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ORIGINAL

Sediment distribution and evolution of sedimentary processes in a small sandy turbidite system (Golo system, Mediterranean Sea): implications for various geometries based on core framework

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Abstract The Golo Margin in eastern Corsica is dissected by four canyons and two gullies which fed turbidite systems. Study of the dispersal of surficial sediments and flow dynamic in the Golo system is based on Kullenberg and interface cores interpreted in relation to a previously published seismic dataset. Cores were described in detail and interpreted within a sedimentary and stratigraphic framework. During the last 42,000 years, gravity processes which occurred in the large systems with a canyon source were mainly slide-induced, differentiated turbulent surges and hyperpycnal flows. Processes occurring in the small system with a gully source are mainly hyperconcentrated and concentrated flows. Deposits from the Corsican Margin can intercalate with products of processes triggered on the Pianosa Ridge located in the eastern part of the basin. During relative sea-level lowstands or during periods of rapid or high-amplitude sea-level fall, only large canyons (South and North Golo) are supplied by carbonate-rich hyperconcentrated and concentrated flows which are channelled in incised valleys on the shelf. During periods of slow or low-amplitude sea-level fall and during sea-level rise, sediments are trapped on a shelf delta and intensely winnowed by shelf hydrodynamic processes. Sand-rich hyperconcentrated and concentrated flows occur. All the systems fed by a canyon are active simultaneously. Gullies form and are active only during periods of sea-level rise. During relative highstands of sea level (Holocene), all the system is draped by hemipelagic sediments. Relative sea-level changes and canyon location relative to river mouths have a strong influence on the nature of sediment input, and the initiation and type of gravity flows which, in turn, control morphology and geometry.

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Introduction

Our knowledge of the processes, morphology, geometry and evolution of deep-sea clastic deposits have advanced considerably since Kuenen and Migliorini (1950) first suggested turbidity currents at continental margins as the possible process for their deposition. The growth patterns of deep-sea fans are strongly influenced by sea-level changes and the character of gravity flows which deposit on fan surfaces (Shanmugam and Moiola 1982; Normark and Piper 1991; Posamentier et al. 1991). Deep-sea turbidite systems have been studied extensively during the 1970s, essentially for their economic potential as oil and gas reservoirs (Shanmugam and Moiola 1988). However, a difference exists between the large mud- and silt-dominated systems which are active at present along passive margins (e.g. Zaire, Babonneau et al. 2002; Amazon, Pirmez et al. 1997) and the small, outcropping turbidite systems which formed in ancient, usually tectonically active environments (e.g. Mutti et al. 1996). Most modern studies deal with large deep-sea systems (see review by Stow and Mayall 2000), and relatively few are relevant to smaller turbidite systems in which channel and sand lobes are volumetrically important. The Corsican Golo system offers an opportunity to study such a sand-rich, presently active fan at scales similar to those used during subaerial studies or for three-dimensional seismics.

Another problem is the understanding and recognition of the processes able to transport particles, especially coarse particles, over long distance down to distal lobes. Recognition of erosion, transport and deposition processes based on gravity-flow deposits is a challenge. The results concerning these sedimentary processes are particularly important to predict in which parts of the system and at which geological periods sandy beds might be deposited. Implications are directly related to the genesis of hydrocarbon-bearing reservoir rocks.

Four types of classification exist for gravity flows:

1. Classification based on the mechanical behaviour (rheology) of the processes (e.g. Dott 1963; Mulder and Cochonat 1996; Shanmugam 2000). This type of classification is particularly well suited for flow processes but parameters such as viscosity of the flow are difficult to derive.
2. Classification based on the particle-support mechanism, matrix strength, grain-to-grain interactions, fluid support or turbulence (Middleton and Hampton 1973; Lowe 1979, 1982; Nardin et al. 1979). This is the classification most used in the literature on recent deep-sea environments.
3. Classification using flow parameters, in particular flow concentration derived from the observation of flow deposits (Mulder and Alexander 2001). This allows one to consider flow transformation in both space and time as well as its progressive dilution or reconcentration.
4. Classification based solely on the sedimentary facies found along the pathway of the flow (Mutti and Ricci Lucchi 1975). This is extensively used in ancient environments and in the oil industry.

In this paper, we describe the sedimentary facies and sequences observed in the Golo turbidite system. We use these descriptions and a preliminary stratigraphic framework to assess the changes in sedimentary processes occurring in the system over the last 42,000 years.

Regional setting and previous studies

Bellaiche et al. (1993) used seismic coverage to describe several small turbidite systems along the eastern margin of Corsica. The small size of the system (total length <25 km) and the shallow water depth (<900 m) are of particular interest because this facilitates studying a whole system from the canyon head to the distal lobe by means of high-resolution acoustic tools.

Using the preliminary mapping of Bellaiche et al. (1993), several cruises led by Ifremer (CORSTAGE, 1997 and 1998, CORFAN, 1998, CORK, 1998), including multibeam mapping, backscatter imagery of the seafloor, high- and very high-resolution seismics (boomer and sparker) and coring, accurately mapped the system and defined the boundary between the turbidite systems and basin sedimentation. Gervais (2002) and Gervais et al. (2004) showed that the Golo system of Bellaiche et al. (1993) was, in fact, composed of four non-coalescent fans plus two sedimentary bodies which were deposited simultaneously.

Gervais et al. (2004) showed that four architectural elements at the scale of outcrop studies can be recognized in the systems in the Golo area: submarine valleys including (1) canyons and gullies, (2) sandy channels, (3) muddy levees and (4) distal lobes. A high-resolution study focusing on lobes (Gervais et al. 2006) showed the existence of processes such as avulsion, lateral migration, progradation and retrogradation. These processes were related to relative sea-level changes, initial seafloor topography and especially confinement, and the characteristics of sediment supply.

The Golo Margin and the general morphology of the basin

The eastern margin of Corsica is characterised by a continental slope showing a lower slope gradient than on the western margin. A typical continental shelf exists on the eastern margin. Its width varies from 5 km in the northern area to 25 km towards the south. In the Golo area, the width of the continental shelf varies from 9 to 12 km. The maximum width is observed seawards of the Golo River mouth. The shelf edge is at a water depth of approximately 110 m. Gervais (2002) and Gervais et al. (2004) provided detail data on the morphology of this system.

The shelf is incised by several submarine valleys: (from south to north) the Alesani, Fium Alto, South Golo, Pineto, North Golo, Biguglia, St. Damiano, Chiurlino, Bevinco and Fiuminale valleys. Most of these lie directly offshore a river mouth. Valleys extending from Fium Alto to St. Damiano form the Golo system of Bellaiche et al. (1993). Four of the valleys are true canyons, with heads incising the shelf (South Golo, North Golo, Biguglia and St. Damiano). Two are only gullies (Fium Alto and Pineto).

The continental slope in the Golo area deepens eastwards towards the Corsican Trough. The trough is bordered by the Pianosa Ridge on its eastern flank. The Pianosa Ridge has steep flanks (6° in the southern part) with numerous pockmarks. A large slump is located in the north part of the eastern flank. Smaller slumps occur in the southern part. The presence of both ridge and sills confine the Golo Basin.

The Golo turbidite system covers an area of 500 km^2, located in less than 1,000 m water depth on a narrow bulge on the continental shelf which is fed by the Golo River. This river supplies particles with grain sizes ranging from coarse sand to clay, derived from active weathering of the mountainous hinterland (Gauthier and Prone 1980; Mulder and Maneux 1999).

The South Golo Canyon is a steep (3.8°), V-shaped E–W valley with a width of 1.5 km and a depth (elevation between thalweg and top of canyon flanks) ranging from 100 to 170 m. The thalweg is 6 km long. It becomes a U-shaped valley with a width of 3.5 km in its lower part. It is slightly sinuous (sinuosity=0.8). Meanders and associated terraces can be observed.

The South Golo turbidite system shows a channel–levee complex extending over 32 km with bathymetry increasing from 450 to 800 m. The channel is bordered by levees showing a maximum elevation of 55 m from the channel floor in the proximal part and decreasing downstream. At isobath 800 m, the channel enlarges and forms a lobe with a convex-up shape. Slope gradient is about 1° on this lobe. At the beginning of the lobe, the main channel branches, forming secondary channels (channelled lobe). The depth of these secondary channels does not exceed 10 m. Their width is about 100 m.

The North Golo, Biguglia and St. Damiano canyons are straight (sinuosity=1), with a V-shaped valley becoming U-shaped eastwards. Their maximum depths (elevation between thalweg and top of canyon flanks) are 120, 50 and 100 m respectively, and their lengths are 3, 4 and 2 km respectively. Their width is about 1 km.

The North Golo Canyon passes over a short distance into a channel–levee complex. Channel sinuosity is 0.8 and no terraces are observed. It is bordered with well-developed levees with a maximum thickness of 35 m. At isobath 400 m, the channel forms a lobe with a convex-up shape and a slope gradient of about 1°.

The Biguglia and St. Damiano systems show channels with lengths of 10 and 5 km respectively. Levees have both low elevation and lateral expansion, and disappear after the first kilometre. The St. Damiano channel is straight in its upper part and sinuous in its lower part where terraces are observed. Channel slope decreases downstream from 1.4 to 0.7°.

The Pineto and Fium Alto gullies do not show valley heads, clear levees nor terraces. They begin at water depths of 120–300 m for the Pineto and 120–340 m for the Fium Alto. These are straight (sinuosity=0.9), narrow (250 and 350 m respectively) and short (2 and 4 km respectively) valleys. The depth (elevation between thalweg and top of gully flanks) of the Fium Alto gully decreases downstream from 50 to less than 10 m.

The conclusions of Gervais et al. (2004) are that the North and South Golo major systems present similarities to the St. Damiano and Biguglia minor fans in terms of morphology and depositional architecture but that these major systems are very different from the small Pineto and Fium Alto bodies.

Stratigraphic framework

A detailed stratigraphic framework was established for core MD 012434 for the last 42,000 years, based on radiocarbon dating, correlation with the global isotope curve and litho-seismic correlations (Gervais et al. 2004). An age of 42,000 years B.P. for the base of the core (24.9 m) is provided by a *Uvigerina mediterranea* and *U. peregrina* isotope ($\delta^{18}O$) curve (Gervais 2002). An age of 7,340±20 years B.P. was obtained on the same core at 1.5 m depth, using ^{14}C dating of foraminifers. Correlation was possible with the regional seismic markers J, K and L defined by Gervais (2002) and Gervais et al. (2004). These correspond to the latest stage of growth of the Golo turbidite system. The base of the recent lobe deposit (reflector K) is dated at 35,000±220 years B.P. (Gervais et al. 2006). Additional ^{14}C dating on cores Kco 63 and 65 indicates an estimated age of 30,000 years B.P. for the beginning of lobe construction. The K reflector (most recent lobe) is dated at around 17,000 years B.P. (core Kco 64) and the L reflector at around 19,000 years B.P. (Kco 65). The end of modern lobe deposition (stage J–K) is dated at around 17,400 years for the South Golo lobe (Kco 74) and 18,000 years for the North Golo lobe (Kco 66). Using the SPECMAC curve and extrapolated relative sea-level changes (Lambeck and Bard 2000), interval J–K is correlated with the last fall of relative sea level and interval K–L is correlated with the beginning of the last relative sea-level rise. The interval L-surface is correlated with the end of the last relative sea-level rise. The absence of $^{210}Pb_{exc.}$ activity on the cores which sampled the present seafloor suggests that no significant turbidite deposition has occurred recently.

