Alluvial Fans at Cala Gonone (Sardinia), a Fast Deveoping Touristic Village: Origins, Hazards and Potential Risks

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Abstract

The study area of Cala Gonone in NE Sardinia (Italy) consists of a wide terraced re-entrance/valley crowned inland by carbonate hills and, near the coast bounded laterally and partly floored by thin basaltic lava lying over carbonate bedrock. In this re-entrance, several inland alluvial fans have developed, and a local ~ 30 m high, about 10 m wide (thick), 400 m long scarp body-remnant of semi-consolidated alluvial fan deposits is exposed along the coast. The touristic village of Cala Gonone has been rapidly expanding in these last few decades over the mid to lower parts of two coalescing alluvial fans and along the coastal marine scarp edge. The village thus became exposed to natural hazards such as sudden overland and creek floods and debris flows typical of alluvial fans, local rock falls, and to instability of the costal scarp due to wave erosion during extreme sea storms. As commonly occurring elsewhere and since antiquity, the risk perception of such events is low because of the centennial, millennial of longer recurrence. Such perception does not negate the hazards but a long event recurrence can be accepted as a reasonable risk for the human's activity in certain areas. However, serious consideration should be given to potential problems and plan and build for amelioration and defense. Many examples of what can occur and could be done exist from the careful safe-location of the ancient Roman villas to the recent disastrous cases where parts of ill-located villages have been destroyed by debris flows and floods along alluvial fans.

The evidence of what did and could still happen in the Cala Gonone and similar other area is clearly imprinted on the landscape (geology, geomorphology, and with relative details in the stratigraphy as sedimentology of the deposits) and driven by climatic conditions and human activities.

Introduction

Sedimentology is a branch of stratigraphy that developed as an integrated science during the mid-20th Century as a tool to search natural resources, primarily petroleum and coal. One of the major goal was to determine the palaeo-environments where reservoirs of such resources could be found and developed. Notwithstanding the older objectives, modern concerns/applications of Sedimentology are increasingly related to environmental problems. Accordingly, the approach of this study has been to examine some specific environments, such as the alluvial fans, not just as isolated sedimentary bodies (their sedimentological characteristics and infer the processes involved) but also as part of the entire (natural and cultural) landscape (geology, geomorphology, climate, hydrology and natural hazards) (Clemmensen et al., 2001; Martini and Chesworth, 2010).

An alluvial fan is a topographic feature readily utilized for constructions and cultivations since antique times. Roman villas, for example, were located three quarters to halfway the slope to have an upper grazing and a cultivated terrain below, above the unhealthy, fog-ridden valley-plane lands (Martini and Wightman, 1987). Some ancient inhabitants, such as the Bronze Age and Nuraghi in Sadinia utilized the gentle fan slopes, but built their large villages on the fans flank on solid-land not subjected to floods and mass-flows (De Palma and Melis, 2010). During other times, societies, such as the Iron-Age people, for safety reason avoided the gentle slopes and plane areas. However, returns have occurred up to the recent times to the usage of fans also for permanent settlements, although natural hazards such as slumps, debris flow, floods of various types and the inevitable resulting risks were and are well understood. Extensive remediation has been done in some cases, in others the long recurrence of disastrous events does not require numerous and expensive defences.

The processes involved, benefits and hazards have been extensively studied and reported. Commonly the processes have been directly observed during or soon after the events including reporting the damages that may have occurred, or through experiments.

In this paper, we are not reporting on a damaging event, rather on the information that pre-existent sedimentary deposits can provide to guard and prepare inevitable damaging occurrence albeit uncertain on its recurrence time and intensity. The objective of this paper is, thus, to contribute to recognize the potential natural hazards and risks through the study of the Pleistocene sedimentary deposits of an alluvial fan system fed from steep highlands and expanded across an elevated shore re-entrance in front of a cliffed shore in the east coast of Sardinia Island (Italy) (Fig. 1a).

The example dealt with the costal Cala Gonone area of the Gulf of Orosei, west Sardinia, Italy (Fig. 1b, c). The geological (rock source of the sediments and morphology of the terrains allowing for their movement and space for deposition), meteorological (temperate, wet and dry conditions establishing the regular or variable precipitations of rain and snow), hydrologic distribution and anthropogenic activities (conform or not to natural hazards) establish the existing landscape (Fig. 1b, c).

The specific area of Cala Gonone consists of a triangular shaped wide re-entrance/valley crowned inland by carbonate hills (Mt Tului, Mt Bardia, Mt Irveri) (Fig. 2a), and a gently seaward-dipping carbonate terrace partly covered by thin basaltic lava flow (Fig. 2b). In this re-entrance, several coalescent alluvial fans (inland **S**: Stadium, **G**: Gustui; and the coastal **P**: Palmasera, Fig. 2) have developed. The touristic village of Cala Gonone has been rapidly expanding on these last few decades over the mid to lower parts of the alluvial fans and along the coastal marine scarp edge (Fig. 2). In this last part, the Palmasera Village is under continuous expansion (**PV**, Fig. 2b).

Geology

The island of Sardinia detached from the European plate during early Miocene and drifted eastward to the late Miocene when it reached its present position in the Western Mediterranean Sea. Presently it constitutes the eastern continental margin of the Balearic Sea and western margin of the Tyrrhenian Sea (Cherchi and Montardert, 1982) (Fig. 1a). Both sea basins have been affected by rifting to drifting processes that eventually led to the formation of an oceanic crust in their central deeper part (Rehault et al., 1984; Sartori et al., 2004; Marani et al., 2004). Normal and transcurrent faults dissected Sardinian pre-Miocene deposits and allowed the formation of a series of half graben that were filled with Miocene continental and marine deposits and calc-alkaline Andesitic lava flows (Carmignani et al., 2001; Casula et al., 2001; Gaullier et al., 2009) (Fig. 3a). During the Pliocene widespread alkali basalt volcanism and basins uplift was followed by local renewed dissection and tilting of bedrock blocks (Casula et al., 2001; Funedda et al., 2000) (Fig. 3a). Since the Early Pleistocene Sardinia is considered tectonically stable, and the various marine to continental sedimentary successions are the result of repeated variations in sea level associated with the Quaternary global climatic changes (Fig. 3a) (Andreucci et al., 2009; Pascucci et al., 2014).

The present geological setting inland from the Gulf of Orosei consists of two Mesozoic (Jurassic to Cretaceous) sub-parallel N-S oriented carbonate ridges separated by a Palaeozoic granitic-metamorphic zone in part covered by Pliocene basaltic lava flows (Beccaluva et al., 1985; Carmignani et al, 2015) (Fig. 3b). The costal ridge mainly consists of seaward steeply dipping (20–30^{o}) layers composed of Jurassic dolostones containing limestone lenses (Jadoul et al., 2010; Lanfranchi et al., 2011) (Fig. 3c). The coastal ridge is cut by several NE-SW transcurrent and variably oriented normal faults along which few small volcanic vents have ejected lava thinly mantling some coastal areas approximately 1.99–2.83 Ma ago (Figs. 3b, c) (Dieni and Massari, 1966; Massari and Dieni, 1973; Savelli and Pasini 1973; Beccaluva et al., 1985; Carmignani et al., 2015). The carbonate flanks of the highlands have thin talus remnant deposits of various types (**T, Y W, J**) (Fig. 2a), and local erosional amphitheatres at 500–800 m elevation indented by few, steep ephemeral streams leading to toe alluvial fans below (**S**, **G**) (Fig. 2b) and major submarine canyons down to deep sea floors (Giresse et al., 2014) (Fig. 3b).

The carbonates coastal cliffs of the Gulf of Orosei have numerous karstic caves and are dissected by deep, narrow canyons (codule) with ephemeral streams flooding on decals or longer intervals (Fig. 3b) (Cossu et al., 2007; De Waele et al., 2010). Only one of these streams (in Codula Ilume) has its headwaters in the granitic/metamorphic inland zone, cuts through the coastal carbonate range and carry some metamorphic rock to the coast at Cala Luna, occasionally remoulded by large codula floods having a recurrence of about 130 years (Cossu et al., 2007) (Fig. 3b).

Climate

Sardinia has now a typically Mediterranean (temperate) climate tendentially warming-up. It is characterized by very dry summer months, cool winters with annual snow fall in mountain over 1000 m above sea level (asl) and frequent occurrence on hills around 500 m asl (**S** of Fig. 1b) (Canu et al., 2014). During wet transitional seasons (fall and early winter) it experiences local extreme rainstorm events with sudden downpours of 431 mm in few hours particularly in central and northeastern regions (south of Nuoro, **S** of Fig. 1b) (Cossu et al., 2007, 2010; Betrò et al. 2010; Bodini and Cossu, 2010a 2010b; Hewson et al., 2021). These strong precipitations occurring during the fall in eastern Sardinia are related to the Atlantic cyclonic flow that crosses North Africa and the warm southern Mediterranean Sea (Nuissier et al., 2008; Ricard et al., 2012) impinging on the Sardinia highlands (Pensieri et al., 2018). Particularly affected are the intermountain basins of the eastern highlands (**S** of Fig. 1b) but occasional downpours occur also along the coastal mountains and hills such as those of the Cala Gonone area (**C** of Fig. 1b), being also exposed to the northern and eastern wind induced storms (Fig. 1b). In addition, marine storms produce almost yearly strong high waves (order of 7 m) disruptive of the coastlines.

Cala Gonone had colder conditions during glacial times, with small glaciers occurring in higher about 1000 m asl inland areas of Sardinia and more in the adjacent Corsica Island (Hughes and Woodward, 2016). The frigid glacial-time temperatures and, in minor measure, the recent winter ground-frost and freeze-and-thaw cycles, combined along the coastal areas with interstitial salt crystallization have led to rock frost-cracking and comminution of the materials (mainly carbonate rocks) creating much loose sediment. Exceptional rainstorms likely occurred in the past particularly during periods of climatic change, favoured rockfalls, landslides and other mass-sediment movements.

Methods Of Study

Available multidisciplinary information has been reviewed dealing with the geology, sedimentology, geomorphology, and climate of the area, and with mass-wasting processes.

The fieldwork consisted in surveying the location of the major fans, facies analysis, and assembling and photographically documenting the recognized sediment features (textures and structures) generated in various parts of the system. Where possible, major lithostratigraphic units have been defined utilizing differences in lithofacies assemblages and key horizons (Table 1).

