 Ma, which has a smaller error range (Table 3b). These dates indicate an overall Pliocene age for the Colón–Coya Formation, consistent with its unconformable stratigraphic position overlying the Upper Miocene Farellones Formation. This Pliocene age is also supported by the occurrence of debris deposits of the Colón–Coya Formation that, according to Gómez (2001), overlie lamprophyric dykes dated at $3.8 + 0.3$ and $2.9 + 0.6$ Ma.

4. Discussion

4.1. Interpretation of field data

The La Cueva Formation represents the terminal phase of Neogene marine sedimentation in central Chile. During the late Miocene–Early Pliocene, this area was subjected to important subsidence, and deep marine sedimentation took place (basal member of the Navidad Formation) (Encinas et al., 2003a,b). Subsequently, the basin shallowed to shelf depths, and the two upper members of the Navidad Formation (Licancheu and Rapel), as well as the La Cueva Formation, were deposited during the Pliocene. Finally, after the Pliocene, this part of the Coastal Cordillera was uplifted, and no further marine sedimentation is recorded except for local Quaternary marine terraces (Encinas et al., 2003a).

The characteristics of the La Cueva Formation indicate it was deposited in a shallow marine environment, which we interpret as a wave-dominated deltaic system. Although wave-dominated delta successions are generally difficult to distinguish from wave-dominated coasts (Bhattacharya and Walker, 1992), the occurrence of locally abundant vegetal matter, abundant conglomerates with erosive contacts, and an overall coarsening-upward succession suggest a deltaic environment. Deposition took place during a relative rise in sea level, probably reflecting coastal subsidence. A basal ravinement conglomerate overlying the Navidad Formation was formed by wave reworking of sediments during the marine transgression. The bioturbated firmground underlying the conglomerate indicates that a period without sedimentation preceded deposition of the La Cueva Formation (Buatois and Encinas, in press) (Fig. 2). Above the conglomerate, fine sandstone and siltstone beds with abundant articulated mollusks were probably deposited on the prodelta zone, indicating deepening of the basin. Sandstone and conglomerate beds overlying these facies indicate prograding successions. Herringbone cross-bedding (Fig. 3), paleocurrent bipolarity, and planar and trough cross-bedding indicate the complete tidal and wave reworking of these sediments. The intercalation of sandstone and conglomerate beds showing abundant and

Fig. 11. (a) Pliocene Colón–Coya Formation rock debris in a road cut north of Maitenes gate (north of Coya Village); the light-colored part is composed of disaggregated dacite ignimbrite, and the darker fraction is formed by fragmented andesitic materials; (b) detail of fragmented andesite of the Colón–Coya Formation (photo by courtesy of Estanislao Godoy).

irregular erosional contacts at La Estrella (Fig. 7) and coarse conglomerates capping the succession at Las Damas indicate the onset of episodic, catastrophic floods that originated by tectonic movements or unusual meteoric events. The thorough bioturbation of sediments (Figs. 4 and 7) indicates periods of slow deposition between these floods.

Levels with abundant pumice clasts are interpreted as originating from pyroclastic flows, which probably were channeled along river valleys that debouched into the shallow coastal environment. These inferred pyroclastic flows carried enormous amounts of volcanic material that was rounded and mixed up with fluvial and coastal sand and gravel. As these flows emptied into the marine environment, they produced increased turbulence and sedimentation rates, which led to the development of profuse reactivation surfaces and escape fossil traces (Fig. 6).

Table 1
K–Ar data for samples from La Cueva Formation

Sample	Material	%K	Rad. Ar nl/g	% Atm. Ar	Age Ma ± 2σ
Las Damas; scoria clast	Whole rock	0.978	0.161	89	4.2 ± 0.8
		0.978	0.180	76	4.7 ± 0.4
				Weighted mean age	4.6 ± 0.4
Campo Alegre; pumice clasts	Amphibole	0.447	0.134	79	7.7 ± 1.0

Notes: K–Ar analyses performed at the Geochronology Laboratory of SERNAGEOMIN, Chile.