Materials and methods

Bathymetry data were collected using a multibeam echosounder SIMRAD EM 12 during the MESIM survey (Bellaiche et al. 1993), and processed using Caraïbe software (Ifremer). More than 1,000 km of high-resolution seismic lines was collected during the CORFAN and CORK cruises, by means of a 300 J multitip sparker operated in the 200–800 Hz frequency range. Vertical resolution is 2–3 m on seismic lines and penetration is 200–300 m. Seismic profiles were processed with the Sithere software (Ifremer). Concurrently to the seismic surveys, 35 Kullenberg cores with an average length of 10 m were collected during the CORFAN and CORK cruises (1998) from onboard the RV *Le Suroît* (Fig. 1). At each coring site, a 0.85-m-long trigger core collected the very top layer on the seafloor. A 25-m-long Calypso core (MD 012434) was retrieved during the GEOSCIENCES cruise (2001) on the RV *Marion Dufresne 2*. The positions of the cores and

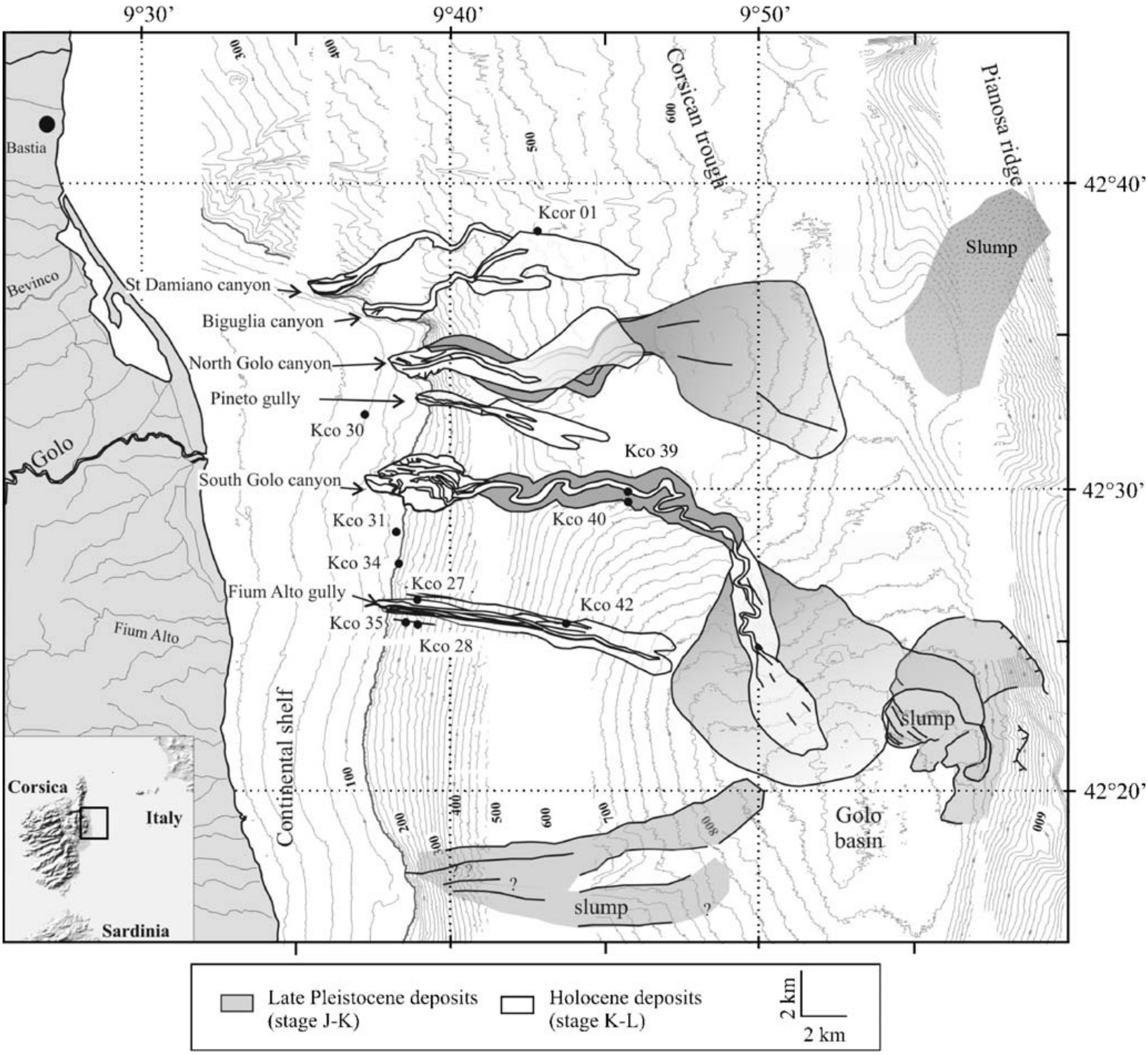


Fig. 1 Morpho-sedimentary map of the Golo depositional system, showing the main morphological features, recent and modern sedimentation, and location of studied cores. Contours of the bathymetric map are in metres. *Open areas* correspond to those with no data

seismic profiles were determined by means of a DGPS (accuracy about 2 m).

Gamma-density, magnetic susceptibility and P-wave velocities were measured on all cores. After core splitting, a 1-cm-thick sediment slab was collected for each split core section, and X-radiographed and processed using the Scopix system (Migeon et al. 1999; Lofi and Weber 2000). The digital images were then processed using Optilab and Image SXM software. Sediment slabs were sub-sampled for selected grain-size analysis on sedimentary sequences and facies recognized by means of visual description, and X-ray images and carbonate content measurements were made at a sample interval varying between 2 and 5 cm.

Grain size was measured by means of a Malvern laser granulometer. Carbonate content was determined using a Bernard calcimeter. Stratigraphic framework is based on AMS ^{14}C dating as well as sedimentary and seismic correlations (lithostratigraphy).

Sediment facies were defined according to the maximum measured grain size (sand, silt or clay). Note that facies percentages in cores represent the proportions of dominant facies, rather than the proportions of individual grain-size fractions.

Results

Facies and sequences

Seven sedimentary facies were recognized in cores from the Golo area. These facies types have been defined using: (1) photography and X-ray imagery, (2) grain-size analyses and (3) $CaCO_3$ content. These facies can be grouped into several sequences described below.

Facies 1 (homogenous, structureless clay: pelagic to hemipelagic marly ooze) is composed of centimetre- to decimetre-thick, structureless light brownish-grey ooze. The mean grain size is less than 10 µm. $CaCO_3$ content is about 30% at the top of the cores and about 15–20% when associated with other facies. Facies 1 is found over almost the whole area. Near the Pianosa Ridge, high concentrations of monosulphides are also observed.

Facies 2 (homogenous, structureless silty clay) consists of thin (few centimetres) to thick (around one metre) intervals of structureless olive-grey clay, with abundant monosulphides. The mean grain size ranges from 10 to 20 µm and $CaCO_3$ content is about 15%. Locally, near the shelf and Pianosa Ridge slumps, carbonate contents reach 25%.

Facies 2 and 1 are usually co-associated. They form grey-olive silty-clayey beds grading into homogeneous grey-olive clay. The lower and upper contacts are gradational and, in some cases, difficult to distinguish. The thickness of beds made of these two facies varies from a few centimetres to several tens of centimetres. They are observed in all cores but mainly on the levees of the south Golo system and on the lobe fringes of the South and North Golo and Pineto systems.

Facies 3 (massive silt) consists of a thin (few centimetres) layer of silty clay. Bioturbation is very abundant. The mean grain size is around 30 µm and $CaCO_3$ content ranges from 10 to 15%. This facies shows bioturbated, disrupted contacts or gradational contacts at the base and top. Some intervals present fine sand lenses and crude planar laminae (in cores on the distal south Golo and Pineto lobes). Main constituents are abundant micas and shell fragments as well as benthic and planktonic foraminifers.

Facies 4 (massive fine sand or graded fine sand showing a variety of sedimentary structures) consists of beds of a few centimetre-thick fine sand. At first, the absence of structures during visual description made the interpretation of these beds difficult. The X-radiographs of sediment slabs, however, revealed several types of facies and small-scale sedimentary structures within the sand beds. They can be massive (Fig. 2, image a) or with structures: wavy parallel or convoluted laminae, diffuse laminae or climbing ripples (Fig. 2, image b). The mean grain size is around 50 µm, and $CaCO_3$ content is less than 10%. Main constituents are subrounded quartz, abundant micas and shell fragments as well as benthic and planktonic foraminifers.

Facies 5 (laminated graded sand) consists of centimetre- to several decimetre-thick medium- to coarse-sand beds. The mean grain size varies from 63 to 200 µm, and $CaCO_3$ content is less than 15%. Some intervals present higher carbonate contents, about 30%. Numerous inframillimetric laminae are visible on X-ray images (Fig. 2, image c). The number of laminae increases from the bottom to the top of a single bed, as grain size decreases.

Facies 6 (massive sand) consists of massive centimetre- to metre-thick medium- to coarse-sand beds. The mean grain size varies between 90 and 250 µm, and $CaCO_3$ content is less than 10%. Near the shelf and the slumps on the Pianosa slope, some centimetric levels exhibit high carbonate contents of around 25%. Some levels show centimetric mud clasts of facies 1 (Fig. 2, image d). The main constituents are similar to those described in facies 4: subrounded quartz, abundant micas and millimetric shell fragments as well as benthic and planktonic foraminifers.

Facies 7 (coarse homogeneous shelly sand) is made of homogeneous and unsorted, coarse to medium sand with very abundant millimetric to centimetric shell fragments (Fig. 2, image e). Mean grain size varies from 63 µm to 2 mm and $CaCO_3$ content from 35 to 70%. This facies consists of subangular quartz, with very coarse and fine entire shells or fragments thereof (coral, gastropods, pteropods, bivalves and foraminifers). This facies is observed only in shelf deposits and locally on the northern Pianosa slope.

Sequence I fines upwards (Figs. 3 and 4) and consists (from base to top) of the following superposition of facies 6 to 2: massive sand (<5 cm), laminated sand (few cm to 20 cm) with the number of lamina increasing upwards, fine sand (few cm) which can be massive, cross-laminated or with silt lenses, silt, silty clay (1 to few cm) and clay (cm to dm). The basal contact is erosive. The upper contact is sharp to gradational. This is the most abundant sequence in the study area but is found only along the South Golo channel.

Sequence I is usually truncated (Itr in Fig. 4). Three main sub-sequences can be found:

1. Sequence Itra consists only of fine sand, silt and clay. Facies 6 and 5 are absent (Fig. 4). The basal contact is erosive. The upper contact is sharp to gradational. The contact between sand and silt is usually sharp. The sandy facies can show undulating laminae, cross lamination, and convolute or deformed laminae.
2. Sequence Itrb consists only of silt and clay. The three sandy lower facies are absent (Fig. 4). The lower contact is sharp and deformed. The upper contact is

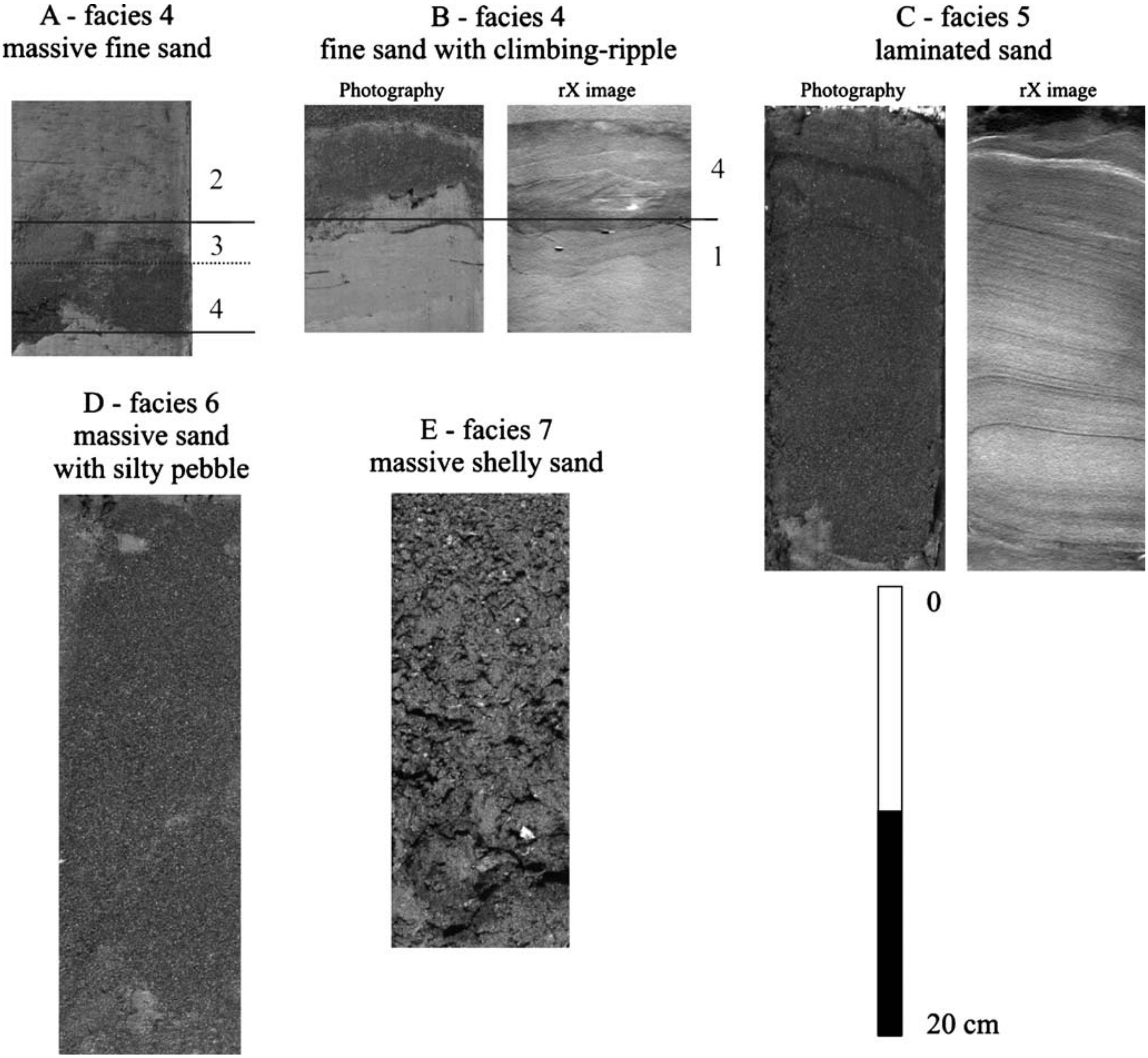


Fig. 2 Photography and X-ray images of the sand facies identified in the Golo turbidite system. *a* Massive sand or graded sand showing various dynamic structures. *b* Fine sand with climbing ripples. *c* Laminated graded sand. *d* Massive sand. *e* Coarse homogeneous shelly sand