Freshly exposed palaeosol deposit was collected and dated using both quartz OSL (optically stimulated) and K-feldspar post IR IRSL (pIRIR= post infrared stmulated) luminescence methods. Samples were prepared under controlled red light conditions following the conventional procedure in order to obtain pure quartz and K-feldspar grains. Luminescence analyses were conducted at Luminescence Laboratory of the Sassari University. Measurements were made using two automated Risø TL/OSL readers (DA-20 and DA-15; Bøtter-Jensen et al., 2010) with calibrated 90Sr/90Y beta sources (~0.15 Gy/s and ~0.08 Gy/s). The OSL age of quartz samples is limited by the saturation of the natural signal. Therefore, K-feldspar SAR post infrared stimulation (post-IR IRSL) at elevate temperature (290°C) protocol was applied to the samples for which an enough grains were obtained (Thiel et al., 2010; Andreucci et al., 2017).

Some uppermost Pleistocene dates are also available from literature for the study area: K-Ar for the Basaltic lavas dated at 2.34 ± 0.05 (Sarria et al., 2016), Radiocarbon ages (^{14}C) of 19365–17485 y BP for the basal part of Palmasera alluvial fan (Coltorti et al., 2010). Others were obtained from coastal deposits trapped inside the Bue Marino cave close by to Cala Gonone (Fig. 3b). Ages derived using both luminescence and U/Th methods range from 134±32 to 86±13 ka. The uppermost dated colluvium inside the cave has a luminescence (post IR IRSL) age of 86±4 ka (Andreucci et al., 2017).

Results

Alluvial fans

The Cala Gonone fan system is made of a series of smaller telescopic and coalescent fans developed along the inner valley from the saddle between Mt. Tuui and M. Bardia to Cala Gonone village (Fig. 2).

Remant of such fans can be observed at sites (**T, Y, W, Z)** (Fig. 2a). Lower fans affecting the village and costal area in more recent times were/are fed by ripid streams from steep coastal hills (Fig. 2b). Two well defined and well exposed ones are the Stadium (**S**) and Gustui (**G**) alluvial fans, which also contributed to the formation of the larger Palmasera coastal alluvial fan system (**P**) (Fig. 2). Minor sediment contribution to the apron system is also from northern Mt Irveri valley (Fig. 2b). The entire system is now crossed by the ephemeral, steep mountain torrents that from the north are: Rio Irveri (ir), Rio Ischirtiore (is) Rio Sos Dollores (sd) (Fig. 2b). The system could be ideally subdivided in three parts all experiencing different depositional models.

The uppermost part of the system develops in the valley between Mt Tului (915 m) and Mt Bardia (882 m). It has a length of approximately 500 m and width of 500 – 700 m (Fig. 2a). It is made of slope deposits occurring in several lateral, small, steep-sided head-valleys developed along the mountain flanks (Fig. 4a). Locally they resemble *grèze litée* (*ebulis ordonnès* of Ozer and Ulzega, 1981) and consist of lenses of greyish orange (10 YR 7/4) to moderate yellowish brown (10YR5/4), fine carbonate pebble to granule conglomerates (breccias) (Fig. 4b, c). They generally occur in openwork framework, frequently showing inverse (coarsening upward) grading (Fig. 4d), alternating with thinner lenses of poorly sorted, matrix rich (primarily sand with minor silt, and traces of dust as coating) pebbly to granule deposits, and few, thin, residual lenses of laminated coarse-grained sandstone (Fig. 4b, c). Occasional isolated boulders to large cobbles are present (Fig. 4d). The layering consists primarily of thin elongated lenses dipping locally up to 30–32^{o}, generally 20–25^{o}. Small cut-and-fill structures are locally present (Fig. 4b); rare large gullies occur filled with a variety of slope deposits (Fig. 4c).

Near the apex, significant unconformities (diverging attitude of strata, or locally large gullies filed by mass flow deposits) indicate switching of sites of deposition (Fig. 4c). Non-cohesive and cohesive debrisflow (*df*), grain flow (*gf*), overland sheet-wash/flood (*sf*) and canalized flow (*cf*) are the recurrent depositional features (Fig. 4b-d). Some of the resulting deposits show imbrication clusters in section sub-parallel to the slope and some finer-grained gravel layers show well developed fining upward trend (tied to *df/gf*) (Fig. 4b). In the saddle west of Mt Irveri closer to the steep calcareous hill, bouldery rockfalls (*rf*) prevail (Fig. 4e).

The lower, central part of the Cala Gonone system includes the Stadium (**S**) and Gustui (**G**) alluvial fans (Fig. 2). They have length of approximately 500 m and width of 500 – 700 m, and variable slope ranging from 20° at the apex to 2° in the low parts. They mostly consist of poorly cemented carbonate pebble, with some cobbles and rare small size boulders and variable amounts of sandy, muddy matrix. The clasts are angular primarily in the upper part of the fans to subangular lower down. The sorting varies from poor to moderately well-sorted in different layers, which indicates variable transport agents. Both fans are now covered in the upper part by bushy vegetation, and the lower part is progressively anthropized by the enlarging village of Cala Gonone (Fig. 2b).

Stadium fan (**S**)

The sediments of the Stadium alluvial fan are exposed in two long outcrop sections cut sub-longitudinally **(S1, 2** locations) and diagonally (**S3**) to the fan slope (Fig. 2). Closer to the hills the longitudinal section **S**1 shows two uncomformably superimposed units with slightly different sediment characteristics and dip of the beds (Fig. 5a). The lower unit consists of steeper (~ 10–12^{o}) thin, lenticular beds of very poorly sorted, sandy, muddy pebble to locally cobble, alternating with lenses of sand to granule deposits with disseminated fine grained pebbles and faintly lamination (Fig. 5a). The upper unit consists of gently sloping (~ 2–3^{o} in this exposure) thin, lenticular, muddy, sandy pebble layers alternating with thin sandier lenses and drapes (Fig. 5a).

The lower unit were affected mostly by overland fluid flows, sheetflood (*sf*) and possibly watery debris flows (*cf*). The upper unit shows sandy conglomeratic horizon likely deposited primarily by sheet flood (*sf*) and canalized floods (*cf*) (Fig. 5a).

Gustui fan (**G**)

The deposits of the Gustui alluvial fan are exposed in sand pits in its middle-upper part (**G1, G2**) and more extensively along quasi-transversal and diagonal road cuts in its downslope part (**G3 to G6**; Fig. 2b). At **G2** locality three major stratigraphic units may be identified: (i) the lower unit consists of basal steeply inclined thick lenses of small boulder, cobble to pebble openwork conglomerate overlain by massive pebbly sand-granule-deposits and very coarse sands with disseminated pebbles lenses. (ii) This is overlain by continuous, at the outcrop level, unit with apparently massive to slightly laminated sandy to granule deposit some with sparse pebbles, enclosing some pebbly lenses and small cut-and-fill structures. This second unit is cut in the up-dip part by a small channel filled with pebble to cobble openwork conglomerate. (iii) Everything is uncomformably overlain by massive, disorganized pebbly sand- to granule- deposits with sparse pebbles and rare boulders, capped by organic rich, dark colored soil of similar lithology (Fig. 5b).

The entire deposit at **G2** records the infilling of a deep gully by powerful events. The lower unit is dominated by granular not-cohesive debris flow (the coarser lenses) (*gf*) and sandy/muddy matrix rich watery debris flows (*df*). The overlaying unit is dominated by sheetfloods (*sf*) possibly reworking also debris flows, and local channel flow (*cf*). The capping unit resembles the underlying one, being however partially reworked by man (*hm*). A thin, dark-brown, sandy pebbly soil cap the unit (Fig. 5b). No ancient soil horizons has been encountered in these sections

The adjacent (20 m apart) thinner exposure at **G1** location a thin (~ 3 m) near top-fan surface exposure shows a regular alternation of clast-supported, fine pebble to granule conglomerate lenses resting with sharp bases on predominantly sandy layers with disseminated fine pebbles, and very fine pebble to granule laminas (Fig. 5c). This unit is best interpreted as an alternate of grain flow (*gf*) and sheetflood deposit (*sf*) with some very small cut-and-fill structures (*cf*). A thin sandy pebble to cobble medium-thick conglomerate lens occurs at the base of this section possibly associated with a debris flow (*df*) event (Fig. 5c).

The transversal, middle, roadside exposures of both the Stadium and Gustui alluvial fans (**G4**, **G5**, **G6**, Fig. 2b) shows sandy pebble conglomerates occurring in sequences predominantly of cuts-and-fills channel flow and quasi regular alternation of thin lenses of sandy, pebble conglomerates, and granular very coarse-grained sandstones with sparse fine pebbles (Fig. 5d). These deposits here and along the road outcrops are interpreted as formed by debris flows reworked in part by sheetflood (*sf*) and shallow channel flows (*cf*), possibly in a braided system (Fig. 5d, e). Occurrence of unsorted sandy pebbles to pebbly sands local deposits suggest the presence of mid to distal parts of debris flow (Fig. 5e).

Rock-falls of carbonate blocks occur over the northeast lateral terminal part of the Gustui fan (Fig. 2b). This indicates that tail ends of debris flows, muddy sandy gravely floods (and local and minor rockfalls) did reach the edge of the present village and possibly could also reach the entire area down to the coast.

Coastal alluvial fan (P). The Plio-Pleistocene small volcanic vents poured a basaltic cover (10–20 m thick) on the carbonate terrace of the south-eastern lower part of the Cala Gonone reentrance (Fig. 2a). Part of it forms the substrate of the village almost up to the brink of the conglomerate scarp at Palmasera (P) (Fig. 2). The morphology of the sedimentary deposits exposed along the coastal scarp, arcuate away from a centrally located feeding stream (Rio Sos Dollores Codula = sd, Figs. 2b, and T of Fig. 6a), and their sedimentological characteristics, such as sedimentary structures, indicate these outcrops to be the inner remnant exposures of a relatively large, ancient coastal alluvial fan (Palmasera fan) (Fig. 6a, b). The transversal section has width of 450 m (terminating to the northeast against basalt and to the southeast against carbonate bedrock, Figs. 2a, 6b), maximum thickness of 24–28 m, and a maximum remnant ~ 20 m thick-slice on the scarp-face (Fig. 6c). The longitudinal sedimentary sections along the flanks of the Rio Sos Dollores Codula are not as well exposed but have similar measurements with a length of 250 m (Fig. 2b).

The coastal alluvial-fan deposits **(F)** generally rest over a basaltic key-bed (B) composed primarily of rounded pebbles and large to very large, sub-angular to sub-rounded basaltic boulders and few carbonate ones (Figs. 6b, c, 7). This basaltic boulder bed overlies thinner layers (T) composed primarily of carbonate and minor basaltic openwork rounded and flattened pebbles, frequently imbricated. This in turn overlies a Late Pliocene-early Pleistocene fine to medium grained well rounded, openwork, fine stratified and well-imbricated clasts refereed to beach deposit (L) (Massari and Dieni ,1973). The T carbonate pebble layer and the basaltic basal B boulder key deposits are interpreted as beach deposits and referred to last interglacial highstand Marine Isotopic Stage (MIS) 5e (Sarria et al., 2016). These last occur now at about 6 + m above the present sea level.

