1 POSTGLACIAL DEFORMATION HISTORY OF SACKUNGEN ON THE NORTHERN SLOPE
2 OF PIC D'ENCAMPADANA, ANDORRA (manuscript v.4; 08-JAN-2019)
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7 **ABSTRACT**
8 The northern slope of Pic d'Encampadana descends steeply 800 m down into the glaciated
9 Valira d'Orient Valley of Andorra, in the eastern Pyrenees. This high, steep slope is underlain by
10 foliated metamorphic rocks (slates, phyllites) and has long been known for its numerous
11 antislope scarps (sackungen), indicative of deep-seated gravitational slope deformation
12 (DSGSD). We excavated trenches across antislope scarps and their adjacent troughs at three
13 locations, to expose the trough stratigraphy, to map and date the deformation structures, and to
14 infer slope kinematics at each location. Sackung troughs formed at Encampadana have acted
15 as sediment traps since formation, and are underlain by distinctive post-faulting strata that
16 permit reconstructing the evolution of the scarp/trough pair. The oldest strata exposed in our 2-
17 2.5 m-deep trenches are coarse, angular talus deposited as slope-mantling sediments predating
18 the modern narrow sackung scarps and troughs. These deposits have been disrupted by normal
19 and reverse faulting, with the largest fault zone underlying the antislope scarp and dipping into
20 the slope at 40°-80°. Each trench contains subsidiary north-dipping normal faults beneath the
21 southern edge of the trough, giving the appearance of a graben. In two of three trenches post-
22 faulting deposits have subsequently been tilted or folded down toward the main fault, as if
23 sagging into a void space created by horizontal extension and/or outward toppling of the
24 footwall. The trough fill is generally dominated by poorly-sorted sandy slopewash, but does
25 contain two other important facies: (1) thin clay and silt deposits deposited in standing water,
26 found beneath the center of the trough, and (2) gravelly scarp-derived colluvial wedges, found
27 beneath the edges of the trough. Paleosols have formed on the top of fining-upward sequences
28 of strata, permitting interpretation of several cycles of: (1) episodic downdropping along graben
29 faults and deepening of the topographic trough, (2) filling the trough with marginal colluvial and
30 axial sag-pond sediments, followed by (3) a hiatus of soil profile development. Despite their
31 shallow depths, each trench preserves evidence of multiple unconformities and 3 to 5
32 deformation events, recognized by: (1) upward termination of faults at various stratigraphic
33 levels; (2) angular unconformities between trough infill units or fining-upward packages; and (3)
34 by coarse, angular colluvial deposits that thin away from the footwall (scarp-derived colluvial
35 wedges). The average time between deformation events in any one trench in the past 12-15 ka
36 is about 3-3.5 ka. Deformation seems to have begun first in the lower part of the northern slope
37 (Trench 2, 1935 m elevation) about 15.3 ka, and had spread to the upper parts of the slope
38 (Trench 3, 2320 m) by 11.6 ka. Deformation in the lower slope ceased after 5.5 ka, but still
39 continued higher on the slope into the mid-late Holocene. The youngest deformation dated (1.4-
40 1.6 ka) occurred in the highest trench on the slope. This pattern of younger deformation with
41 increasing elevation has been documented at several other sites (e.g., Panek and Klimes, 2016)
42 and has been ascribed to an upslope-migrating extensional stress field which originated at the
43 base of the slope from glacial oversteepening and end-glacial debuttressing.
44