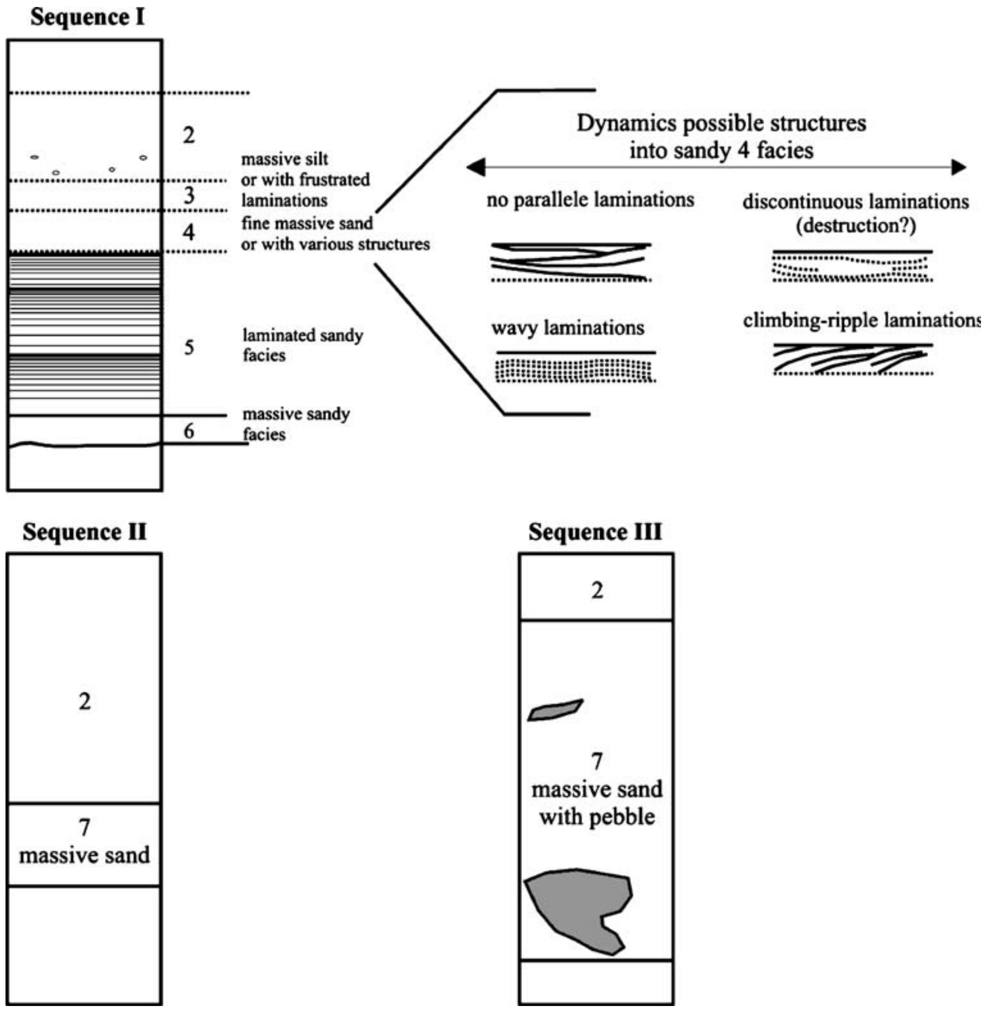
usually gradational. The silty facies (mean thickness of 5 cm) is either massive or exhibits silty-clay lenses. This sequence is observed on the upper levee and the distal lobe of the South Golo System and on the distal lobes of the Pineto gully.

3. Sequence Itrc consists only of massive sand and clay. Sequence I is truncated of the laminated and fine sand and silt. This sequence is thin (<5 cm), and is observed in the Fium Alto lobe in addition to the distal part of the South Golo channel.

Sequence II (Figs. 3 and 5) consists of centimetre- to decimetre-thick, coarse to medium massive sand (facies 6) grading to silty clay through an intra-sequence sharp contact. Carbonate content is usually high (approx. 30%). The basal contact is sharp to erosive and the upper contact is sharp. Grading in this sequence is absent or poorly developed. This sequence is observed on the St. Damiano levee and on the side and lobe of Fium Alto.

Sequence III (Fig. 3) consists of metre-thick massive sand (facies 7) with no grading, and scattered centimetre- to decimetre-thick silty-clay clasts. Both basal and upper contacts are erosive. This sequence is observed in the distal part of the South Golo channel and in lobes (South and North Golo, Pineto and Fium Alto).

Fig. 3 Schematic representation of sedimentary sequence types observed in cores on the Golo Margin



Regional sedimentary map and litho-seismic correlations

Using the previously published seismic dataset of Gervais et al. (2004), the sedimentary distribution identified on cored bodies (Fig. 6) can be extrapolated to the whole Golo Margin (Fig. 7) to provide the distribution of lithofacies in the Golo system.

The continental shelf is characterised by coarse massive shelly sand facies associated with bedded, high-amplitude seismic facies (Figs. 6 and 7). The interfluves and Pianosa slope are characterised by silty clay and by continuous to discontinuous bedded seismic facies (Figs. 6 and 7). Two slumps have been mapped along the slope of the Pianosa Ridge (Figs. 1 and 7). The northern slump corresponds to chaotic seismic facies associated with massive shelly sand (Figs. 7 and 8). The southern slump, near the South Golo lobe, shows silty-clayey deposits with abundant monosulphides and continuous to discontinuous transparent seismic facies (Figs. 7 and 8). This lithofacies is observed also in the eastern part of the lobe. Core Kco 74, collected in the distal part of the lobe, shows good litho-seismic correlation particularly with boomer data (Fig. 9).

Channels are characterised by sandy facies (Fig. 6) with abundant sedimentary structures (Fig. 10), and by chaotic seismic facies with hyperboles or very high-amplitude bedded seismic facies (Fig. 7 and Kco 62 in Fig. 9). Major channels show numerous sequences I and I-tr (lacking upper silty-clay units) and massive sequences III (Fig. 10).

Levees of the major systems are composed of silty-clay facies alternating with some sequences I-tr (lacking upper silty-clay units; Fig. 10) and associated with continuous bedded divergent seismic facies (Fig. 7). Levees of the minor systems (Biguglia and St. Damiano; Fig. 11) and flanks of the Pineto and Fium Alto gullies (Fig. 12) are sandier than those of the major systems and characterised by sequence II. Carbonate content is higher in levees of the minor systems than in levees of the major systems, and seismic bedded divergent facies present higher amplitude than levees of the major systems (Figs. 6 and 7).

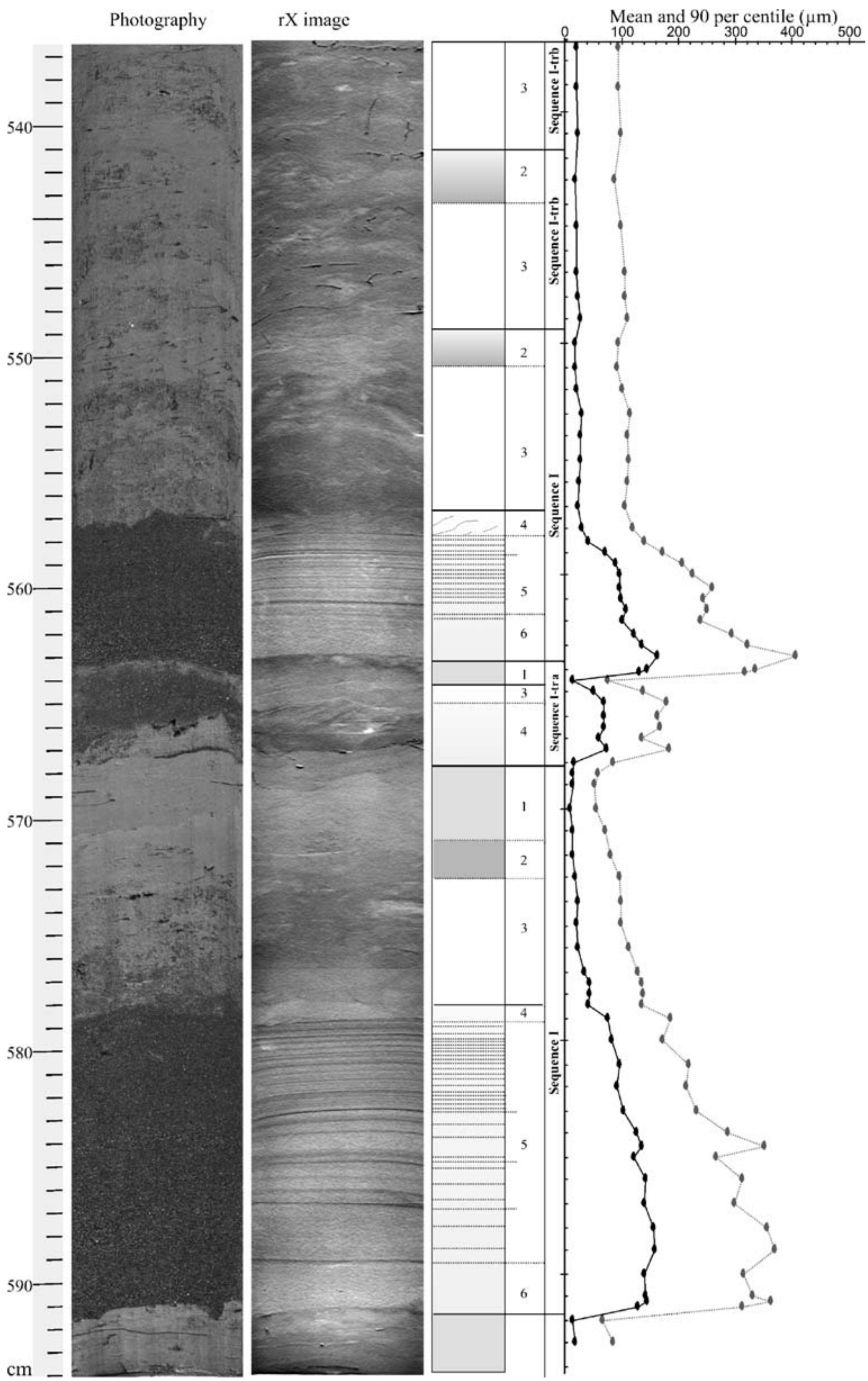


Fig. 4 Sequence I and Itr: photograph, processed X-ray image and grain-size curve showing the vertical succession of structure and normally graded sand. Interval from core Kco 58 in the South Golo channel (see Fig. 1 for core location)

Lobes are characterised mostly by massive coarse sand (sequence III; Figs. 13 and 14) associated with chaotic seismic facies (Fig. 7). Numerous sequences I-tr are observed in the small, South Golo secondary channel lobe associated with high-amplitude bedded facies (Kco 62 in Fig. 9). Mud clasts are generally observed in the proximal lobe and sand content decreases downlobe (Fig. 6). Distal major lobes are characterised by low turbidite activity

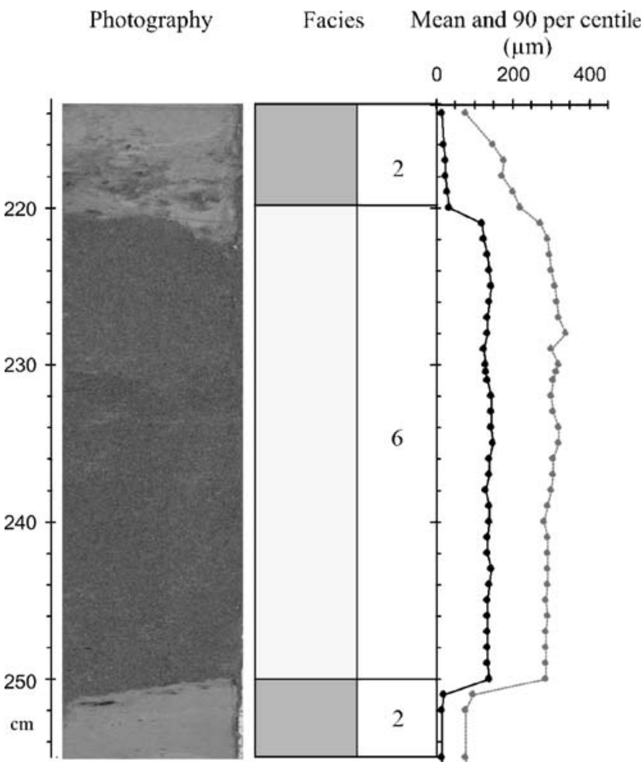


Fig. 5 Photograph and grain-size curve showing structureless non-graded sandy sequence II: example from core Kcor 01 on the St. Damiano Levee (see Fig. 1 for core location)

(sequence II-tr in core Kco 73; Fig. 14) whereas no turbidite is observed for the Pineto lobe characterised by silty-clay beds and continuous bedded seismic facies.

Discussion

Sedimentary processes on the margin

Facies 2 and 1, with high carbonate content (30%) and abundant bioturbation, are interpreted as hemipelagites. They drape the whole study area.