The fan deposits **(F)** have similar characteristics throughout, such as poorly cemented sandy conglomerates dominated by carbonate sub-angular pebbles with local cobbles and isolated boulders (Fig. 7). Isolated basalt pebbles, cobbles and few boulders occur sparsely at different horizons. Most layers do not present preferred depositional fabric. Predominant sedimentary structures include definable bedding generally discontinuous and with erosional boundaries (Fig. 6b, c). Along the transversal section subparallel to the coast, slight accumulations of poorly sorted coarser material suggests either channeled or, if arcuate, overland deposits.

Vertical and lateral differences mainly related to changes in grain size and sedimentary structures, and the local presence of poorly developed/preserved, discontinuous palaeosols, contributes to a gross subdivision of the **F** deposits into four subunits: **F1, F2, F3** (Figs. 6b, c, 7). Along the transversal section, they are thicker near the codula and thin out to the northeast (Fig. 6).

Sub-unit F1 is exposed in the lower SW part of the Palmasera section. It has a pale yellowish brown color and is characterized by carbonate with scattered basaltic clasts deposits containing numerous cobbles and few disseminated boulders (Fig. 7a, b). It shows irregular, lenticular, thin- to medium-thickness beds of alternating cobble to coarse pebble conglomerate and of sandy pebble conglomerate, and few gravelly (fine pebbles) very coarse-grained sandstone. Some clasts layers are openwork or with very little matrix, (Fig. 7c). Carbonate clasts are prevalently sub-prismoidal to sub-discoidal, angular to sub-angular. Conversely, most of the basaltic clasts, except some of the largest boulders, are sub-rounded to well rounded (Fig. 7b, c). No definite grain size grading occurs within the beds, some have sub-discoidal clasts showing preferred imbrication (Fig. 7c). The beds are generally sub-horizontal to-slightly inclined (less than 10°), with sharp basal contact, flat in most layers, slightly concave upward in others indicating shallow cuts-and-fills (Fig. 7a, b).

Sub-unit F2 dominates the central part of the Palmasera section (Figs. 6b, c,). It has a pale yellowish brown coloration similar to **F1** and contains a predominance of sandy carbonate fine pebble to granule conglomerates, and pebbly very coarse-grained sandstone beds (Fig. 7a, d, e). The clasts are mostly of carbonate with minor basalt. It has a few isolated large clasts (up to boulders) (Fig. 7f). The beds have thin- to medium-thickness, thinning and lensing out toward the northern termination of the fan body (Fig. 6b, c). They generally have flat, sub-horizontal to slightly concave-up lower boundaries (Fig. 7a, d, e, f). Some shallow, wide cut-and-fill structures occur involving both gravelly layers and, at a smaller scale, sand/granule beds (Fig. 7g). A large slab of basaltic lava was emplaced in the central lowermost part of the **F2** sequence, indicating rockfall and sliding from an adjacent, still- or re-exposed basaltic scarp (Fig. 7d.

Sub-unit **F3** is a carbonate sandy and gravelly deposit with no (or rare) basaltic clasts. It is separated from F2 locally by few remants reddish palaeosol and it has a marked difference in structures (Figs. 6c, 7a, d). It has a predominance of thinner lensing beds with more numerous sandy interlayers, fewer cobbles and boulders of carbonate (Fig. 7a, d). The principal structures are shallow cannels, cut-and-fills, cross-bedding and laminar structures. Locally has also openwork pebbly gravels alternating with lenticular sandy laminas (Fig. 7g, h).

Depositional model

F1 clasts mainly deposited ad consequence of mega-floods and debris flow from the local coastal scarp filling large channels (Figs. 6, 7). Local channel flows (*cf*) and sheetfloods (*sf*) may develop as well as

(Fig. 7b, c). Most likely, the basalts and some of the carbonates boulders have been added to the inland-derived sediments by rockfall (*rf*).

F2 was not greatly affected by debris flows but by sparse channels and sheetwash (overland flow) flood events (Fig. 7e, f).

F1 and **F2** sub-units record the coarsest channelized flood deposits in both subunits. Fairly good palaeosols are clearly identifiable (Figs. 6c, 7a, d) suggesting time of inactivity. Furthermore the northeastern side of the Rio Sos Dollores Codula mouth (*T* of Fig. 6a) shows a sequential stepwise erosion of the original sequence and large carbonate boulders are found toward the center of the codula (Fig. 6a, b).

On the whole, **F3** structures are typical of a braided stream, perhaps with frequent channel migrations, erosions and overland deposits. In better, smaller exposures along the top accessible right codula section, debris flow, cross-bedding and other small scale structures and various types of vertical and lateral grain size sorting indicate predominance of relatively shallow channels and sheetfloods (*cf*) complex attributable to a braided stream (Fig. 7h).

The proposed depositional model where sheetwash (*sf*) alternate with channelized (*cf*) deposits in places resembling Ostler lenses (*Osl*) (Martini, 1973, Fig. 7g) is in agreement with erosion and sedimentation processes related to recurring strong floods.

On the whole the Rio Sos Dorroles (could have been very active in the past and, under appropriate climatic conditions, it may have acted as the filling-and-eroding system of a ‘deep valley’ and fed the frontal coastal alluvial fan.

Sediment source

The Pleistocene-Holocene deposits of Cala Gonone have a primary source in the coastal hills, have undergone different modes of weathering/comminution, and have been affected by various transport and depositional processes under different climatic conditions from glacial to interglacial periods with significant climatic fluctuations and variations of sea level.

Comminution of sediment to be transported downhill derived from the intensely fractured carbonates both at the macroscopic and microscopic scale and have a range of intercrystalline porosity (Lanfranchi et al., 2011). Intense solution has developed surficial structures, numerous karst caves as well as enlarged fracture porosity. Furthermore intense thermal, frost and salt-weathering should have occurred. (1) The rock-temperature variation (insolation variations) may lead to thermal stress, fatigue and thermal shock particularly in carbonates (Siegesmund et al, 2000). The rock may start to deteriorate, microfractures may enlarge, and the rock may exfoliate and comminution occurs. This may happen preferentially during hot and dry periods, but it has been observed also in other conditions including in Antarctica polar areas (Hall and Andrè, 2001). In the Mediterranean area it may have occurred throughout the ages, perhaps proportionally more significantly during warmer rather than colder and drier periods. (2)

Frost shattering is indeed a very efficient process in humid cold settings such as in Subarctic zone where numerous freeze-and-thaw cycles occur. Its importance drops off rapidly in the warmer zones. During colder Pleistocene periods the temperature of Sardinia may have been about 5 to 9 ^{o}C lower than the present as suggested by the estimated surface water temperature of Western Mediterranean Sea (Martrat et al., 2004; Pascucci et al., 2014) (Fig. 8). The costal hills of Cala Gonone received significant amount of snow and possibility of active freeze-and-thaw processes leading to fracturing of the weak bedrock carbonates into angular clasts. Traces of this happening are the produced nevee-like niches on the hills above the Stadium and Gustui fans. (3) Salt weathering is another process that leads to comminution of rocks as indicated by the deterioration of ancient monuments and observed in various environments including hot and cold desert areas and, routinely, in coastal areas (Goudie et al., 1997; Goudie, 2000; Hall et al., 2002; Hartley et al, 2005). As water (liquid or moist transported by winds and fogs penetrates into the rock pores, it carries dissolved salts that can precipitate as drying occurs because of evaporation or cooling. Weathering may act through primarily crystallization pressure and thermal expansion, osmotic pressure and chemical weathering. Repeated cycles of crystallization and solution of soluble salts within the pores lead to damage and comminution of the rocks (Coussy, 2006; Ruiz-Agudo et al., 2007). Salt weathering contributes with the other types of weathering to the breakdown of the carbonate rocks of the coastal ridge of the Gulf of Orosei forming in time considerable amount of transportable sediment in the hilly source area.

Basaltic megaclasts and boulder- to pebble-sized clasts are secondary constituents of the deposits of Cala Gonone. They derive from rockfalls from the local Plio-Pleistocene basaltic lava of the area. Some clasts have been reworked and partially rounded of by stream and coastal wave flows. Others maintain they native angularity.

Sediment transport and timing

Similarly to other world areas, various transport and sedimentation processes can be invoked for the colluvial and alluvial fans of Cala Gonone. Some of them are azonal, such as slump, rock fall, debris falls, debris avalanches, debris flows (cohesive and non-cohesive), hyperconcentrated to high-density flows, and fluid flows (water and wind) (Bertran et al., 1992; Blikra and Nemec, 1998; Nemec Kazanci, 1999; García-Ruiz et al., 2001; van Steijn et al., 2002; van Steijn, 2011). Most of them require water in some form to perform. When in quantity, water actively increases the weight of the sediment and passively reduces the friction and cohesion between the particles or layers favoring mass movement on slopes (Lorenzini and Mazza, 2004). In central-east Sardinia occasional extreme rainfall events have ben experienced pouring in a short time, order of few hours or day, large quantity of water, order of 500 mm in in few hours (Cossu et al. 2007), leading to debris flows, channel floods and overland sheetfloods (Bodini and Cossu, 2008, 2010a, 2010b; Betro et al. 2008; Hewson et al., 2021). The composite Stadium and particularly Gustui fan systems are dominated by remnants of debris flows heavily reworked by sheetfloods close to the feeding valley and upper part of the fan. The sediments were, however, mostly redistributed by sheetfloods and channelled flow over the mid-lower portions of the fans, and contributed to the feeding of the coastal alluvial Palmasera fan. Other sediments transported by stream to the south of the Stadium fan contributed to those funneled through the Rio Sos Dollores Codula into the coastal fan. Additional coarse carbonate and basaltic clasts were added to the coastal fan as rockfall from the open coastal scarp. The codula acted as a deep narrow valley filling up and feeding repeatedly the coastal fan that was totally or in part eroded and reformed during upper Pleistocene recurring sea level oscillations occurred.