1. Introduction

The formerly glaciated valleys of Andorra, like valleys elsewhere in the Pyrenees, display abundant landforms attesting to post-glacial rock slope failure (Jarman et al., 2014). In the Valira d'Orient (Fig. 1) a large trunk glacier has eroded a U-shaped valley in multiple Pleistocene glaciations to a depth of 600 m below the global Late Glacial Maximum (LGM) trimline. The valley walls in central Andorra are composed of relatively weak, foliated Paleozoic slates and phyllites, similar to those studied by Zischinsky (1966) in his classic early paper about sackungen.
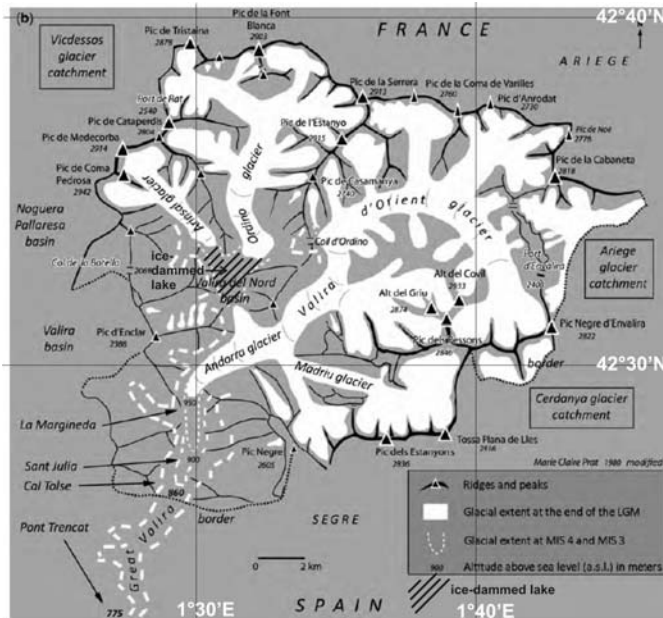
Fig. 1. Late Pleistocene ice extent at the end of the global Late Glacial Maximum (LGM) in Andorra, in relation to the Encampadana study area (box at center; also the area of Figs. 4 and 6). Canillo village is located at the NW corner of the box. Adapted from Turu et al, 2016.

This combination of deep valleys, steep valley sidewalls, weak foliated rocks, and moderate precipitation (1100 mm/yrin Canillo village)has spawned a wide spectrum of postglacial slope failures, including (in order of increasing size) slumps, earthflows, rockslides, and deep-seated gravitational slope deformation (DSGSD). This study focuses on the well-known DSGSD landforms on the northern slope of Pic d'Encampadana, which lies directly west of the GrandValira – Soldeu ski resort (Fig. 2).

Figure 2. Overall view of the northern slope of the Encampadana massif (center) looking East, with Pic d'Encampadana (2472 m) at upper right and the Valira d'Orient (1561 m) at lower left. The steep forested slope at center contains the studied sequence of approximately 10 antislope scarps (which can be seen as small nicks in the skyline profile) and our three trench sites.


2. Geological Setting

Geologically the Encampadana massif is located in the Central-Eastern part of the Pyrenean Axial Zone. The geology of the Central Pyrenees was described by Hartevelt (1970), Zwart (1979), and Barnolas and Chiron (1996). The massif belongs to the synclinorium of Tort-Casamanya which is arranged in a E-W direction. The bedrock of the study area is composed of rocks of Paleozoic age (Silurian to Mid Devonian). An updated summary of the composition and stratigraphy of the geological formations outcropping in the massif is provided by Clariana (2004) and references therein.

The stratigraphical succession in the Encamapadana massif includes the following materials:
 (i) Cambro-Ordocian rocks, which outcrop in the Northern part of the slope (Fig. 3). They consist of dark coloured phyllites, quartz–phyllites and light coloured quartzite layers with thicknesses ranging from a few millimetres to a few metres. They are assigned to the Seo formation (Hartevelt, 1970)
(ii) Silurian rocks, (Hartevelt, 1970) which are mainly composed of black carbonaceous shales and of an alternation of black limestones and shales in the upper part. The Silurian rocks are intensely foliated and folded. The unit has variable thickness because it is often the decollement level of the Pyrenean thrusts and this causes shearing and squeezing of the beds. Locally this unit forms diapiric structures of incompetent behaviour (Zwart, 1979). Silurian rocks appear strongly weathered in outcrop. They are characterized by rusty brown yellow and white colors due to oxidation of pyrite and subsequent sulphur precipitation.