The remaining facies are discussed below in terms of the sequences which they form. The presence of a sharp or erosive basal contact associated with normal grading (Kuenen and Migliorini 1950) is a common criterion to distinguish waning flow (Kneller 1995) corresponding to a turbulent surge (Middleton and Hampton 1973). In that case, sequence I can be interpreted as a classical Bouma sequence where the massive or poorly graded sandy facies at the base of the sequence corresponds to the freezing of a concentrated flow (Mulder and Alexander 2001), equivalent to a Ta unit of the Bouma sequence, and the superposed facies correspond to deposition by turbulent flow (type 1 flow). Sequence I corresponds to deposition by sandy flow with a thin laminar lower part and a thick turbulent upper part. Truncation of the base of sequence I (sequences Itra, Itrb and Itrc) suggests a more distal deposition from the flow source than in places where the whole sequence is observed.

Sequence II can be interpreted similarly to the base of sequence I. It results from deposition by concentrated flow (Ta unit). The high carbonate content suggests direct supply from the continental shelf where biologic activity is the most intense.

Sequence III consists of massive sand. Several types of flows can generate massive sands: laminar grain flows of Middleton and Hampton (1973), debris flows (Nardin et al. 1979), sustained turbidity currents (Kneller 1995) or hyperconcentrated flows (Mulder and Alexander 2001). The presence of floating mud clasts suggests the existence of upward dispersive pressure associated with buoyant lift due to a fine-grained matrix (Lowe 1982). This characteristic, associated with both sharp basal and upper contacts and absence of grading (or a crude inverse grading), suggests a deposit resulting from laminar flow. The presence of a poorly graded or massive facies suggests that sequences III is deposited by sandy hyperconcentrated flows with a thick laminar basal part, despite that a turbulent upper part might exist (type 2 flow).

Sedimentary processes in canyons

Because flows do not spill over canyon walls, the maximum flow thickness can be estimated using the height of these walls. Consequently, flow thickness does not exceed 170 and 120 m in the South Golo and North Golo canyons respectively. The presence of terraces suggests that nested levees form (Pichevin et al. 2003). Gervais (2002) already demonstrated that slumping occurs on the canyon flanks. These slumps could be at the origin of some of the terraces (see Gaudin et al., this volume).

Deposits in canyons of the small sedimentary systems (Biguglia, St. Damiano) are mainly sequences of type III with high carbonate content, especially in the upper part of the canyons. This suggests the canyons are bypass areas. Deposition occurs only from thin hyperconcentrated flows generated by slumps initiated close to the shelf break. These hyperconcentrated flows are not able to spill and to build extended channel–levee complexes.

Sedimentary processes in the channel–levee complex

The proximal (upper) part of the South Golo channel shows meanders. Meandering suggests that flows are relatively continuous through time (Babonneau et al. 2004). Based on

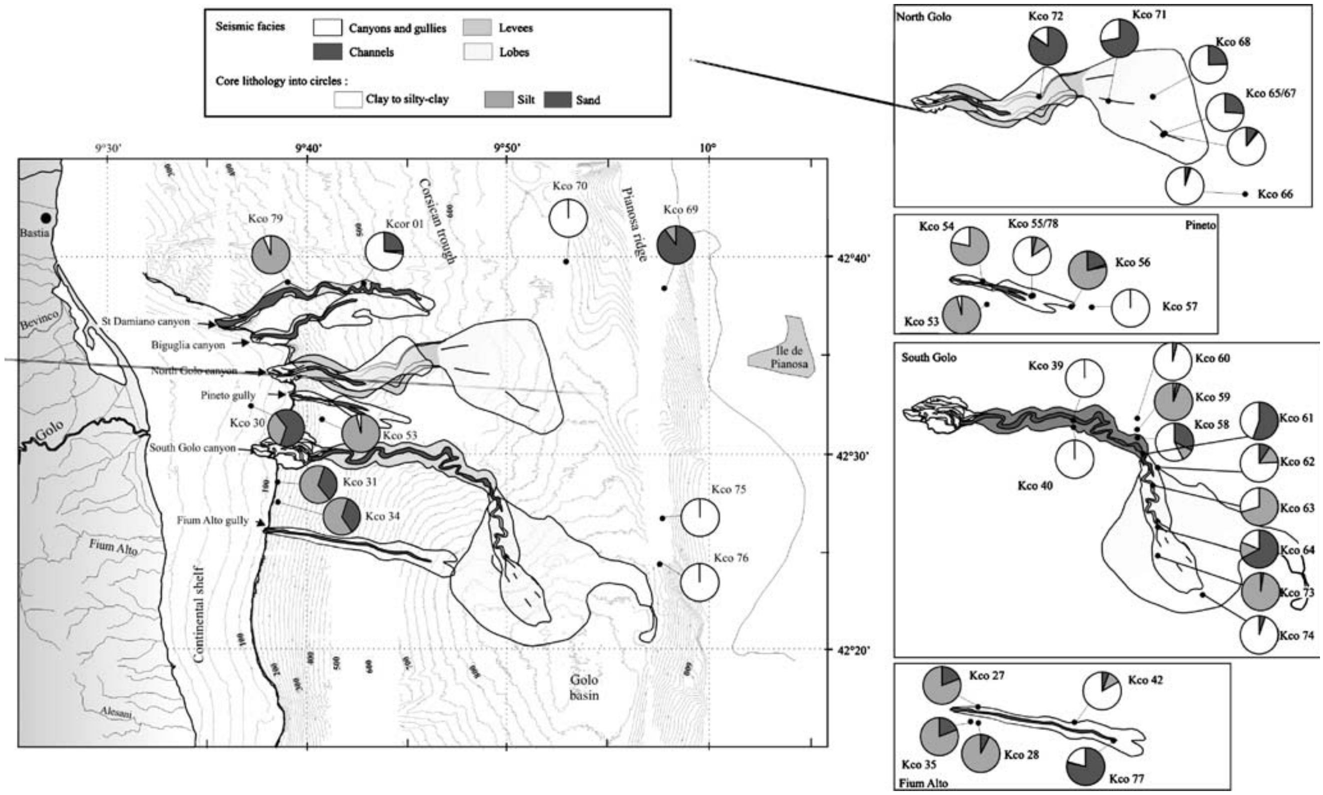


Fig. 6 Map of surficial sediment distribution on the Golo Margin, indicating percentages of clay, silt and sand

the elevation of the levees, flow thickness in this area decreases from 70 to 35 m.

The proximal South Golo levee shows facies association 2 and 1 and only one centimetric-scale Itrb sequence (Kco 40 and 39 in Fig. 10). No sand is observed. This could be explained by the shortness of cores collected on this levee. Downstream, cores on the distal levee are still dominated by silty-clay facies showing sequences with increased proportions of silty to sandy facies (Kco 59 and 60 in Fig. 10). The presence of numerous sedimentary structures including laminae suggests a slow rate of deposition from an individual flow. In particular, the increase in the number of laminae in the top part of the sequence and the normal grading of laminae suggests that fluctuations occur at a high rate within the basal boundary layer of the flow. Such pulses have been described by Hesse and Chough (1980), Migeon (2000) and Migeon et al. (2001).

In the channel, numerous centimetre- to decimetre-thick sandy sequences (I and I-trc) are observed (Kco 58 and 61 in Fig. 10). This suggests that flows channellised in this area are almost fully turbulent with a thin laminar basal concentrated flow. Sequences II are also observed in the upper part of the core (Fig. 10). The Kco 61-58-59-60 transect from the channel axis to the outer levee (Fig. 10) illustrates a sharp decrease in the proportion of sandy facies and mean grain size as well as a thinning of sandy beds (Figs. 6 and 10). Sand content decreases from 32% in the channel to 3% in the proximal levee and 0% in the outer levee. Mean grain size is about 200 µm in the channel (Kco 58) and only 70 µm on the proximal levee (Kco 59). These observations suggest that the levee in this area forms via a classical flow spilling process (Hiscott et al. 1997). The finest upper part of a turbulent surge flowing in the channel spills over the channel sides and deposits fine-grained Bouma sequences.

The core collected in the upstream part of the St. Damiano levee is composed of 90% carbonated silt (Kco 79 in Fig. 11). Kcor 01, collected in the downstream part of the St. Damiano channel, is composed of 25% sand (Fig. 11). Massive centimetric to decimetric sandy carbonated sequences II are observed (Fig. 11). This suggests that processes in the St. Damiano system are hyperconcentrated to concentrated laminar flows (type 2), resulting from the differentiation of failures initiated on the upper slope, close to the continental shelf.

Sedimentary processes in channelled lobes

Cores were collected on both the North and South Golo lobes. The actual lobe of the South Golo system has a radial shape, suggesting coarse-grained sediments (Reading and Richards 1994) deposited by rapidly decelerating flows after clearing the mouths of the channels. Proximal (upper) lobe sequences are of type III composed of decimetre- to

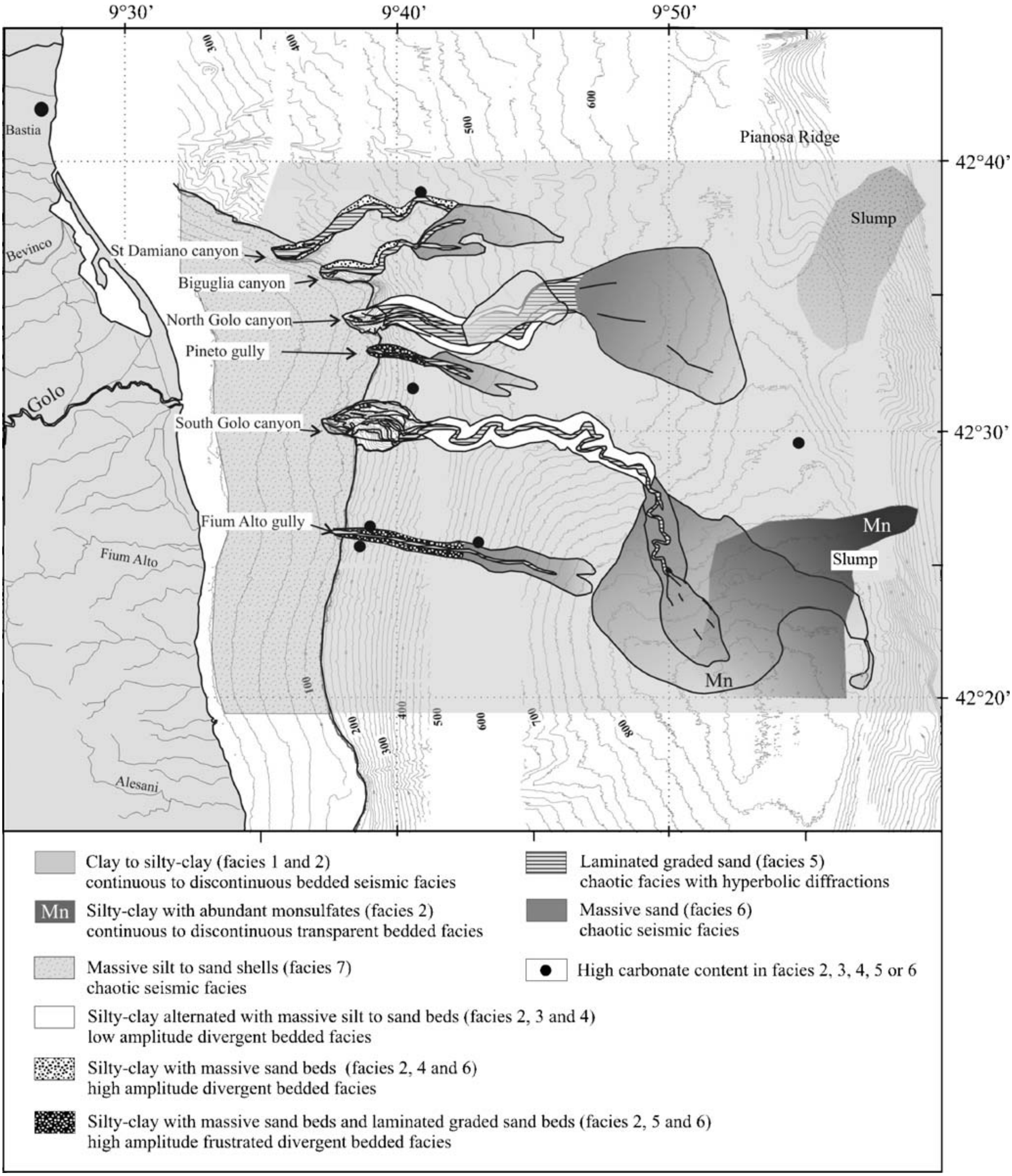


Fig. 7 Map of core facies distribution on the Golo Margin. Comparison with the 3.5-kHz echofacies of Gervais (2002)

metre-scale, massive structureless coarse sands (Fig. 14). In the distal (lower) part of both lobes (Kco 66 for the North Golo lobe and Kco 74 for the South Golo lobe in Fig. 14), the deposits form part of sequence Itrb. Unusually high carbonate contents (70%) were recorded in the sandy North Golo sequences, suggesting flow initiation close to the continental shelf. In the South Golo lobe (Kco 74), sandy sequences alternate with monosulphide-rich silty clay