The relatively low costal carbonate scarp partially capped by basaltic lava could not have supplied sufficient amount of material to form the deposits of the coastal alluvial fan (**P**). Such deposit can, thus, be considered an extension of the inland upper valley and of the alluvial-fan aprons including the Stadium and Gustui ones. A complex waterway system may have conveyed floodwaters and sediments from the carbonate highlands directly to the inland talus and alluvial cones and reworked material funneled through various passages to the most important channel, being the Codula Sos Dollores (Fig. 2b). Such codula area may have been a lowland partially filled by lava in early Pliocene, later eroded into a narrow deep coastal valley. At the present, the codula starts about 250 meters inland and its sequential excess infilling led to the development of the Palmasera coastal alluvial fan (Fig. 8a). The development of such fan would have occurred primarily during period of major climatic changes that led to variation in sea-level and to periods of intense precipitation and floods. Quiescent times or temporarily inactive areas of the fan led to the formation of palaeosols.

This coastal system seems to have several times repeated deposition mainly during sea regression, and erosion of the fan during sea transgression. Evidence of this has been preserved in the remnant deposits along the coastal scarp at the present sea level. It has not been yet possible to obtain reliable numerical dates from the **F** carbonate deposit. Dates available in the area are limited to a $pIRIR_{290}$ age of 87 ± 4 ka of putative basal paleosol at the base of the Palmasera fan (Fig. 6c). The paleosol separates Eemian MIS5e (about 136 – 116 ka) beach **B** from fan **F** deposits. The fan deposits in their central part completely erode those of the beach. It has to be noted that same paleosol, however, has also been dubiously dated at 19—17 ka using ^{14}C (Coltorti et al., 2010; Thiel et al., 2010). This age is probably affected from contamination having been sampled in a site reached by modern storm wave. Comparable ages have been derived in the close by Bure Marino Cave where a colluvium filling a tidal notch scour, referred to MIS 5e (Carobene and Pasini, 1982) has been $pIRIR_{290}$ dated to 86 ± 4 ka (Andreucci et al., 2017).

This age uncertainty had led to two interpretations of formation of the Palmasera coastal fan outcrop.

1. The basal palaeosol is indicator of the change from interglacial to glacial conditions and the other palaeosols of the successions of climate oscillations occurred during the glacial time.
2. The coastal fan sequence formed during climate deterioration occurred post Eemian; that is post 116 ka.

The first hypothesis (our preferred) is in agreement with reconstructions made in other places of northwest Sardinia in Alghero (Andreucci et al., 2010) and Argentiera (Andreucci et al., 2014; Pascucci et al., 20014) (Fig. 8a), whereas the second was the preferred interpretation of Massari and Dieni (1973) based on the regional geological analysis of the area.

If Cala Gonone alluvial fan developed during the cold post MIS5 glacial stages, it is possible to hypothesize that most of the material available for the fan was formed during repetitive periods of cold and dry and transported during the more wet and humid. In this case, the Cala Gonone alluvial fans may have started to form during MIS4 and reached their maximum activity during MIS3 when repetitive high frequency warm and cold cycles (Dansgaard–Oeschger and Henrich events, Rahmstorf, 2003) occurred. Thus, fans could be related to Unit 4 and 5 of northwest Sardinia. In the Argentiera area (NW Sardinia), water dominated MIS3 deposits (alluvial fan) are associated to Dansgaard–Oeschger interstadial events when warm and humid conditions occurred, while wind dominated deposits (aeolian) to cold and very dry stadial conditions (Heirich events) (Pascucci et al., 2014) (Fig. 8b).

Natural Hazards And Risks

The processes involved in the generation of loose sediments and then transport and deposit them in fans have been long studies under several climatic zones. The basic processes are generally similar although the result may vary for flood dominated, debris flow dominated or mixed alluvial fans (Harvey et al., 2016). Great effort is made globally to recognize the hazards and the risks of alluvial fans and possible remediation, if necessary. Much information on the occurrence of disasters is available and good guidelines have been written for detailed surveys of the landscape, taking also account of climatic and geological/geomorphological conditions (such as structure, stratigraphy, sedimentology, numerical dating procedure and geotechnical characteristic of the bedrock and sedimentary deposits). Geotechnical and other scientific analyses can help in establishing any probable recurrences and intensity of events. Guidelines and specifications for flood hazard mapping in papers, books and reports (Fema, 2000, 2021; Lancaster et al., 2015; Da Silva Nascimento and Alencar, 2016). Lancaster et al. (2015, p.1) stressed the geological approach to "*identify the general distribution of alluvial fans, the relative age of alluvial deposits, and the relative likelihood of alluvial fan flooding*". Extending this approach to the sedimentological and numerical dating of the deposit also allow the analysis of long dormant fans that could be revived under changed climatic condition such as the high frequency Dansgaard–Oeschger or Henrich similar events. In addition, the short intense meteorological events nowadays increasing the frequency of extreme short-lived rainstorm.

How does all this apply to the Cala Gonone area? The Cala Gonone village is expanding on an inland mixed dormant alluvial fans down to the brink of the coastal cliff coated with residual conglomerate remnants of the coastal fan (**P**), subject to persistent sea wave erosion (Figs. 2b, 9a, b).

Cala Gonone historically became a small harbour for Italian fisherman at the beginning of 20th century but remained isolated from the rest of Sardinia because of the impervious high costal hill barrier. In 1860 a small walking tunnel for people and animals was perforated near of the saddle between the Mt Tuli and Mt Irveri. As the village prospered, particularly for the recent touristic explosive increase, modern motorvehicle tunnels were open along the road to Dorgali on the northwest flank of the coastal hill barrier (Fig. 2a). Cala Gonone is now a preferred touristic area for the magnificent landscape. Beach and hill places and various permissible activities such as unusual canyoning, climbing, paragliding, and all other activities offered by pleasant touristic resorts.

All this happened despite the hazards facing the area. The municipality of Dorgali (to which Cala Gonone belongs) has provided a detailed survey of the landscape of the area determining the best use of the land. Recognition of the various existing natural hazards, risks, and in recommending operas that are continuously attended to. Extensive reports and maps on the methodology used and the observations and recommendations made have been written and available at https://www.comune.dorgali.nu.it/area-tecnica/attivita-e-servizi/piano-di-protezione-civile.html, including the hydrogeological risk map (Fig. 9c). These reports, however, seem to be more addressed to rockfalls (Hg3 and Hg4, Fig. 9c) from the nearby high cliffs than to potential flood of the village (Hg1, Fig. 9c). In Cala Gonone the conditions of potential instability are, instead, numerous. In particular, the areas close to Rio Ischirtiore, the adjacent coast, the beaches of Palmasera and Sos Dorroles Codula mostly classified as minor Hg1 risk (Fig. 9c).

Floods risks

Streams such as those flowing at Cala Fuili and Luna (Fig. 3b) and in more coves along the coast south of Cala Gonone, are potentially flooding systems. These flooding streams pose significant hydrologic hazards, however not much potential high risk because they flow in scarce populated areas. However more ominous hazard exist from the sediment mass wasting and channel floods and sheetfloods along the numerous streams flowing from the hills transporting in the past the sediments to the Stadium (**S**), Gustui,(**G**) and coastal Palmasera alluvial fans (**P)** (Fig. 3). They have also left braided stream traces across parts of the village (Fig. 7h), and they are likely to reoccur in an unpredictable intensity and time. Their happening is sudden, of short duration, unpredictable, and associated to mega-pluvial events. This greatly damaging processes may have a centennial or millennial recurrence. Nevertheless, considering that warming climate is still going on, attentive warnings and remediation, in little part already initiated, should continue. Extreme weather, such as floods, heatwaves, droughts and storms have been a recurrent phenomenon in Sardinia during the past decades. Moreover, cyclones (i.e. Cleopatra Niedda et al., 2018) and high-intensity flash floods are becoming normal occurring events (Amponsah et al., 2018). In addition Cala Gonone is also affected by problems associated with global sea-level rise. The main effect of this is the erosion of coastal beaches and collapse of the remnant sedimentary slices of the ancient coastal fans from the frontal Palmasera scarp. Here the village modern habitations have been built near the cliff-top brink at the northeastern fan termination against a basaltic lava flow to about sea level (Fig. 9a, b). The habitations have started to show structural weaknesses and they are likely to experience increasing damage as the conglomerate will continue to be removed and eventually even if the most exposed basalts may collapse as well. This process has been temporarily remediated by an extensive replenishment of the beaches in late 1990s (Fig. 9d, e) (Pranzini and Mania, 1996) The replenishment has added a great touristic beach attraction and significantly reduced wave erosion damage of the coastal cliff of the Palmasera village. The effort of maintaining a good beach needs to be attended together with a good, watch for the persistent hazards of continuous rockfall and slumps from the scarp (Fig. 9d).

Conclusions

Pleistocene to Recent sedimentary deposits like those associated with rocky coasts of the Gulf of Orosei have a scarce to nil probability of preservation in the geological record. Their sedimentological studies have still intrinsic scientific and practical values emphasizing the complexity of the sedimentary facies (events) that have developed reflecting the influence of multiple processes in different parts of the systems under different climatic conditions. There is a tendency to create manageable, simple, useful models of systems for colluvial and alluvial fans. They are, however, complex features of our landscape, which need to be understood also sedimentologically to contribute effectively to landuse safe-keeping and sensible future development planning. Sedimentary deposits contain a record of past environmental conditions and events and can aid in predicting potential future happening as the climate changes. Much is known about the present environment of the coast of the Gulf of Orosei and of Cala Gonone area in particular. The detailed study of the deposits can aid further in establishing here and elsewhere the existence of potential hazards that, although associated with low recurrence events such as sheetfloods, may be very damaging to communities. Once the degree of risk is established, a good, well informed resolution can be made on future developments and what precautions could be opportune to take, if any, and what possible remedial action may be needed.

A good survey of the landscape was done for the Dorgali/Cala Donone area in early 2000–2018 including standard geological and geomorphologic features, but not including the climate, as possible increase in “recurrence” due to “extreme rainfalls”, and not examining the interesting and common interrelations between the volcanic eruptions/lava flows, the “deep valley” Sos Dollores codula, the Palmasera alluvial system, the pulsating sea level, and lately the refurbished beach of Palmasera in particular.

Cala Gonone is a small typical recently developed site waiting for something to happen, perhaps in hundred to thousand or more years (?) depending on future climatic changes. Hazards are shown to exist there and to have recurred from both the inland alluvial fans and along the coast by erosion due to rising sea level. Some local remedial work would be advisable.

Declarations

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Tables

Table 1 is available in the Supplementary Files section.