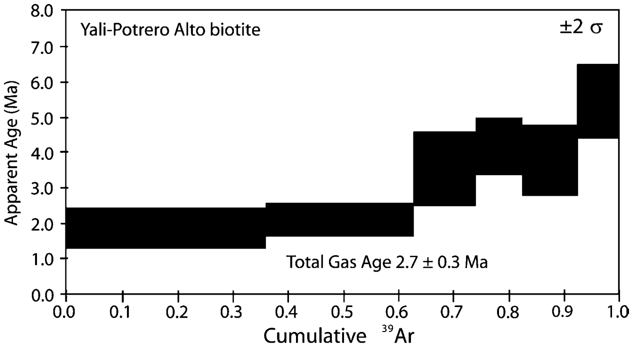

Fig. 12. Apparent ^{40}Ar/^{39}Ar age spectrum ($\pm 2\sigma$) for biotite of pumice clasts from pumice-rich sandstone of La Cueva Formation at Estero Yali (see Fig. 1) interpreted as generated by a pyroclastic flow channeled along the river drainage system and deposited in a shallow marine environment. The total gas age of 2.7 ± 0.3 Ma is a minimum estimate; the spectrum reveals a disturbed isotopic system with a gradient of apparent ages from 1.78 ± 0.28 to 5.31 ± 0.52 Ma, consistent with partial argon loss.

The conglomerates that crop out around Las Damas are interpreted as having been generated by lahars. The term 'lahar' has commonly been applied to any poorly sorted volcanoclastic deposit, including many that lack definite evidence of debris-flow deposition (Smith and Lowe, 1991). Lahars can be divided into two types (Smith and Lowe, 1991): those associated with eruptive activity and those not temporally related to eruptions. The first group may be derived from the transformation of pyroclastic flows to aqueous flows and the dilution and erosion of hot pyroclastic debris or fragmented lava flows by heavy rain or snowmelt. The second group can be generated by the mixing of eruption material with water from crater lakes (Neall, 1976). They also may be due to avalanches produced by mass failure of a large part of the source volcano, which can become diluted if they mix with water liberated at the site of the landslide or enter stream water. 'Cold' lahars can also be generated by intense rain during noneruptive periods in tropical climates (Rodolfo and Arguden, 1991).

The interpretation of these conglomerates as being deposited by lahar events is based on the occurrence of an abundant volcanic matrix, profuse angular volcanic clasts, and the presence of megaclasts, some of which reach several meters in diameter. These indicate a very competent flow, characteristic of lahar events. The matrix is rather hard due to cementation, which is typical of this material because of the abundance of unstable minerals (Mathisen and McPherson, 1991). The occurrence of clasts of different compositions, as well as the presence of rounded clasts, is interpreted as the product of bulking produced by the movement of the flow along the river valley. This process enabled the entrainment of rounded clasts from the streambed, as well as clasts with lithologies different from those of the angular volcanic clasts of

Table 2
^{40}Ar/^{39}Ar data summary of Yali–Potrero Alto biotite sample from pumice clasts in deposits of the La Cueva Formation at Estero Yali

Power/temperature	^{36}Ar/^{39}Ar	^{40*}Ar/^{39}Ar	Mol ^{39}Ar	% ^{39}Ar released	App. age Ma $\pm 2\sigma$
3.0	0.187234	0.86291	0.0710	36.1	1.78 ± 0.28
6.0	0.124869	0.98512	0.0522	26.8	2.03 ± 0.23
8.0	0.120929	1.68366	0.0222	11.4	3.48 ± 0.52
10.0	0.118896	1.99176	0.0167	8.4	4.11 ± 0.41
20.0	0.103378	1.79445	0.0197	9.9	3.70 ± 0.48
30.0	0.084621	2.57617	0.0151	7.4	5.31 ± 0.52
Total gas age					2.7 ± 0.3

($J = 0.0011425 \pm 5.300000 \times ^{-6}$). Notes: laser beam, step-heating ^{40}Ar/^{39}Ar analysis performed at the Geochronology Laboratory of SERNAGEOMIN, Chile.