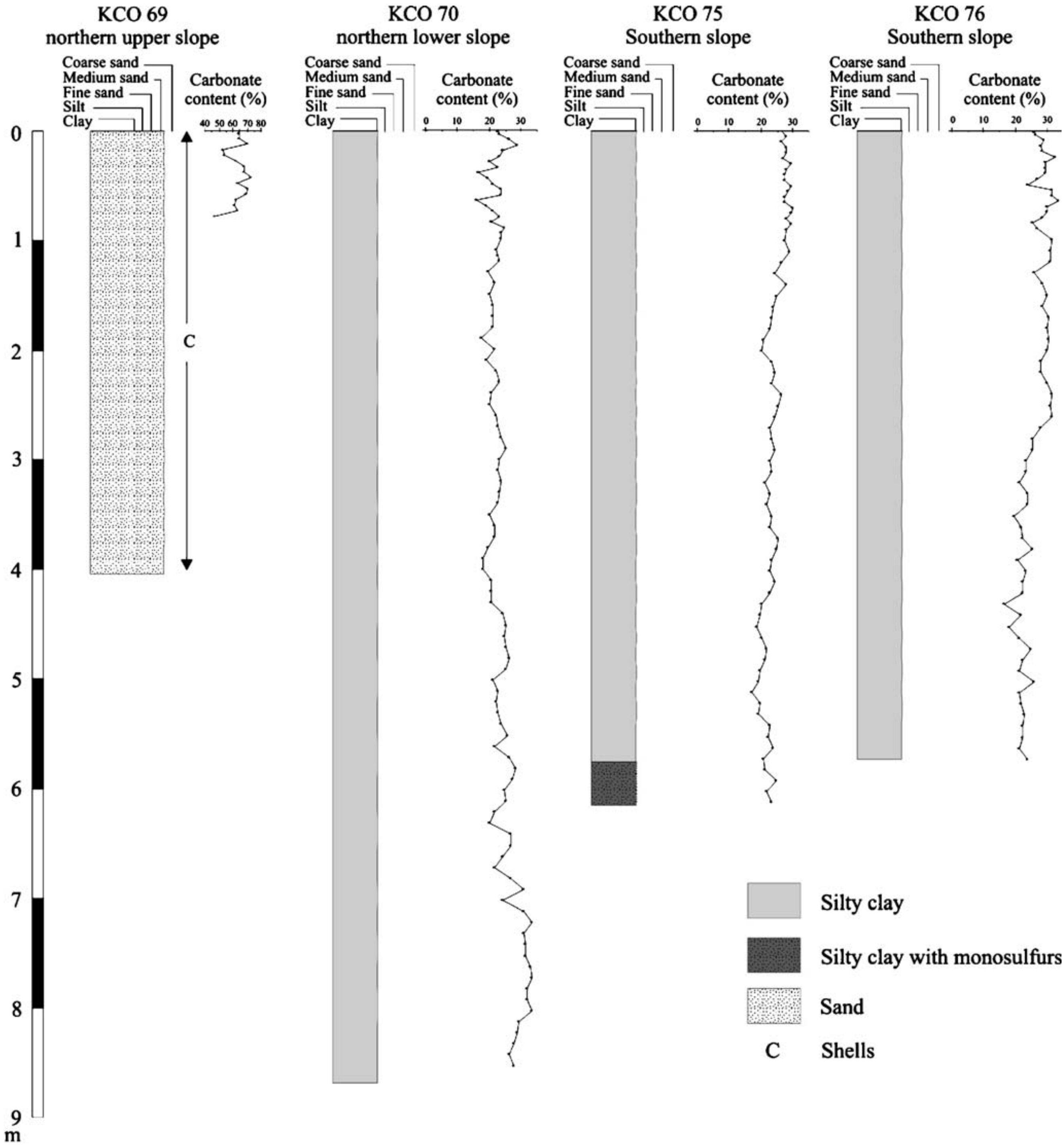


Fig. 8 Core logs of the four cores collected on the Pianosa Ridge, showing the main lithologic facies variations (see Fig. 6 for core locations)

(facies 2; Fig. 14). These lobe sequences are interpreted as resulting from deposition by thin hyperconcentrated flows, with a high sand content and a thick basal laminar part. This suggests that the thickness of the basal laminar part progressively increased in the channel–levee system because of the progressive deposition of fine particles on the levees through spilling. The sequences I trb could be deposited by turbulent flow not thick enough to spill over the levees. Because they are deposited by turbulent (type 1) flow, deceleration is lower than for type 2 laminar flows. Type 1 turbulent flows travel farther away after channel termination, and sequences Itrb are deposited more distally on the lobe than are type III sequences. Sand contents are very high and decrease downlobe from generally more than

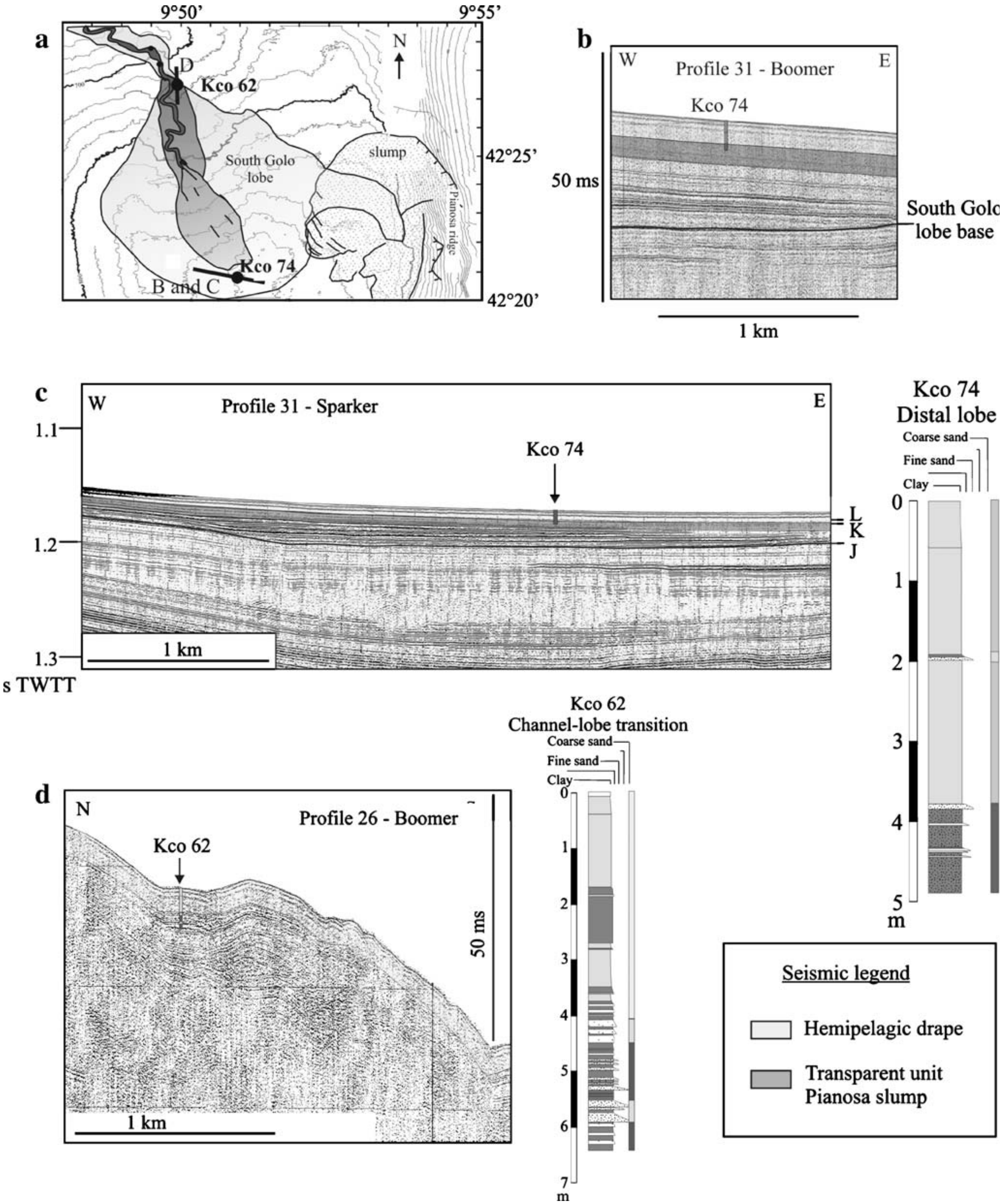


Fig. 9 a–**d** Seismic profiles illustrating litho-seismic correlations for the South Golo lobe (**a**) boomer (**b**) and sparker (**c**) data for profile 31, and boomer data for profile 26 (**d**)

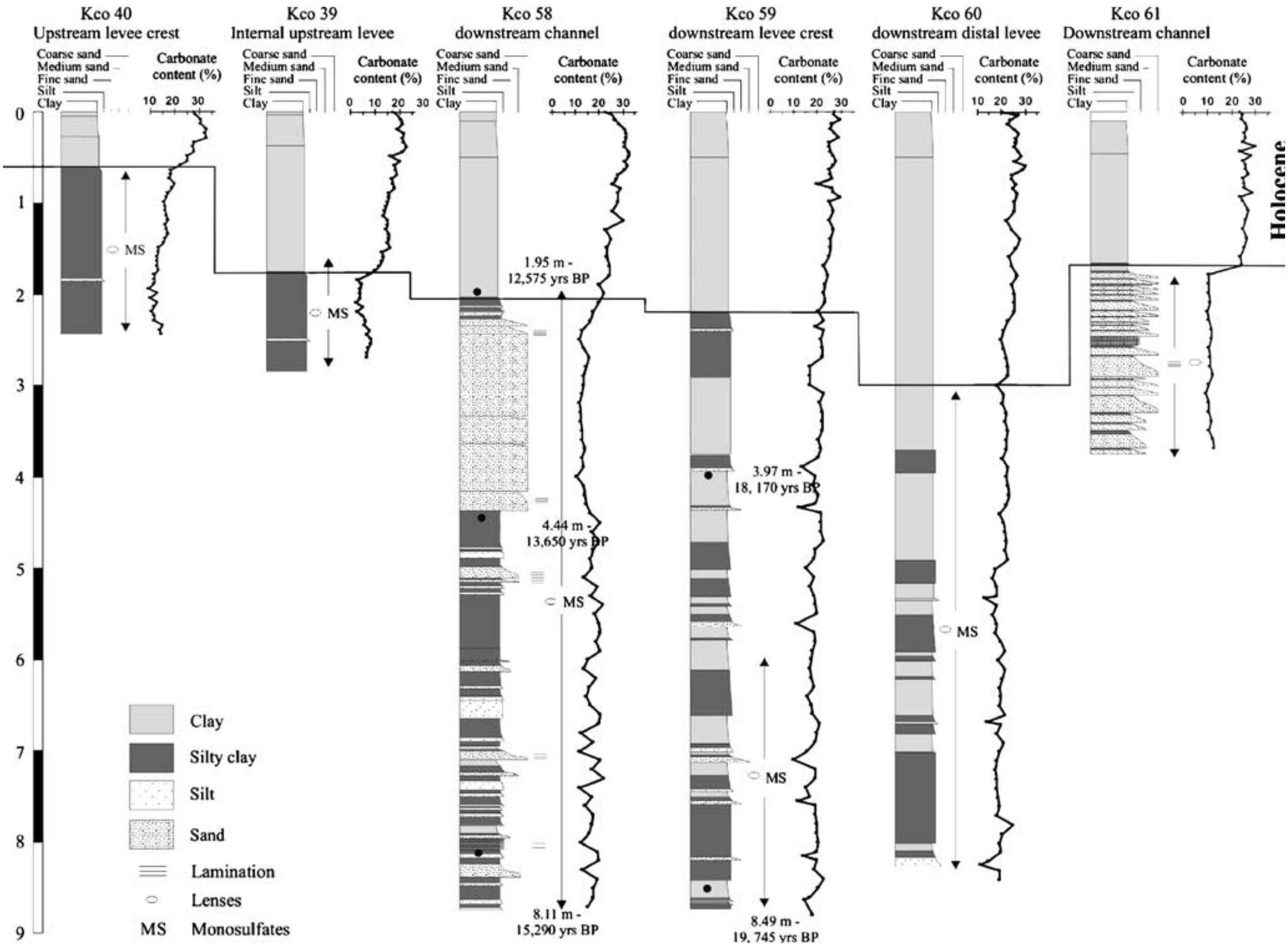


Fig. 10 Core logs of the six cores collected in the South Golo channel–levee complex, showing the main lithologic facies variations. Lateral correlation using carbonate content measurements is also shown (see Figs. 1 and 6 for core locations)

50% in the proximal lobe (Kco 62-63-64 and Kco 71–72 in Fig. 6) to less than 10% in the distal lobe (Kco 73–74 and Kco 66 in Fig. 6). This high sand content explains the sharp deceleration of flows at the channel end and the radial shape of the lobe.

Lobes of the small sedimentary systems (Biguglia, St. Damiano) have a more elongate shape than do the larger systems but are thinner and smaller. The overall volume of sand entering these small systems is smaller than in larger systems such as the South Golo. Consequently, flow deceleration is less intense at channel termination than in larger systems.