Figures

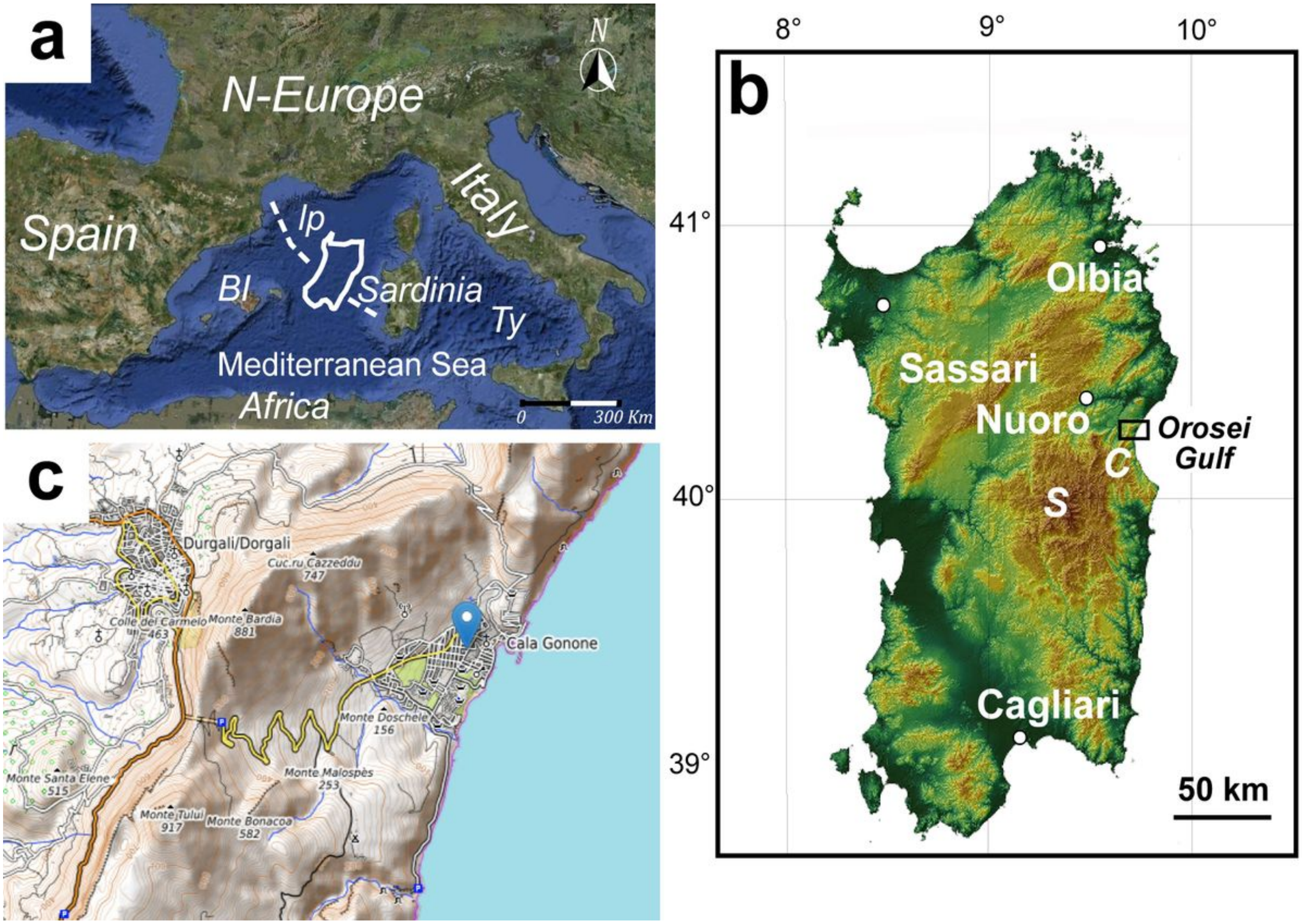


Figure 1

Study location at Cala Gonone, northeastern Sardinia. **a)** Satellite view of the Mediterranean region where Sardinia occupies a central position. Dashed line indicates the Sardinia anticlockwise rotation occurred in the Neogene time; **b**) Digital terrain model of Sardinia; in the map are reported the main cities. With C is indicated the area close to Cala Gonone, with S the high mountains (up to 1800m) in the centre of the island that make a barrier to the east coming winds. In the square the studied area of Cala Gonone presented is in the frame; **c**) The studied site of Cala Gonone (belonging to the municipality of Dorgali) located in a coastal terrace at the base of steep mountain flanks (image from road map of Google Map). Abbreviations: BI=Balearic Islands; lp= Liguro-Provençal Basin; Ty=Tyrrhenian Sea.

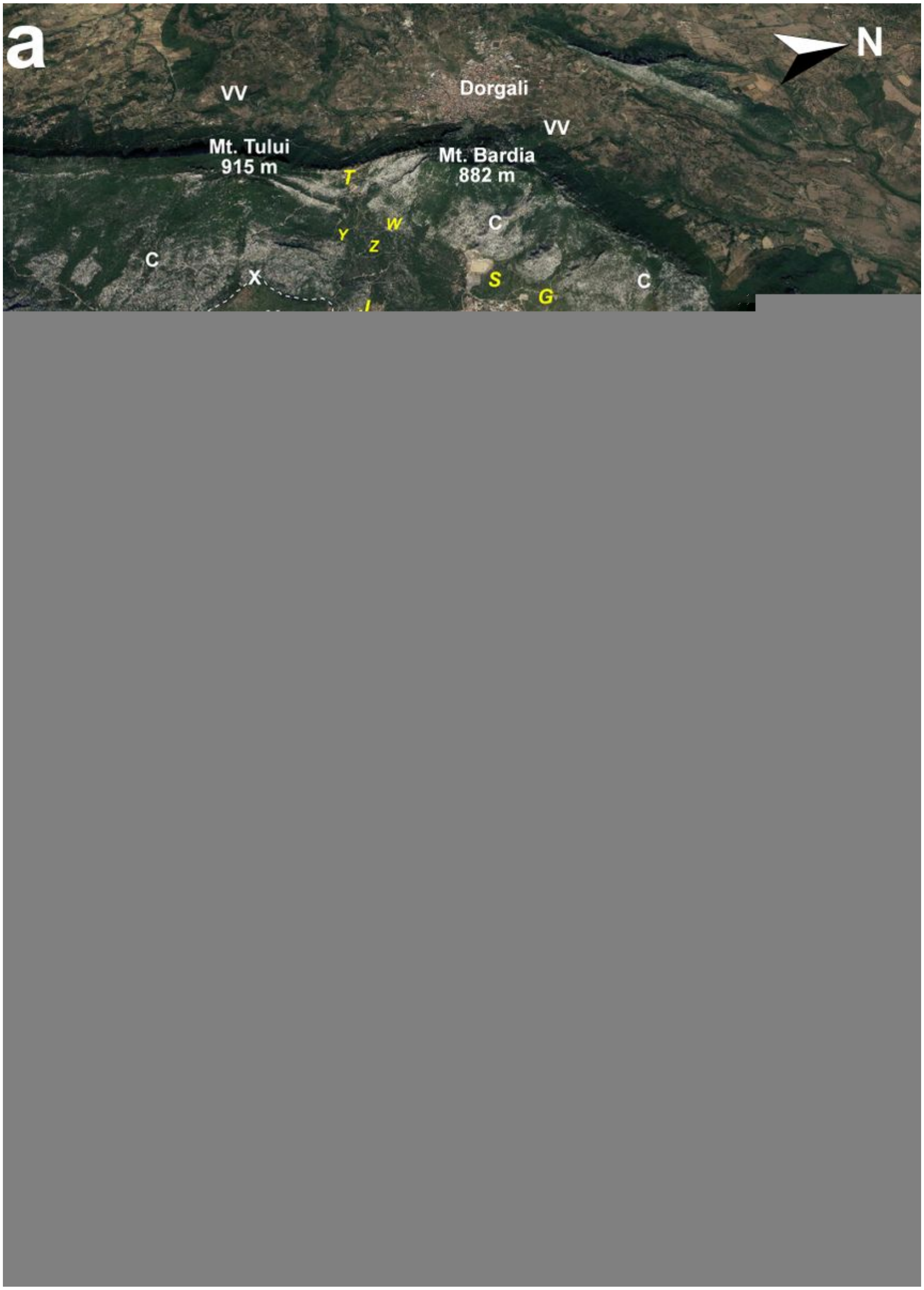


Figure 2

Cala Gonone area. **a**) Major morphological features and localities studied; **b**) Detail of the Cala Gonone surrungind area. **C**: Mesozoic carbonates; **V**: uppermost Plio-Pleistocene basalts; **VV**: Palaeozoic to Pleistocene volcanics; **X**: Plio-Pleistocene volcanic vents; white dashed line are indicated the boundary of lava flows; **I**: Narrow Irveri—Bardia valley; ***S***: Stadium alluvial fan; ***G***: Gustui alluvial fan; ***T,Y,W, Z, J***: outcrops of residual parts of talus deposits in the inland higher valley of Cala Gonone mostly visible along the road SP26 (these are the *éboulis ordonnées* of Ozer and Ulzega, 1981); **P**: coastal Palmasera alluvial fan system;; **M*N***: Nuraghe Mannu; ***NA***: Nuraghe Arvo; **ir**: Rio Irveri; **sd**: Rio Sos Dollores Codula; **is**: Rio Ischirtiore (Google Earth images).