Table 3
Fission track age data

Sample	Grains	ρ_s	N_s	ρ_i	N_i	χ^2	ρ_d	N_d	Pooled age $\pm 1\sigma$
(a) Apatite fission track age data for a superficial volcanic ash deposit of the Colón–Coya Formation									
TT-111	13	0.018	6	1.059	353	100	1.21	5405	3.6 ± 1.5
TT-111	25	0.021	21	0.810	791	76.7	3.339	4279	4.63 ± 1.03
(b) Zircon fission track age data for a superficial volcanic ash deposit of the Colón–Coya Formation									
TT-111	13	1.468	285	12.331	2394	100	0.670	4030	4.97 ± 0.35

Notes: Analysis in (a) by A.M. Grist, Fission Track Laboratory, Dalhousie University, Canada. Analysis in (b) by P.B. O'Sullivan at Apatite to Zircon Inc., USA. All samples pass the χ^2 test at the 95% confidence level (i.e. appear composed of one age population). Values of 124.7 ± 3.2 (CN-1) and 353.5 ± 7.1 (CN-5) were used for the zeta calibration factor at Dalhousie University and of 104.5 ± 2.6 (CN-1) at Apatite to Zircon Inc. The reported fission track ages are pooled ages. Abbreviations are as follows: ρ_s, $\rho_{i,}$, and ρ_d are the density of spontaneous, induced, and flux dosimeter tracks, respectively ($\times 10^6$/cm^2). N_s, N_i, and N_d are the number of spontaneous, induced, and dosimeter (CN5 or CN1) tracks, respectively.

the source area. The huge granite boulders likely were thus incorporated into the flow due to the abundance of this lithology in the Coastal Cordillera. The conglomerate beds are matrix- to clast-supported, which indicates deposition from debris and hyperconcentrated flows, respectively. Therefore, flow transformations took place during transport due to dilution and bulking. Massive sandstone beds with floating angular volcanic clasts underlying conglomerate beds are interpreted as the deposits of sandy mass flows produced by less competent lahar events (Fig. 9a). The occurrence in some localities of a thin layer of fine sandstone with parallel lamination and low-angle planar cross-bedding between two conglomerate beds indicates more than one lahar event and that 'normal' shallow marine sedimentation took place between these catastrophic events (Fig. 9e and f). The large size of the clasts and the long distance traveled by these flows suggest that the lahar events were probably triggered by major rockslide-debris avalanches (Smith and Lowe, 1991) (Fig. 9d) and reflect the high competence of the flows.

The rock debris deposits of the Colón–Coya Formation have been interpreted as avalanche deposits, though there is no agreement about whether they were exclusively cold landslides (Godoy et al., 1994) or a combination of hot avalanches, landslides, lahars, and volcanic effusions (Camus, 1977; Gómez, 2001). The interpretation is further complicated because some parts of the rock debris have been reworked by local, more recent debris flows and active fluvial erosion. The occurrence of clasts with different lithologies and the important variation in clast sizes, however, suggest that these deposits are associated with cold landslides.

The presence of coarser, more chaotic deposits in the northeastern and more elevated outcrops suggests that the rock debris provenance area was located to the east and northeast of the headwaters of the Coya River, where the late Miocene–Pliocene El Teniente orebody occurs (Godoy et al., 1994).

4.2. Relationships and timing between the coastal deposits and Main Andean Cordillera deposit

Mineralogical analysis of the La Cueva Formation lahar deposits indicates a volcanic source composed mainly of amphibole and ortho-clinopyroxene andesites. Only two possible source areas for these deposits exist in this part of central Chile: the eastern part of the Coastal Cordillera and the Main Andean Cordillera, farther east.