Sedimentary processes at the lobe fringe

The recent lobe fringe of the South Golo system is characterised by a decrease in both frequency of turbidite sequences and sand content. The only observed sequences are base-truncated successions of sequence type II. They are interbedded with monosulphide-rich clay. This suggests that the lobe fringe is rarely affected by turbidity currents. Only the strongest currents are able to transport and deposit sediments in this part of the system. Seismic data (Fig. 9) show that the large slumps initiated on the Pianosa Ridge and on the Corsican slope located south of the Golo System (cf. Figs. 15 and 16) probably generated flows which reached the South Golo lobe fringe. However, no sedimentary evidence is observed in the cores.

The North Golo lobe fringe is characterised by complete and truncated type I sequences with high carbonate contents. The upper part of the lobe deposit does not show high carbonate content. This eliminates Corsican shelf as carbonate source. The northern slump of the Pianosa Ridge corresponds to chaotic seismic facies associated to massive shelly sand (Kco 69 in Fig. 6). The only source for deposits with such high carbonate contents is the Pianosa Ridge. The large slump observed in the north part of the Pianosa Ridge probably generated flows supplying the fringe of the North Golo lobe (Fig. 16), and interbedded with turbidite deposits from the Corsican Margin.

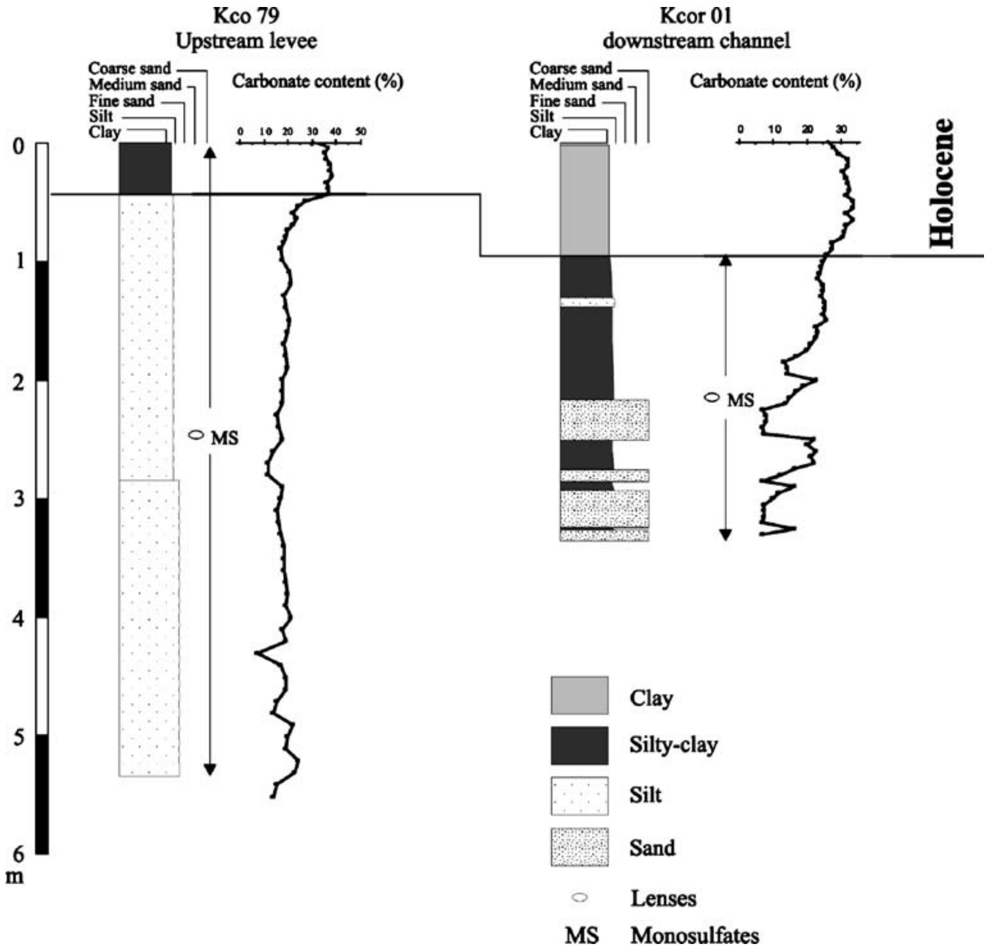


Fig. 11 Core logs of the two cores collected in the St. Damiano channel–levee complex, showing the main facies variations. Lateral correlation using carbonate content measurements is also shown (see Figs. 1 and 6 for core locations)

Sedimentary processes in the Pineto and Fium Alto gullies

Cores collected on the flanks of these gullies are composed of centimetre- to metre-thick silt and sand beds representing up to 80% of the core (Kco 54-27-28-35 in Figs. 6 and 12). Sequences are mainly of type III with high carbonate contents (Kco 35 in Fig. 12), suggesting that hyperconcentrated flows with a thick laminar basal part are the dominant process. The sand/clay ratio compares well with values obtained in small-sized systems. The presence of truncated sequences of type I suggests that turbulent flow may also travel in these gullies and that flow differentiation occurs sometimes along the steep slopes of the gullies.

Downstream, on the lobes, the percentages of sandy facies range between 10 and 20%, except in Kco 77 where massive, metre-thick sandy deposits of sequence III occur (Kco 55-56-42-77 in Figs. 6, 12 and 13). Centimetre- to decimetre-thick laminated sands of sequence Itrc and centimetre-thick massive deposits of sequence III are observed. This confirms that, in these small gullies, flows can slightly differentiate longitudinally. Downstream from the Pineto lobe, sequences corresponding to gravity deposits are not observed. Core Kco 57 (Fig. 6) contains more than 10 m of silty clay to clay, suggesting that no fine-grained turbidites were deposited here in recent times.

Origin of flow feeding the Golo System

Flows can be initiated by two kinds of processes: (1) direct supply by rivers and (2) sediment failures (Fig. 16).

On the Golo Margin, direct supply by rivers is suggested by the connection between canyons and rivers. This connection is interrupted at present on the continental shelf but was direct during periods of sea-level lowstands. The Golo River provides coarse sand material. The presence of incised valleys on the shelf (Gervais 2002; Gervais et al. 2004) suggests that canyons began to form during the Plio–Quaternary in a subaerial setting. However, the freshness of canyon flanks suggests that canyon morphology was maintained until the Holocene by frequent activity of continuous flows. These flows can be either the hyperpycnal flows of Mulder and Syvitski (1995) or frequent turbulent surges triggered by successive failures on the upper continental slope or at the shelf break when sediment load is high at river mouths. A direct initiation of turbidity currents by hyperpycnal flows triggered during river floods

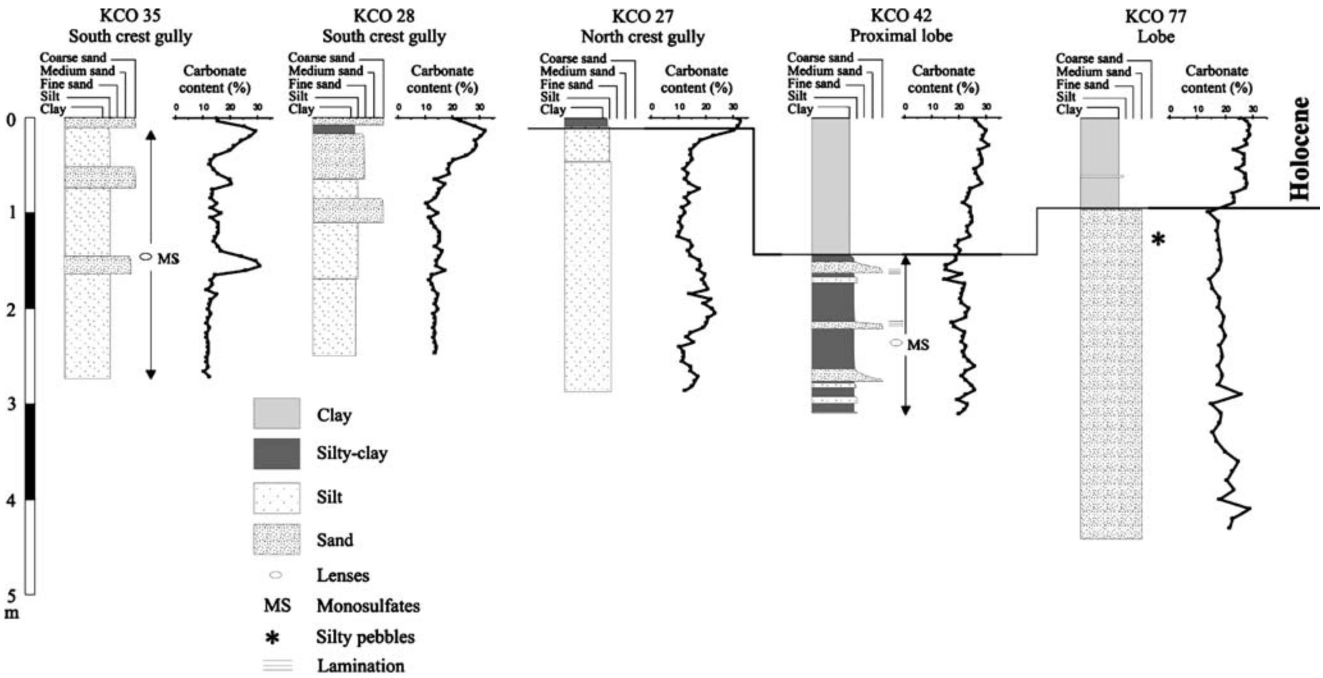


Fig. 12 Core logs of the five cores collected in the Fium Alto gully and lobe, showing the main facies variations. Lateral correlation using carbonate content measurements is also shown (see Figs. 1 and 6 for core locations)

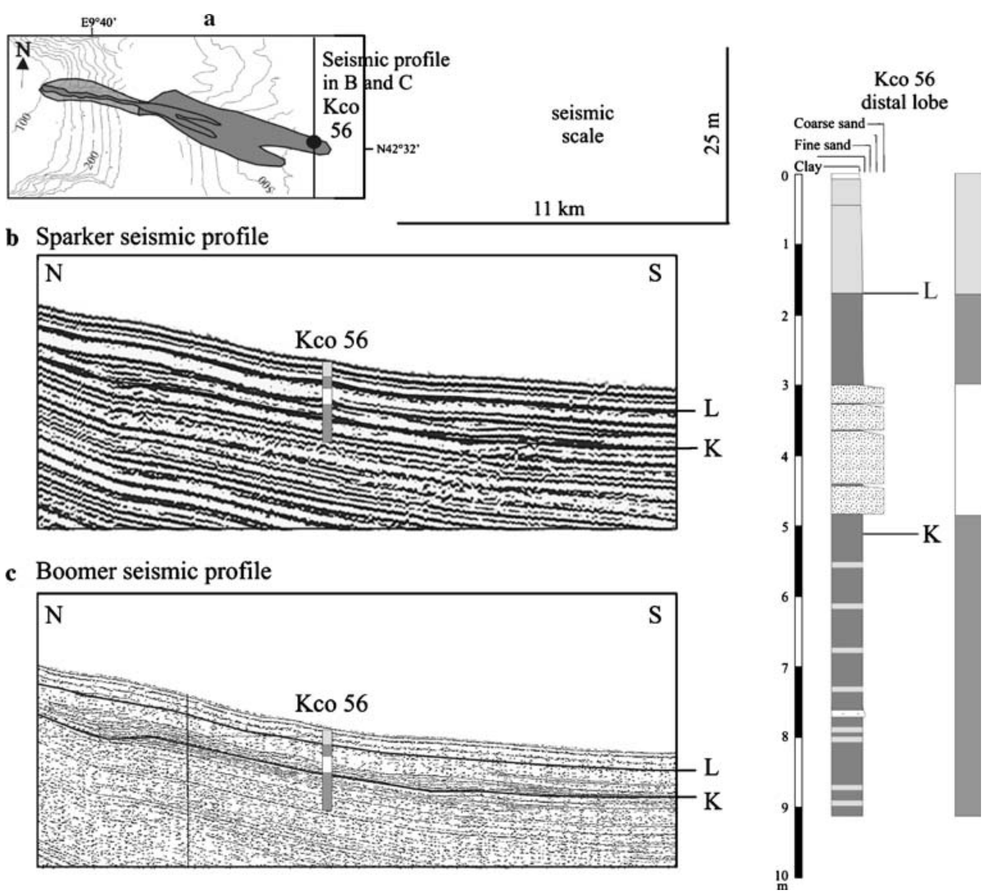


Fig. 13 a–**c** Seismic profiles illustrating litho-seismic correlations for the Pineto lobe (**a**) sparker (**b**) and boomer (**c**) seismic profiles