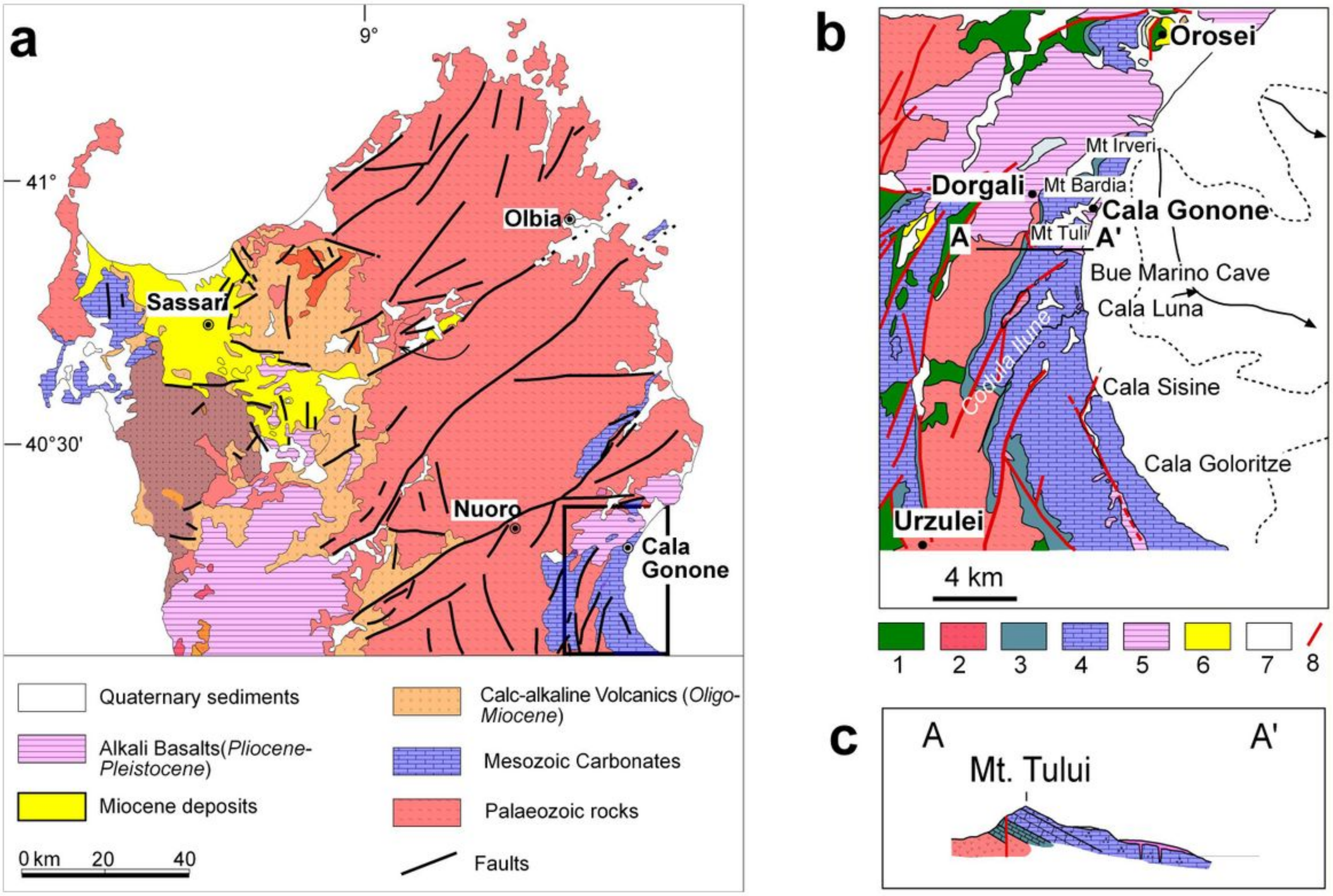
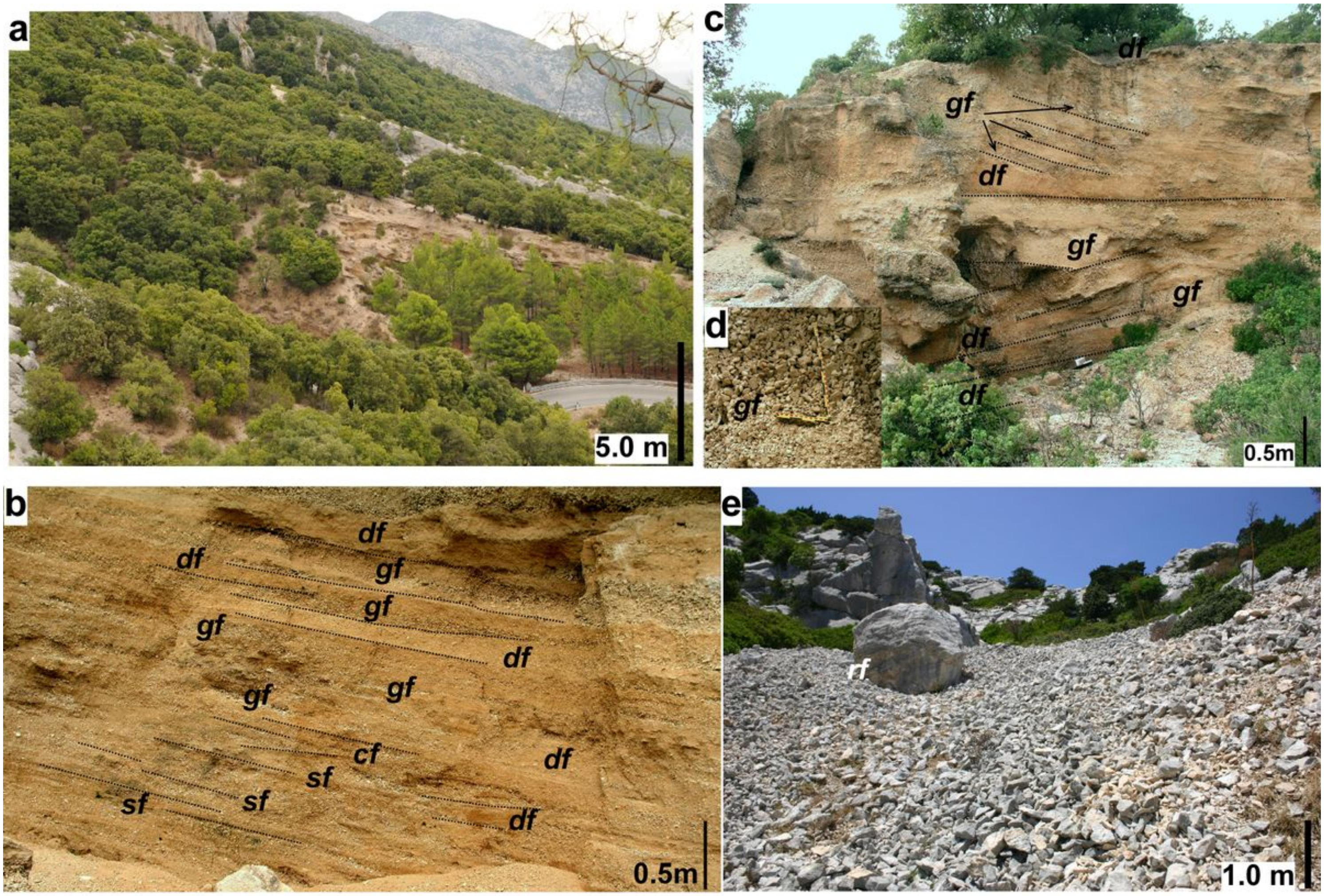


Figure 3

Geology of north Sardinia. **a**) Simplified Geological map of the north-central part of Sardinia; **b**) Geological map of the Cala Gonone area 1-Palaeozoic metamorphic rocks; 2-Late Palaeozoic granites; 3-Jurassic dolostones; 4 Jurassic-Cretaceous limestones; 5-Plio-Plesitocene basalts; 6-Plio-Pleistocene sedimentary deposits; 7-Late Pleistocene-Holocene deposits; 8-Faults; dashed line indicate -50m water depth, solid lines with arrows the two main canyons developing in front of Cala Gonone and Orosei (after New Geological map of Italy 1:50,000 scale – Foglio Nuoro Est, available at: https://www.isprambiente.gov.it/Media/carg/500_NUORO_EST/Foglio.html); **c**) Cross-section of the Mt. Tului area (location is in Fig. 3b), (after Lanfranchi et al., 2011).



A

Figure 4

Greze litée (upper fan system) between Mt Tuli and Mt Bardia. **a**) General view of the well stratified, steeply dipping deposits in the foreground, dipping Jurassic carbonate layers in the background; **b**) Typical internal stratification the deposits with indication of principal facies (*df*: debris flow to hyperconcentrated flow, *gf*: grain flow, *sf*: sheet-wash/flood), **c**) Gully filled primarily with mass flow deposits (*df*: debris flow *gf*: grain flow); **d**) Detail of grain flow layers, note the openwork framework and the inverse (coarsening upward) grading; **e**) Debris accumulations composed of heterometric, angular carbonate cobbles and pebbles with some isolated boulders (Higher-slope colluvial fans, Mt Iveri).