The western part of the Coastal Cordillera at this latitude is composed of extensive batholiths of Paleozoic, Jurassic, and Lower Cretaceous granitoids, whereas the eastern part is formed by volcanic and sedimentary rocks of the Cretaceous Lo Prado, Veta Negra, and Las Chilcas formations (SERNAGEOMIN, 2002). The andesitic and rare felsic rocks from these formations lack orthopyroxene (Vergara et al., 1995; Morata and Aguirre, 2003). Intrusive rocks in the Coastal Cordillera comprise gabbro-diorite, tonalite, and granodiorite, which are mainly composed of calcic plagioclase, K-feldspar, and quartz. Heavy mineral associations include orthopyroxene, but it is very rare (Parada et al., 2002).

Rocks from the Main Andean Cordillera in central Chile are dominated by intermediate andesites of the Abanico and Farellones formations that contain ortho- and clinopyroxene

(Godoy and Koëppen, 1993; Nyström et al., 2003). These minerals are also present in the late Pliocene–Early Pleistocene andesite lava flows that crop out along the Cachapoal River near Coya (Charrier and Munizaga, 1979). Clast analysis of the Colón–Coya Formation indicates that they are mostly composed of andesites and dacites from the Farellones Formation and therefore have the same composition.

From the comparison of the mineralogy of the Coastal Cordillera and Main Andes with the La Cueva lahar deposits, we conclude that the provenance most likely corresponds to the Main Andes. The La Cueva lahar deposits lack quartz or calcic plagioclase, which are abundant in intrusives in the Coastal Cordillera, but include abundant ortho- and clinopyroxene, as well as sodic plagioclase. Cretaceous volcanic rocks in the Coastal Cordillera lack orthopyroxene, which is common in volcanics from the Main Andean Cordillera. The latter is therefore the most probable source area for the La Cueva lahar deposits.

These mineralogical data indicate that lahar flows originated in the Main Andean Cordillera, which is located more than 100 km east of the La Cueva Formation outcrops. The long distance traveled by the lahars, which coincides with the maximum distance reached by this kind of flow elsewhere, as well as the large clast size, indicate that these constituted events of great magnitude probably were triggered by rockslide-debris avalanche processes, as described by Smith and Lowe (1991). In addition, the presence of more than one lahar deposit indicates a long-lived process. We suggest that the huge avalanches that deposited the rock debris of the Colón–Coya Formation were transformed into lahars by stream water dilution, were channeled along river valleys, and reached the Pliocene coastline, where they deposited the conglomerates of the La Cueva Formation. Although the ages attributed to the Colón–Coya and La Cueva formations are somewhat problematic, they strongly suggest a Pliocene age. The age of the Colón–Coya Formation apparently extends from the Early to the middle–late Pliocene, according to the 4.97 ± 0.70 Ma fission track data obtained from an ash horizon and the position of this formation overlying lamprophyric dykes dated at 3.8 + 0.3 and 2.9 + 0.6 Ma (Gómez, 2001). Radiometric and fossil data from the La Cueva Formation indicate a Pliocene age, most probably middle–late Pliocene according to its position overlying the Late Miocene–Early Pliocene Navidad Formation. The Pliocene ages of these formations suggest a temporal correlation between lahar deposits of the Coastal Cordillera and avalanche events.

Drainage systems similar to the present Cachapoal and Rapel rivers with their tributaries apparently were in place during the Pliocene lahar events; these followed them down to the sea that at that time covered the westernmost part of the present Coastal Cordillera (Figs. 1 and 13). K–Ar whole-rock ages of 1.8 + 0.2 and 2.3 + 0.2 Ma in andesite lava beds (Charrier and Munizaga, 1979) overlying river terraces along the Cachapoal Valley (Gómez, 2001) indicate that this river existed at least since the late Pliocene. In addition, paleocurrent directions obtained from conglomerates with erosive bases and trough and planar cross-bedded pumice clast-rich sandstones show an approximate northerly trend, which roughly coincides with the present NW alignment of the Rapel River. These paleocurrent directions, interpreted as having been generated by catastrophic fluvial flows, also suggest that the present drainage system was in place during the Early Pliocene. However, the river system was not exactly identical to the present one, as is shown by the occurrence of La Cueva shallow marine deposits southeast of the present Rapel River mouth, which indicate that the western part of the present Coastal Cordillera was submerged at the time.