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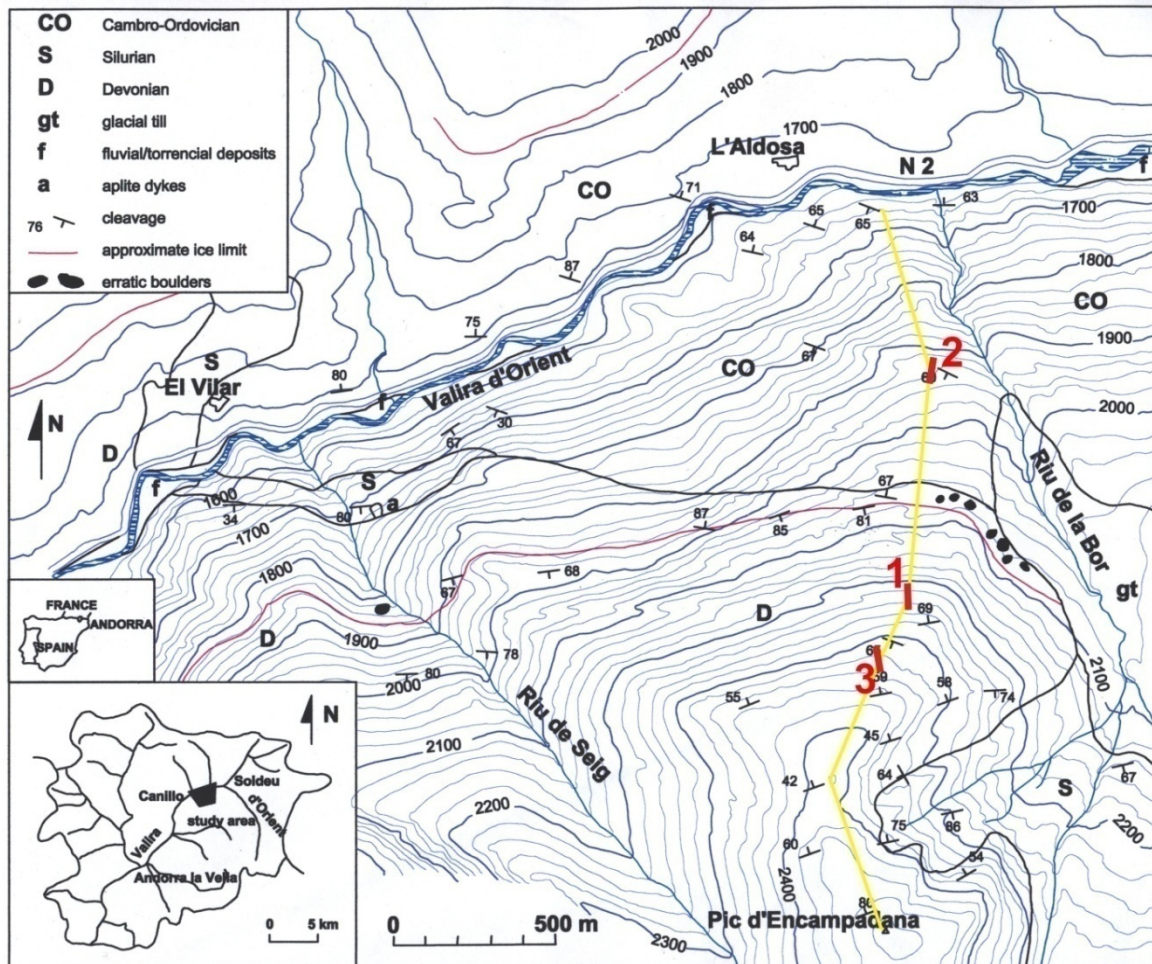
Fig. 3. Geologic map of the northern slope; contour interval 20 m. Yellow line shows line of topographic profile in Fig. 4. Trenches 1, 2, and 3 in red.

 (iii) The Devonian series range from lutites and calcareous lutites interbedded with thin limestones layers (Rueda formation) to massive (up to 60m thick) limestones and marly limestones (Castanesa Formation), and to green to beige marly limestones (Manyanet formation). All these materials have undergone long and complex deformation processes, due to the superposition of the Alpine orogeny over the previous Variscan phase of deformation.

From a structural point of view, pre-Carboniferous rock formations strike E-W or ENE-WSW. They define antiformal and synformal domes of kilometric extent, bounded by faults and thrusts with the same orientation. The Encampadana massif is mostly composed of Devonian rocks overlaying the Silurian shales. The latter outcrop at the Collet de les Solanelles and farther East.