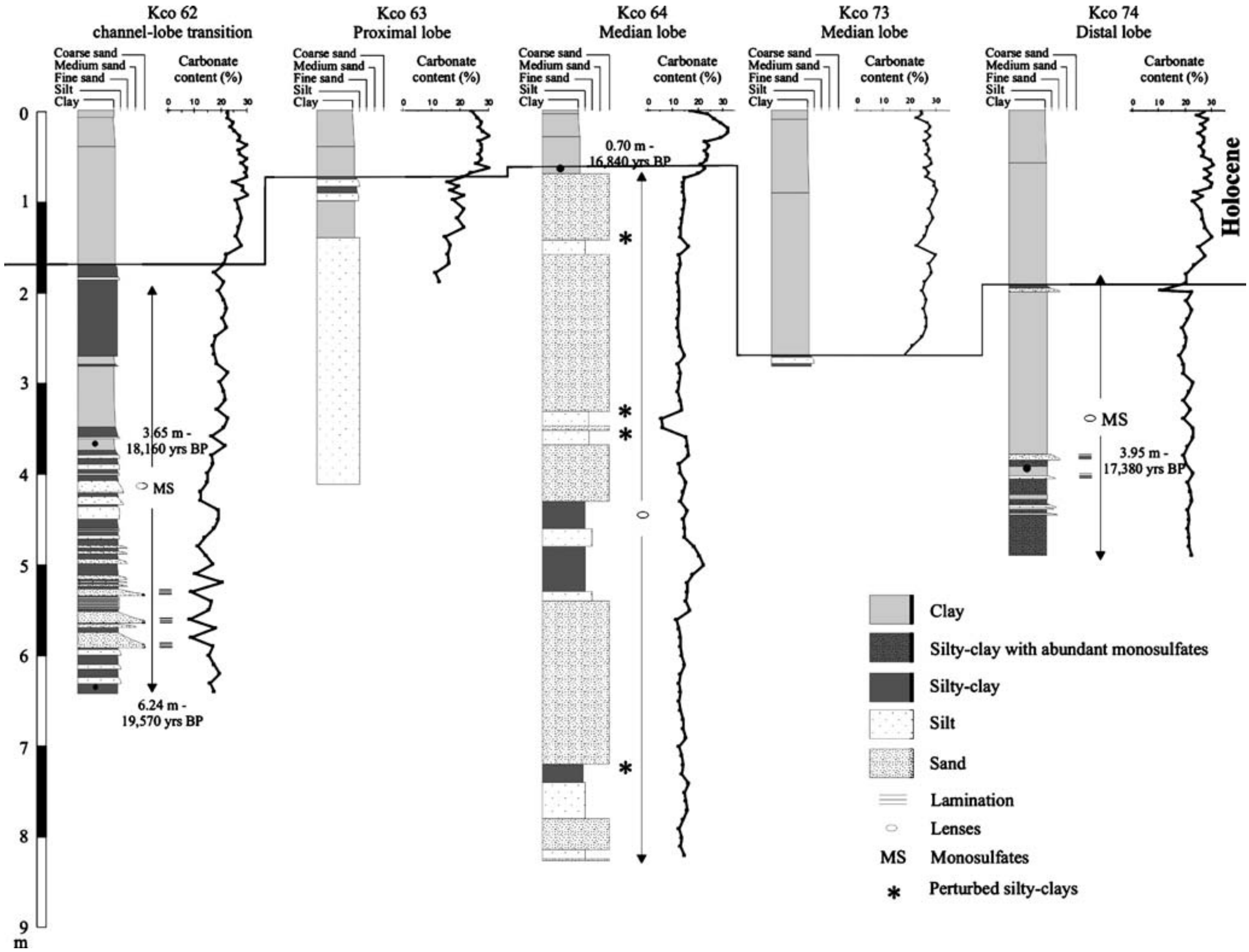


Fig. 14 Core logs of the five cores collected in the South Golo lobe, showing the main facies variations. Lateral correlation using carbonate content measurements is also shown (see Figs. 1 and 6 for core locations)

is also suggested by the direct connection of canyons and rivers through incised valleys which occur especially during sea-level lowstands. In addition, the most developed canyon (South Golo) is presently connected to the most important river (Golo River).

Sediment failures can transform into turbidity currents either by progressive dilution, fine sediment elutriation or because of slope roughness creating a hydraulic jump within the flow (Fisher 1983). During periods of high sediment supply at river mouths, the time of residence of sediment on the continental shelf is short and fine sediments are not winnowed or removed: flow with a thick turbulent upper part can form. During periods of low sediment load at river mouths, sediments are trapped on the continental shelf and fine particle are winnowed and removed by shelf processes. Hyperconcentrated flows with high carbonate content resulting from the transformation of slides or slumps initiated close to the shelf break can thus form. During these periods, a shelf delta can prograde. This would explain the simultaneous activity of all the canyons (Gervais 2002; Gervais et al. 2004). The delta would thus distribute river sediment supply along the margin.

Conceptual model of sedimentation on the Golo Margin

Core dating confirms and provides more precision for the previous conceptual model of the Golo system growth during the late Quaternary (Gervais et al. 2004). During interglacial highstands such as that of the present day, no turbidite activity is observed. At 18,000 years B.P., there were strong changes in flow dynamics, frequency and sediment distribution. Four periods of different turbidite activity can be distinguished (Fig. 17):

1. Slow and low-amplitude sea-level fall (seismic stage I–J or isotopic stage 3; Fig. 17a). The continental shelf remained submerged. A delta prograded onto the continental shelf. Distributaries of the delta supplied all the canyon heads with material for turbidity currents. As the sediments were trapped temporarily

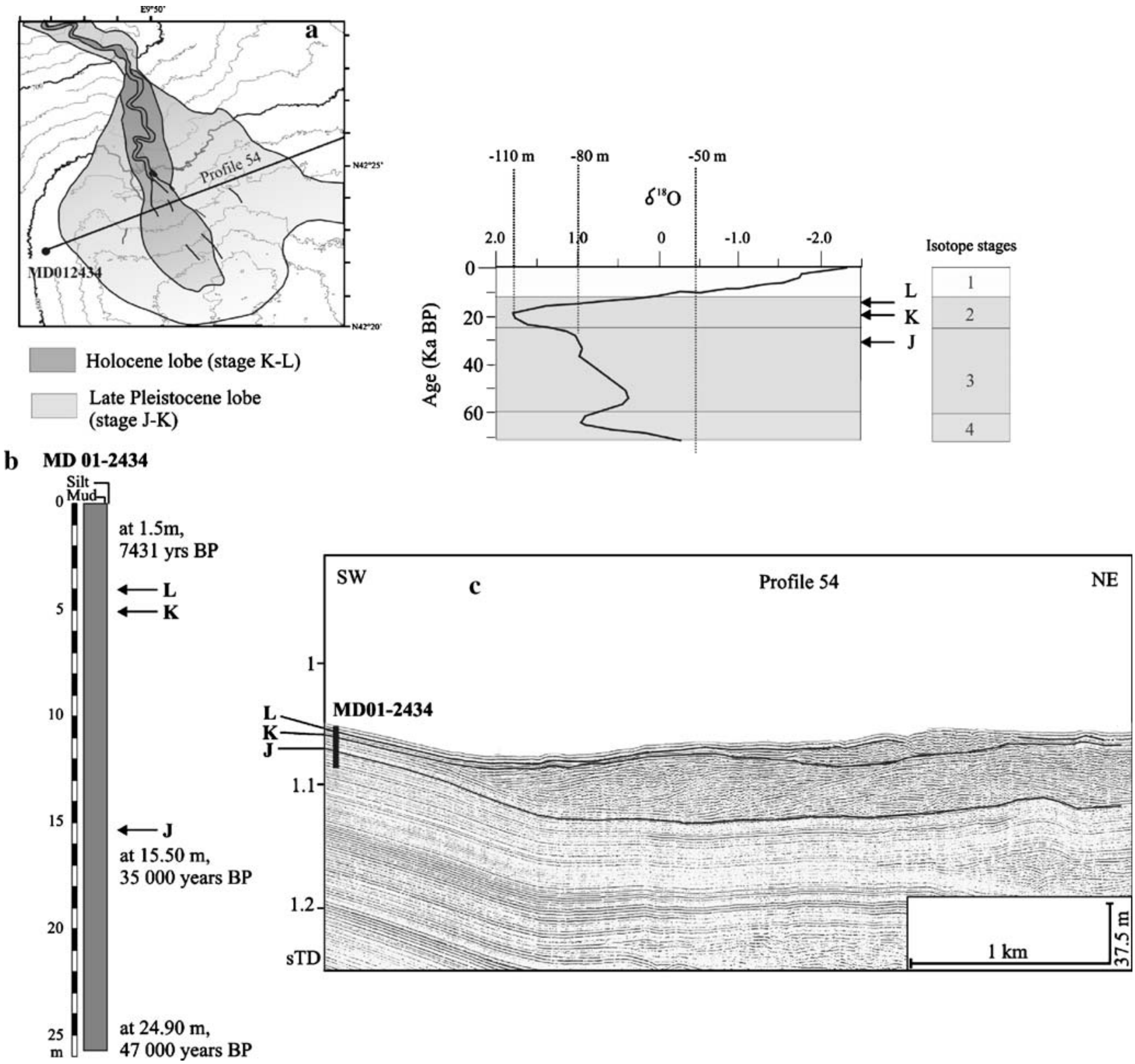


Fig. 15 **a**–**c** Detailed bathymetric map of the South Golo lobe, showing **a** the locations of the seismic profile and core MD 012434, **b** the core log, ^{14}C dates, $\delta^{18}O$ isotopic curve, position of regional seismic markers J, K and L, and sea-level curve extrapolated from the model of Lambeck and Bard (2000) and **c** seismic profile through the South Golo lobe, showing the correlation between the MD 012434 core and the seismic markers K, L and M from Gervais (2002) and Gervais et al. (2004, 2006)

in the delta lying on the continental shelf, the initiation of down-slope flows was dominated by sediment failures close to the shelf break. These failures transformed into hyperconcentrated or concentrated turbidity flows with a thick laminar basal part. These flows were usually sand-rich because fine particles were constantly being winnowed by shelf processes such as shelf currents or littoral drift. Along the Celtic Margin, Zaragosi (2001) suggests tidal intensity to have been two times higher during lowstands of sea level than during highstands. However, as rivers were connected to the shelf break by delta distributaries, hyperpycnal flows could have acted simultaneously with other processes. Levee and lobe growth was moderate (average sedimentation rate was 2 m/1,000 years in the lobes).

2. Rapid and high-amplitude sea-level fall or sea-level lowstands (seismic stage J–K or isotopic stage 4; Fig. 17b). The continental shelf was not submerged. During stage J–K, sea level was 110 m lower than at present. This period was characterised by intense activity of gravity processes in the basin (Gervais

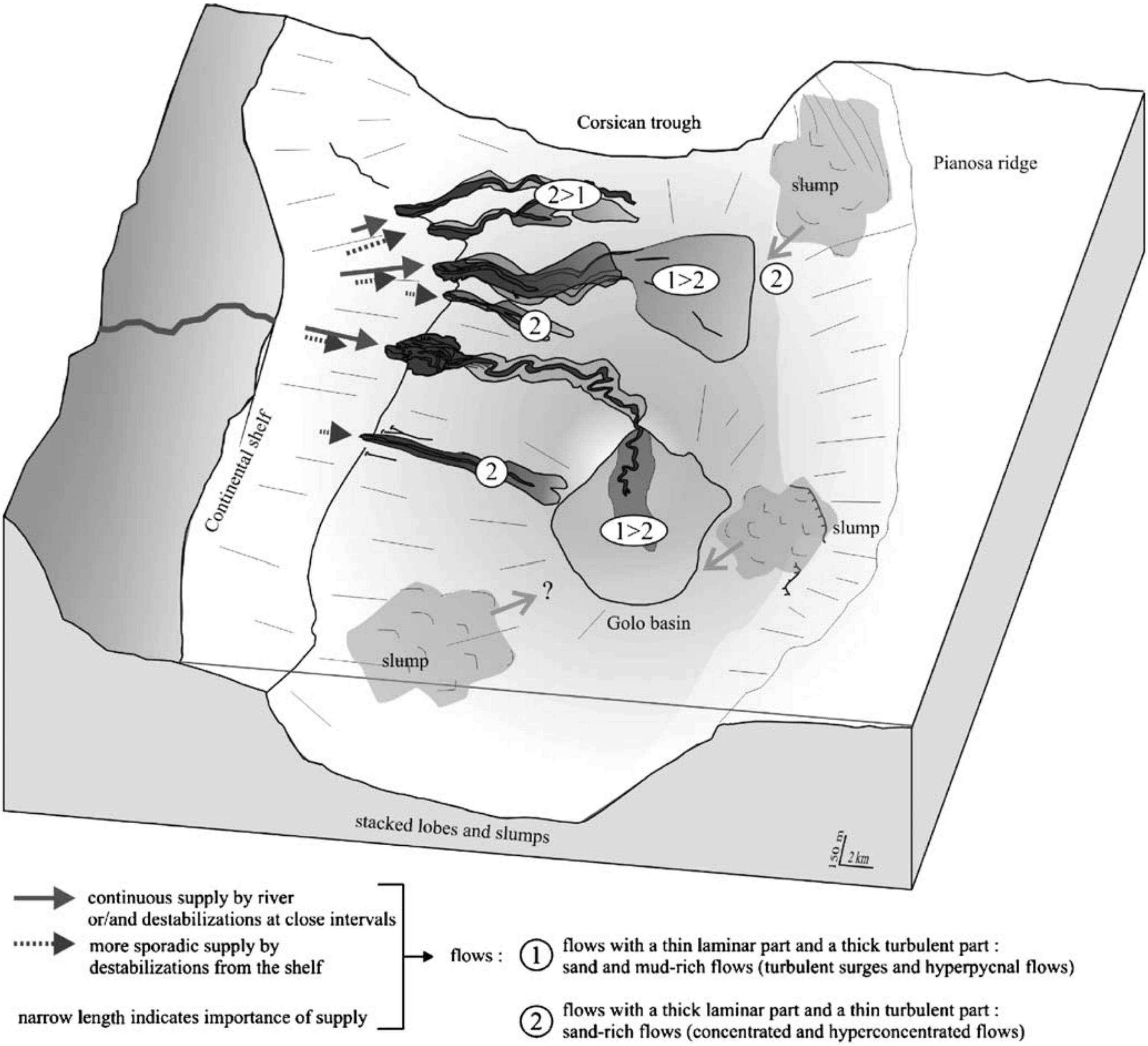


Fig. 16 Schematic representation of flow types along the Golo Margin. *Arrow length* is proportional to the relative importance of a given process