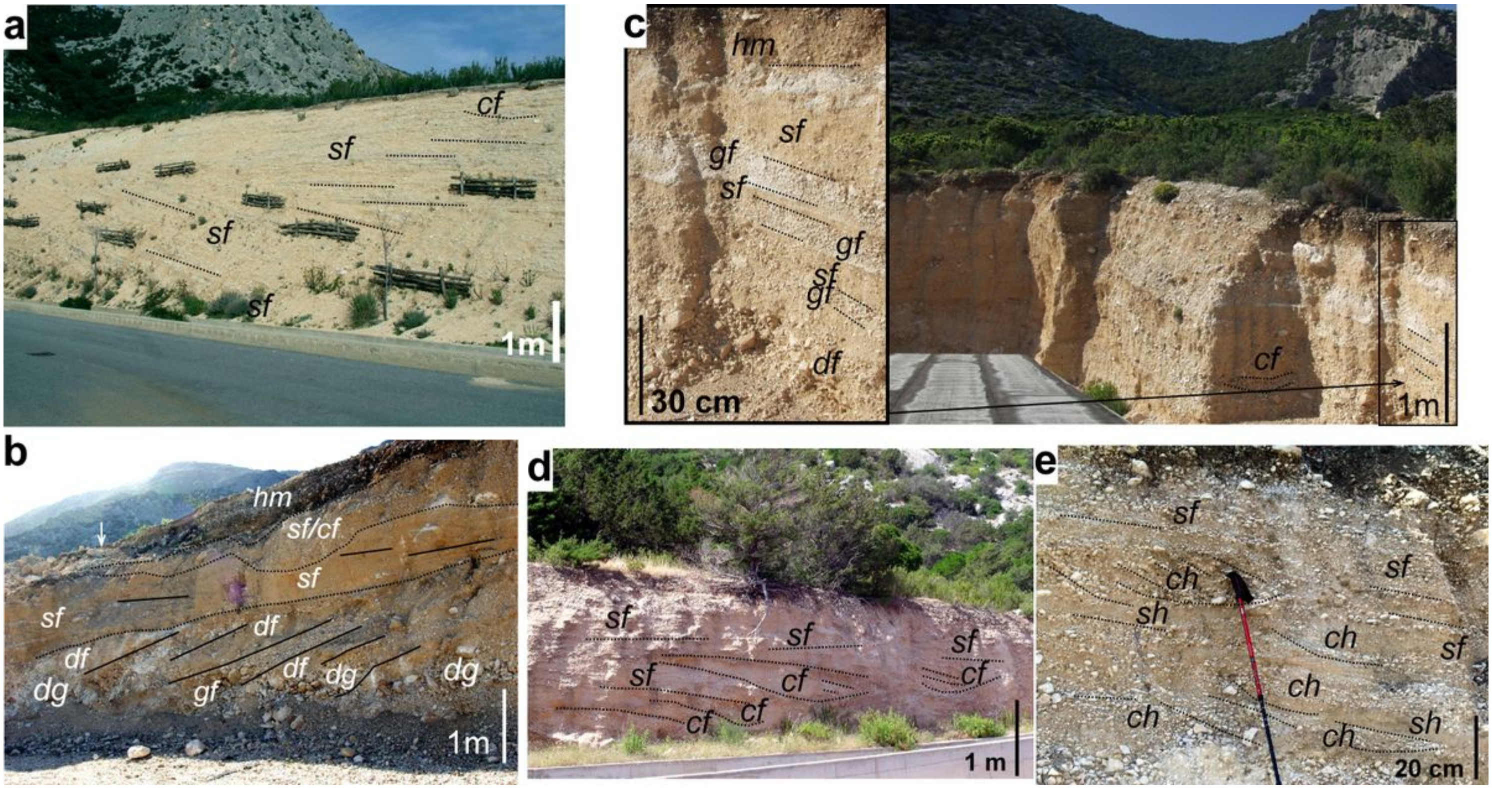


Figure 5

a) The quasi-longitudinal (section **S1**) of the Stadium alluvial fan near the fan apex shows two superimposed systems with different dips mostly characterized by sheetflood deposits; **b**) General view of a deep-gully/flank at location **G2** (Gustui fan) showing three units; (i) a basal one dominated by debris flows (*df, dg*), (ii) an intermediate one dominated by sheetflood (*sf*), and (*iii*) top one with sheetflood (*sf*) and channel flow (*cf*) but heavily modified by man (*hm*). Everything is capped by modern soil. **c**) Shallow longitudinal and transversal sections at location **G1** characterized by a quasi-rhythmic deposits of sandy, fine pebble conglomerate alternating (*gf*) with coarse grained sandstone to sandy granule conglomerate locally laminated (*sf*); **d**) Transverse outcrop in middle part of the Gustui Fan. North-eastern tail end of the alluvial fan characterized by reworked by sheetflood (*sf*) and channel (*cf*) floods. overlain by rock-fallen from the near carbonate bedrock; **e**) alternate of sheetflood (*sf*) and channel flows (*cf*). Walking pool for scale (1.2m).

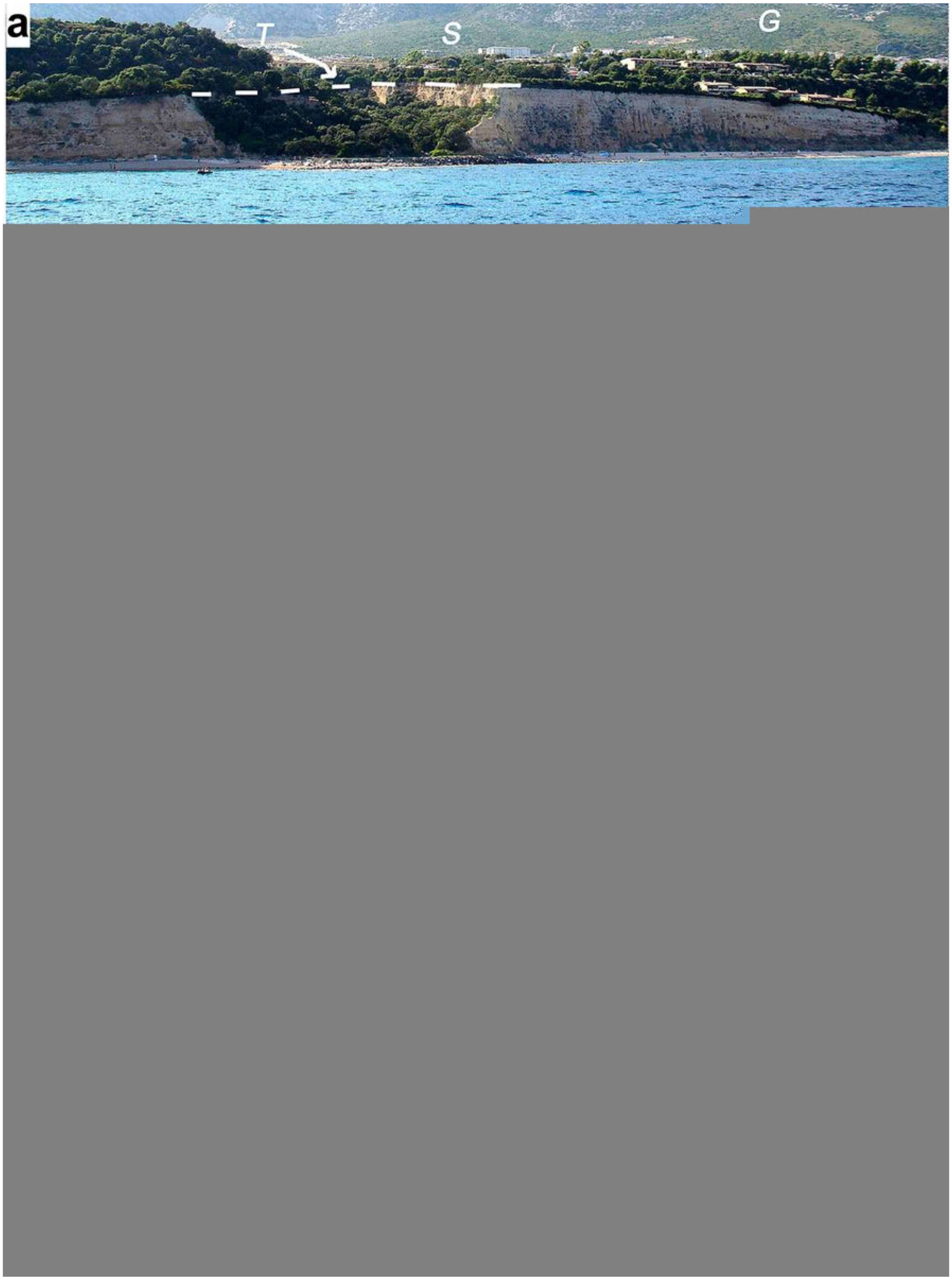


Figure 6

Sedimentary deposit of coastal alluvial Palmasera fan close to the namesake village (**a)** Longitudinal view of the Palmasera alluvial fan complex. T=transversal section along the Sos Dorroles Codula mouth; S=Stadium fan, G=Gustui fan; **b**) Subdivisions into lithostratigraphic units (arrow indicates the direction of the flow of the ephemeral stream of the Sos Dorroles Codula). 1-7 logs location; **c**) Schematic logs (1-7) of stratigraphic sections of the exposed fan with tentative litho-subdivisions **B**: basaltic boulder key-bed; **F:** 1, 2, 3: subdivision (subunits) of the fan; **L**: siliciclastic beach/coastal deposit; **T**: remnants of carbonate and basalt, pebble to cobble beach deposit; **V** basalts.

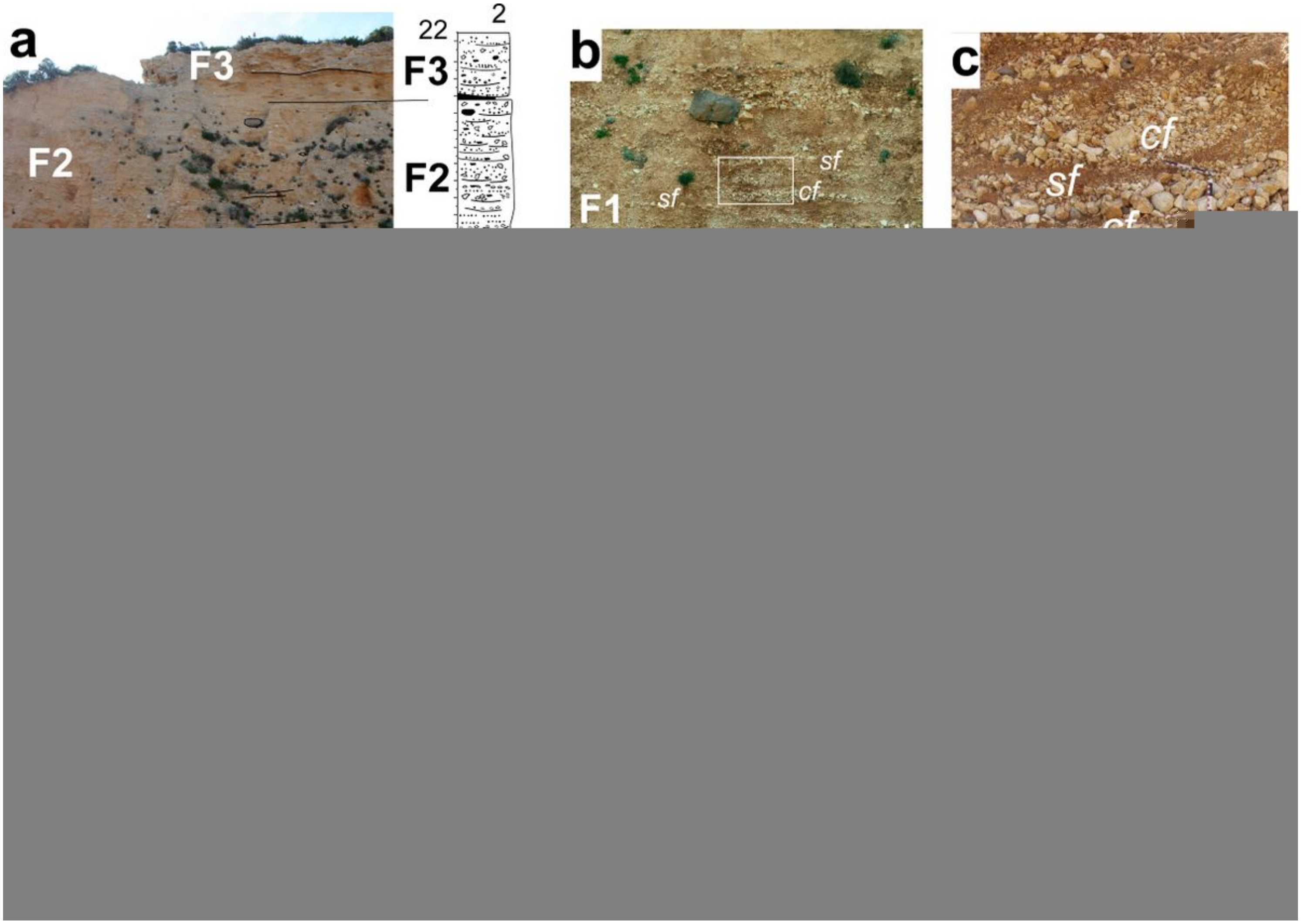


Figure 7

a) View of the alluvial fan at log 2 (Fig. 6b, c) showing the vertical transition between the various units (**F1** to **F3**); **b) F1 unit:** alternate beds of cobble to coarse pebble conglomerate and of sandy pebble conglomerate made of sheetflood (*sf*) and channel flow (*cf*); **c**) Detail of the structure of sheetflood and channel flow of **F1 unit**; **d**) View of the alluvial fan at log 5 (Fig. 6b, c) showing the vertical transition between **F2** and **F3**; **e**) Overall fining upward of **F2** deposits and the thinner lenticular layers of **F3**; **f)** sheetwash (overland flow) events of **F2 unit**; **g**) **F3 unit**: alternate of channel (small braided-like channels) and sheet flood; **h)** Details of conglomeratic sandy layers in a slightly diagonal section of **F3** small outcrop showing a basal poorly sorted flood sandy pebbly deposit overlain by sorted, openwork, sandy gravels channel (*cf*). This is in turn overlain by fine pebble, granule in thin discontinuous lenses related to sheetflow (*sh*) with Ostler lenses (*Osl*).