The avalanche and lahar ages overlap the apatite fission track ages of 5.6–3.1 Ma obtained from Miocene plutons in the Main Andes between 33° and 35°S. These data indicate rapid cooling during the Pliocene, consistent with local denudation rates exceeding 2 mm/year, for an assumed geothermal gradient of 25 °C/km (Maksaev et al., 2003a). Accordingly, approximately 2000 to more than 3500 m of rocks may have been removed during the Pliocene, probably reflecting vigorous erosion activated by the Neogene tectonic uplift of the Main Andean Cordillera (e.g. Godoy et al., 1999; Charrier et al., 2002). This important Pliocene uplift and its associated erosion most likely triggered large avalanches that deposited the rock debris of the Colón–Coya Formation.

The enhanced denudation during the Pliocene also overlaps with the timing of the mineralization processes of the Río Blanco and El Teniente supergiant porphyry copper deposits (6.46–4.37 Ma; Deckart et al., 2003; Maksaev et al., 2003b; 2004). Skewes and Holmgren (1993) infer that crustal thickening, uplift, and erosion brought the tops of the late Miocene–Pliocene magmatic systems closer to the surface and suggest a causal relationship between the rapid unroofing and the release of hydrothermal fluids that generated the mineralized tourmaline breccia complex at the Los Bronces copper deposit. Yet considering that a single intrusion could sustain a hydrothermal system for a maximum period of 1 million years (e.g. Cathles, 1997; Stein and Cathles, 1997; Cathles et al., 1997), it appears unlikely that steady denudation had a direct effect on volatile exsolution from a magmatic system at the exhumation rate of 0.26 mm/year, as estimated by Skewes and Holmgren (1993). However, catastrophic mass wasting events are capable of major denudation with consequent abrupt lithostatic pressure release and the sudden unroofing of an active magmatic system. This sudden depressurization may trigger cataclysmic explosions—as dramatically demonstrated by the May 18, 1980, violent lateral eruption of the Mount Saint Helens volcano in Washington, USA (Lipman and Mullineaux, 1981)—as well as volatile exsolution of porphyry systems (Sillitoe, 1994). We suggest that Pliocene mass wasting processes triggered rapid unroofing of the late Miocene–Early Pliocene supergiant Cu–Mo porphyry deposits of El Teniente and Río Blanco–Los Bronces on the western slope of the Main Andean Cordillera through the generation of rapid and catastrophic avalanches. The conspicuous occurrence of Pliocene diatreme breccia pipes at both Río Blanco (La Copa breccia pipe) and El Teniente (Braden breccia pipe; e.g. Sillitoe, 1985) may be a consequence of sudden lithostatic pressure release, associated with