et al. 2004). The delta prograded rapidly on the upper continental shelf and the river eroded intensively to reach its equilibrium profile. Sediment load was high on the shelf. However, only large canyons such as the South and North Golo canyons were supplied by sediments because sediment flux on the shelf is concentrated in incised valleys. During these periods, sediment processes on the slope were dominated both by mixed (mud and sand) turbulent surge with a thin basal concentrated flow and a thick upper turbulent part (type 1) and probably by hyperpycnal flows. During these periods of high sediment supply, residence time on the shelf was short and associated with little winnowing of fine particles. Average sedimentation rates on the margin were 5 m/1,000 years on the lobes, 3 m/1,000 years in the upper channel–levee complexes and 2 m/1,000 years in the lower channel–levee complexes. Avulsion rate was important both in channel–levee complexes and in channelled lobes. This period also corresponded to important levee growth due to overspill of the upper turbulent part of flows. However, spilling was not frequent. Core dating allowed us to calculated spillover frequency for the period 19,000–18,000 years B.P. (Kco 59 and Kco 62 in Figs. 10 and 14). One spillover deposit was deposited every 200 years and one event produces preserved

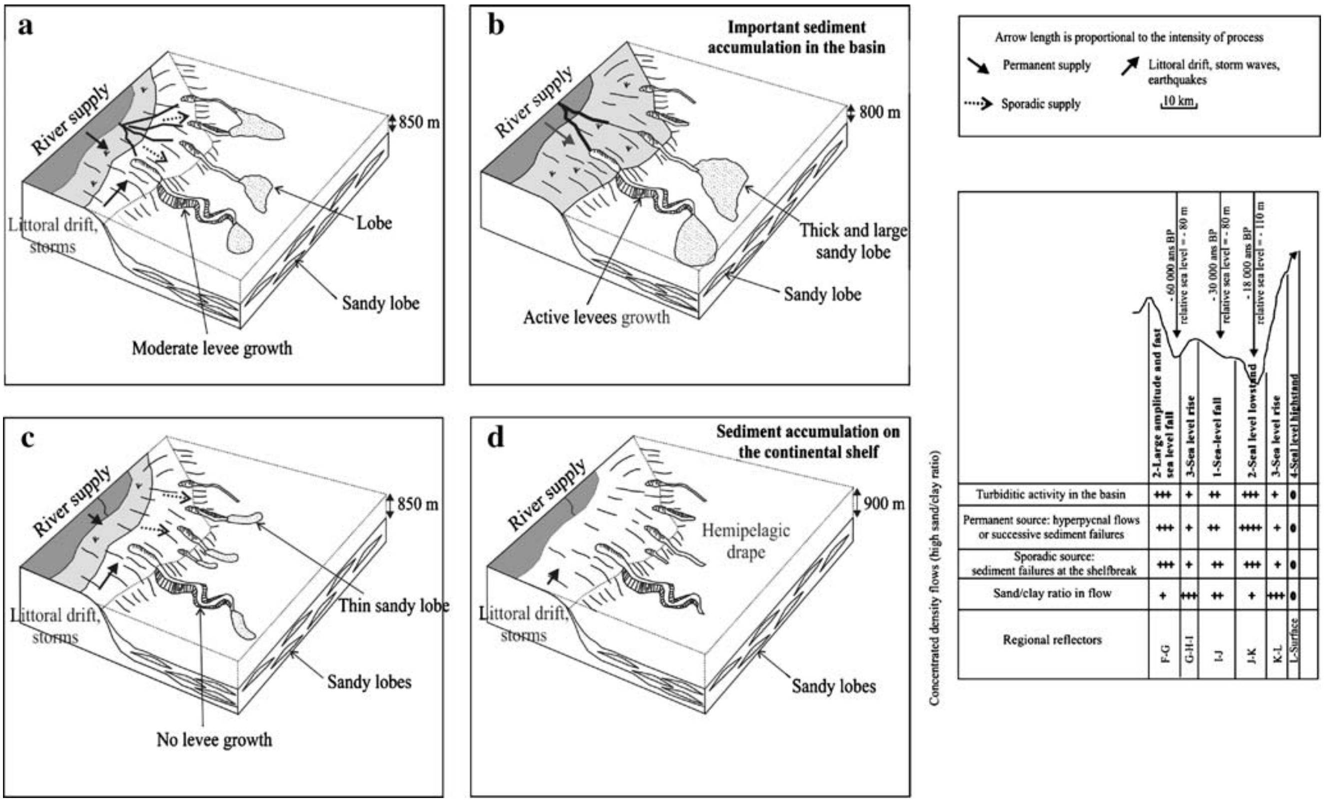


Fig. 17 **a**–**d** Conceptual model showing the evolution of the Golo Margin during the late Quaternary. **a** Slow and small-amplitude relative sea-level fall: moderate turbidite activity. **b** Rapid and high-amplitude relative sea-level fall or relative sea-level lowstand. High turbidite activity. **c** Relative sea-level rise: low turbidite activity. **d** Present-day situation. Relative sea-level highstand, hemipelagic deposition

deposits in a channel every 50 years. This suggests that most of the flows were only channelled and did not spill. This rate of spilling is low when compared to large muddy systems such as the Zaire (Migeon 2000). The presence of sand in levee deposits suggests that flows moving in the system had high sand/clay ratios. This high sand content explains the lack of sedimentary structures in the deposits. When spilling occurs, flows quickly decelerate and grain-to-grain interaction generates quick deposition (frictional freezing) of sand, preventing lamina formation.

3. Sea-level rise (seismic stage K–L or isotopic stage 3; Fig. 17c). The geometry of sedimentary bodies observed on seismic data suggests that flow activity changed with time in the channel–levee systems (Gervais 2002; Gervais et al. 2004). During interval K–L, no spillover was observed in levee cores (KCO58). Hyperconcentrated flows were the dominant process in the large systems. Flow frequency was higher than during period 2. Core dating provides a rate of one event every 30 years in the major channels. During times of rising sea level, such as during the period extending from 18,000 years B.P. to the Holocene, sandier sequences are recorded in all fans and gullies of the margin but no levee growth is observed (Kco 59 in Fig. 10). Core dating suggests that the thin lobe deposits were restricted to the Younger Dryas during a relative rising sea level (Kco 58 in Fig. 10). Deposition occurred on the delta, beginning close to the shelf break and retrograding progressively upward onto the continental shelf. As the river profile was below its equilibrium profile, sediment supply was low due to the generally retrograding trend in the delta. In addition, fine particles were winnowed by shelf processes as the shelf progressively submerged. Turbidite activity was low and dominated by sand-rich, hyperconcentrated and concentrated flows with high carbonate contents. However, the sediment which piled up during the preceding sea-level lowstand resulted in overloading and oversteepening. The flooding of the coarse sediments deposited during the preceding sea-level lowstand reduced their shear resistance by decreasing their friction angle, thereby easily generating slope failures. In addition, excess pore pressure generated by hydrodynamic processes on the shelf (e.g. storm waves, swell, wind-induced currents) helped to generate sediment failures. These failures transformed into hyperconcentrated and concentrated flows with a

thick laminar basal part and a thin turbulent upper part. Such failures and flows occurred not only in the canyon heads but also elsewhere along the shelf break, thereby initiating gully formation. These observations suggest that gullies have a different origin than do canyons. Gully heads are located at the shelf break. They are not connected to a continental river system or to a network of valleys on the continental shelf. According to seismic profiles (Gervais 2002; Gervais et al. 2004), their activity is restricted to the period 19,000–15,000 (stage K–L), corresponding to the beginning of the last sea-level rise. Gully formation would therefore be related to the destruction of the shelf delta deposited during the preceding sea-level lowstand. These would result from the transformation of retrogressive submarine failures into hyperconcentrated or concentrated flows. This rather short period of gully activity differs strongly from the scenario described by Field et al. (1999) for the Californian Margin. Along the Golo Margin, gullies never represent an initial stage of canyon formation.

4. Sea-level highstands (seismic stage L-surface or isotopic stage 1; Fig. 17d). No turbiditic activity occurred. Sediments were trapped on the shelf, the finest particles being transported to the basin by hypopycnal flows, forming a hemipelagic drape when mixing with pelagic particles. Sedimentation rate was low along the whole margin (0.3 m/1,000 years), which is consistent with values published by Stanley et al. (1980).

The difference in feeding process is related to canyon position relative to source area. Thus, the location of a turbidite system with respect to the location of the river source will determine the main feeding processes (quasi-continuous currents or short-duration flows) and the periods of major supply.

1. The major canyons are preferentially fed by large-volume mud-/sand-rich flows due to their proximity to river mouths. Consequently, major systems located in front of rivers are fed mainly by a persistent mud-/sand-rich point source (sandy flows with a thin laminar lower part and a thick turbulent upper part, or type 1 flows) during periods of sea-level lowstands or fall, leading to the construction of deep, stable, more or less sinuous channels with well-developed levees and large, thick lobes in the distal part of the basin (Gervais et al. 2004). Avulsion rates are high and progressive lateral migration is important.
2. The minor systems located far from river mouths are also fed by these types of currents during sea-level lowstands but are fed mainly of sandy flows (sandy hyperconcentrated flows with a thin turbulent upper part or type 2 flows) which may be generated by shelf storms or failures in canyon heads during periods of both sea-level rise or fall. This leads to the construction of unstable, relatively straight channels with low sandy levees. Avulsions and small thin lobes are observed only in the proximal parts of the basin (Gervais et al. 2004). The morphology of the basin, including the slope angle, also has a large impact on the transport capacity of the flows. For example, sandy flows predominated during stage K–L. The pre-existing, well-developed channel–levee complex drains sediment transport and enables sandy flows to form large lobes in the basin (major fans). Simultaneously, minor fans and gullies form small lobes along the slope or in the proximal basin.

Conclusions

Three types of flow contribute to the construction of the Golo system:

1. Turbulent, sand-rich concentrated flows with a strong vertical density gradient. The basal part of the flow is laminar, the upper part turbulent.
2. Continuous (hyperpycnal) flows containing both sand and mud.
3. Sand-rich flows with higher sand concentrations than either (1) or (2) and with a basal laminar part thicker than (1) and (2). Deposits from flows initiated on the Pianosa Ridge are interbedded with sediment coming from the east Corsica Margin.

During relative sea-level lowstands and sea-level fall, flows were initiated either by direct supply from river mouths and via shelf-delta distributary channels or by slope failures. Sediment supply was continuous and fine-grained particles were not winnowed. Concentrated flows containing both sand and mud were the most frequent processes. This favoured levee construction and lobe progradation. Channels were generally stable, moving only by progressive lateral migration. During relative sea-level rises, the four canyons in the study area were supplied with sediment. Flows were triggered by slope failures in the carbonate-rich sediments near the shelf break having low contents in fine particles. Sediments supplied by rivers were trapped on the shelf and fine-grained particles were winnowed. Levee and lobe construction was low and the volume of sediment was lower than during sea-level lowstands. During sea-level highstands, especially during the Holocene, hemipelagic drapes covered the whole area.

In this type of confined sandy margin, relative sea-level changes and potential connections between canyons and sediment sources both have a strong influence on the quantity and quality of sediment supply to the basin. Sea-level changes determine the characteristics of sediment input and canyon connections to sediment sources are the major factor controlling the dominant transport process and its initiation which, in turn, controls the morphology and geometry of the system. The characteristics of sediment input and the initiation mechanism of gravity flows are the most important variables in the whole Golo system because they influence the morphology and geometry of the individual sedimentary bodies.

Mass-transport processes can also be initiated outside of the turbidite systems along the Golo Margin, for example, on the continental slope of the Pianosa Ridge. In this case, debrites or slump deposits can intercalate with gravity-flow deposits coming from the Golo turbidite system. Because of the confinement, several sediment sources are observed, explaining the complexity and the interplay of sedimentary processes. However, the morphology of the basin, including pre-existing topography (variable slope gradients, well-developed channel–levee complexes) and confinement, has a large impact on the distribution geometry and the long-term growth pattern, thus more or less constraining the flows.

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