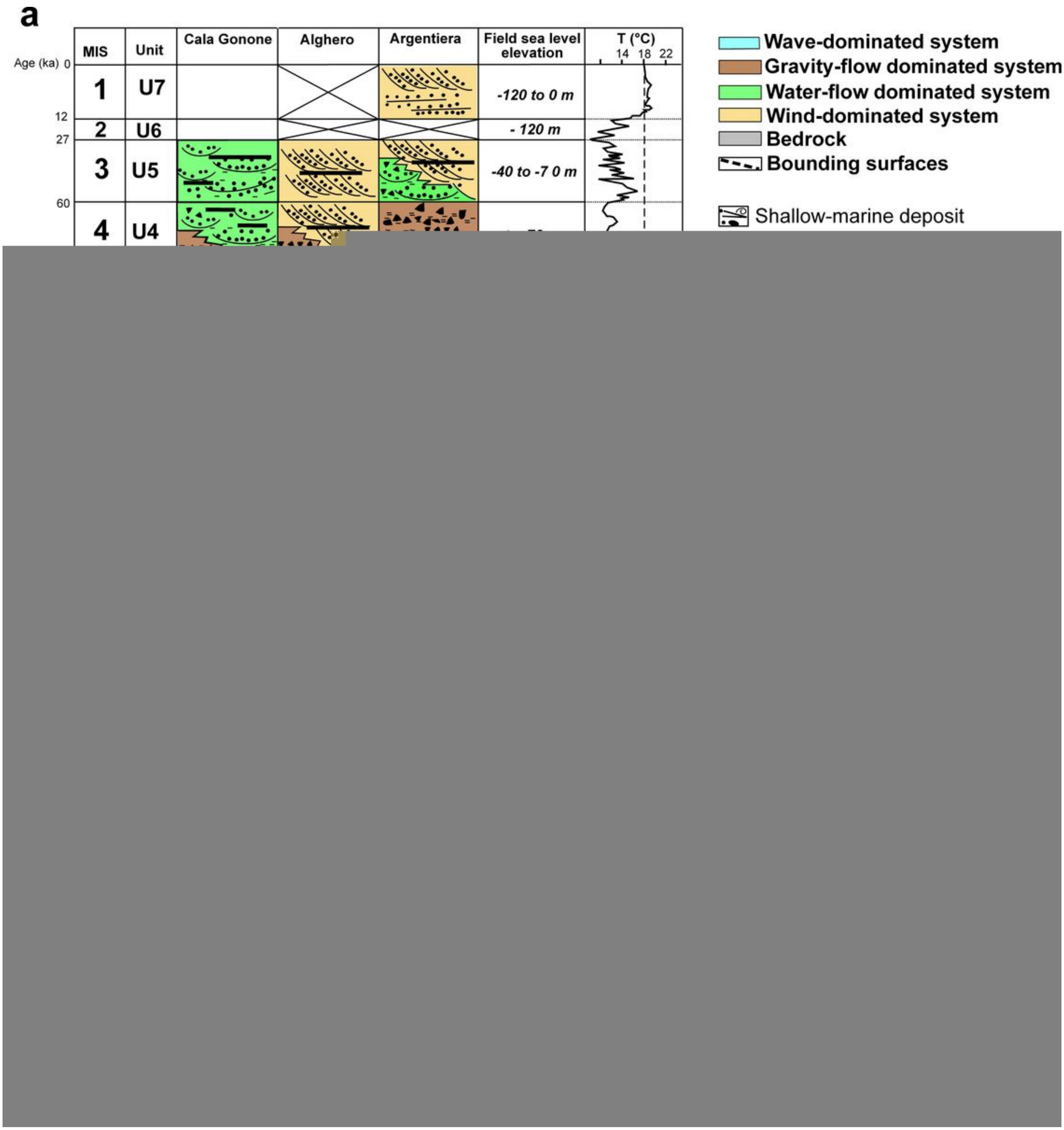


Figure 8

a) Relationships between the Cala Gonone alluvial fans and late Quaternary deposits of northwest Sardinia. Deposits are grouped in eight unconformity bounded units. Units cover the last 300 ka. Few data exist to make precise considerations of units deposited before 130 ka. These, however could be more confidently done from the last interglacial up to the present. In the right columns are reported the estimated sea level elevations and temperatures from Marine Isotopic Stage 5 (MIS 5) to MIS1 as derived from the work of Pascucci et al. (2014). Estimated paleotemperature are from Martrat et al. (2004).

b) The GISP2 ice core climate record from MIS3 to MIS1 (last 50 ka). The climate fluctuations are expressed in $\delta^{18}O$. Dansgaard-Oeschger warming events are labeled with red dots. The grey vertical lines show 1,470-year spacing, small numbers at the bottom count the number of 1,470-year periods from DO event 0. In green and red solid lines are reported the ages and type of deposits cropping out at Argentiera (NW Sardinia). (Modified after Rahmstorf, 2003 and Pascucci et al., 2014).

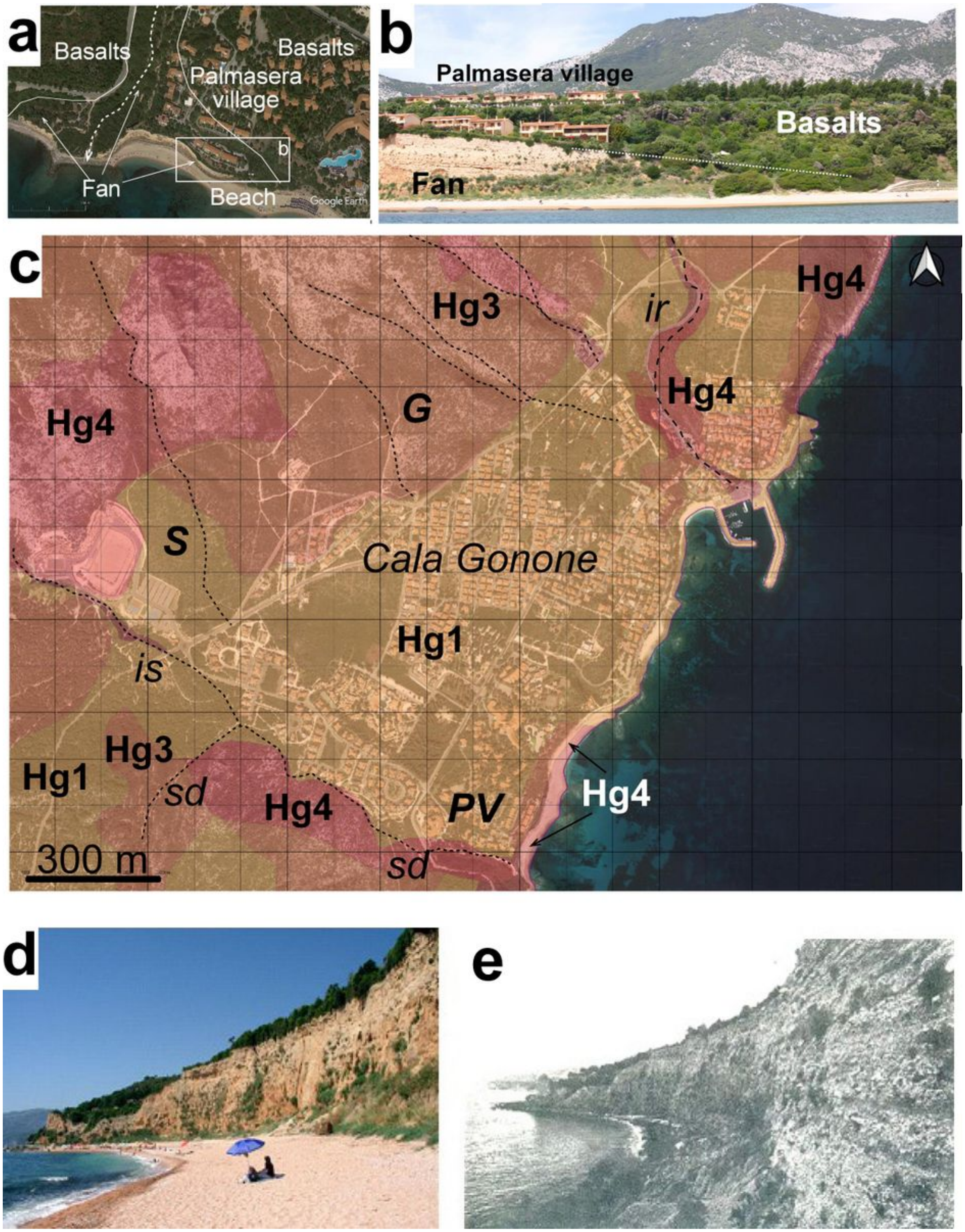


Figure 9

Coastal hazards in the Cala Gonone area. **a**) Satellite view of the terminal part of the Palmasera alluvial fan in front (and under) the Palmasera village. **b**) Houses dangerously built near brink of coastal cliffs on the northeast termination of the fan; **c**) Flood risk in Cala Gonone area: Hg1 low, Hg2 medium, Hg3 high and Hg4 very high. The map takes more in consideration the hazards related to rockfall than potential floods of the Rio Irveri (ir), Rio Sos Dollores Codula (sd) and Rio Ischirtiore (is) (Modified from the 2010 report on Piano Urbanistico Comunale (PUC) of Dorgali Municipality). Stadium (***S***) and Gustui (***G***) alluvial fans; **d**) Modern Palmasera beach replenished with granitic sand in mid 1990s, which in part protect from erosion the remnant Palmasera cliff. Note at the beach inner edge the presence of slumps and rockfall; **e**) Early 1990s Palmasera beach and conglomerate cliff undergoing to significant erosion. Note the persistent rockfall hazard in both views (after Pranzini and Mania, 1998).

Supplementary Files

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- MartiniPascucciTable1.jpg