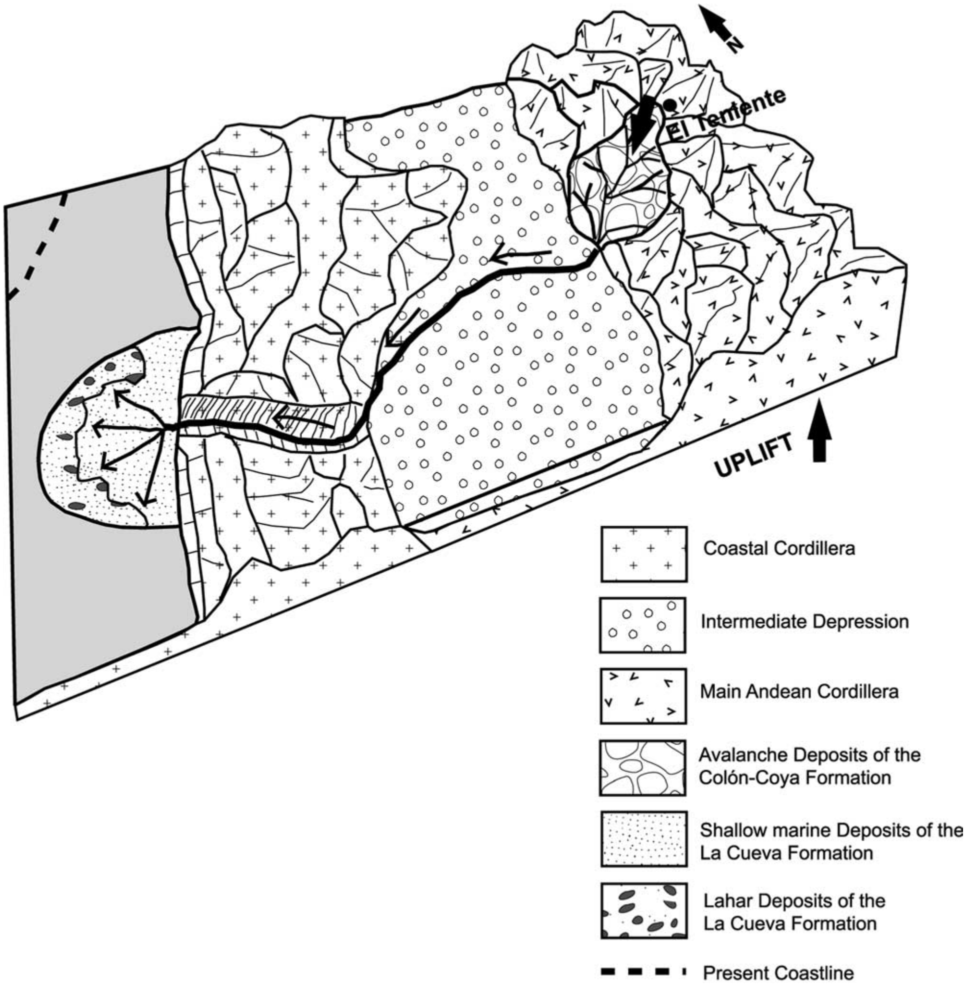

Fig. 13. Block diagram (not to scale) showing avalanche generation in El Teniente area triggered by uplift of the Main Andean Cordillera during the Pliocene. Avalanches were transformed into lahars by stream water dilution, which were channeled along the drainage system and deposited in a shallow marine system.

unroofing by mass wasting of active porphyry systems. Perhaps even the abundance of hydrothermal breccia bodies developed under relatively shallow conditions at Río Blanco–Los Bronces (Serrano et al., 1996) and El Teniente (Skewes et al., 2002) is an effect of the Early Pliocene accelerated unroofing by mass wasting.

5. Conclusions

Shallow marine sedimentary deposits of the La Cueva Formation occur in the present-day Coastal Cordillera. Fossil and radiometric analyses indicate a Pliocene age for this formation. Coarse matrix- to clast-supported conglomerates that occur in the uppermost part of the marine succession are interpreted as lahar deposits. Provenance studies suggest that they derive from denudation of Oligocene–Miocene volcanic rocks on the western slopes of the Main Andean Cordillera at the same latitude, where rock debris deposits of the Pliocene Colón–Coya Formation occur. We suggest that rapid uplift of the cordilleran block generated avalanches that deposited the rock debris of the Colón–Coya Formation. Dilution of avalanche deposits with stream water would have generated lahars that were channeled along the ancient drainage system and reached a shallow Pliocene sea at the site of the present Coastal Cordillera, where deposition of the La Cueva Formation took place.

We suggest that rapid uplift of the western Main Andean Cordillera could have produced an exceedingly rapid exhumation of active porphyry systems during the Early Pliocene, which may have played a role in hydrothermal processes, brecciation, and diatreme formation at the El Teniente and Río Blanco–Los Bronces deposits.

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