Glaciation of Andorra and the Valira d'Orient
Within the past decade the chronology of Pleistocene glaciation in the Pyrenees has been significantly revised based on new suites of numerical ages from: (1) glacial landforms obtained with in situ-generated cosmogenic radionuclide (CRN);(2) glacio-fluvial outwash sediments obtained with optically stimulated luminescence (OSL); and (3) from the cross-correlation of

117   these dates with the radiocarbon ages of the ice-marginal deposits (Calvet et al. 2011). The
118   largest remaining data gap is uncertainty on the extent of pre-Würmian glaciers. During the
119   Würmian maximum ice extent W(MIE), glaciers often buried, eroded or reworked the terminal
120   deposits of earlier glaciations, thus hiding their evidence in today's landscape. An updated
121   review of history of the glaciations in the Pyrenees can be found at Calvet et al. (2011), Delmas,
122   (2015), and in the references therein.
123
124   During the Last Glacial cycle in the Pyrenees, glaciers occupied much of the territory. On the
125   southern side of the range glaciers were confined within the Pyrenean valleys and reached
126   lengths of 20-30 kilometers, with the fronts located between 800-1000 meters elevation (Calvet,
127   2004). According to Delmas (2015), the WMIE in the Pyrenees occurred during MIS 4 (74 – 60
128   ka). This and other recent studies (Calvet et al. 2011; García-Ruiz et al. 2013; Turu et al. 2016)
129   conclude that several episodes of high magnitude glacier advance and retreat existed after MIS
130   4. However, the number and extent of such fluctuations is still subjected to debate. Furthermore,
131   recent dating in several Pyrenean valleys has shown a contrasting behavior of glaciers.
132   Depending on the valley, glaciers reached their respective WMIE at different times, often long
133   before the global Last Glacial Maximum (LGM) (Calvet et al., 2011; Delmas et al., 2011;
134   Delmas, 2015).
135
136   Subsequent to the WMIE, Pyrenean glaciers retreated significantly in some valleys (Delmas et
137   al 2011). A major readvance took place around 23-19 ky BP, synchronous with the LGM
138   although it was less extensive than the WMIE (García-Ruiz et al. 2003, 2010; Delmas, 2015).
139   Soon after the LGM the Pyrenean ice margin went into a major and rapid recession. Even
140   before the beginning of the Late-glacial, the main trunk glaciers had already retreated to the
141   upper part of the valleys. After the Oldest Dryas (13.35-13.48ka) the glacier fronts were
142   confined to the cirques (Turu, 2011). During the Younger Dryas (11.56-12.7 ka) glaciers were
143   only capable of reaching the valley bottom and after 10 ka they were confined to the highest
144   cirques (Copons and Bordonau, 1994).
145
146   In the Principality of Andorra, the Valira d'Orient glacier had a larger accumulation zone than
147   that of the Valira del Nord and due to its orientation it was relatively sheltered from ablation
148   (Turu et al. 2015). These factors allowed the Valira d'Orient glacier to intermittently dam the pro-
149   glacial streams of the receding Valira del Nord glacier at the cuvette of Andorra la Vella (figure
150   1). This situation generated an ice-dammed lake in La Massana, the sediments of which have
151   provided the chronostratigraphic clues for reconstructing the Würmian glacial evolution in
152   Andorra (Turu et al. 2016). The retreat after the WMIE disconnected the glacier of the North
153   Valira from the Great Valira glacier. The former receded upstream of La Massana while the
154   Valira d'Orient receded upstream of Canillo. During the LGM the glacier of the Great Valira
155   reached again Andorra la Vella and was large enough to obstruct again the Valira del Nord
156   Valley. According to Turu et al. (2016), the disconnection of the two glaciers and the formation
157   of the lake took place before 25.64 ± 0.19 ka BP (19,352 to 30,482 cal BP).
158
159   During the WMIE, ice-marginal deposits accumulated on the right bank of the Valirad'Orient
160   river above the village of Canillo, at the Bordes de Montaup, and Bordes de Mereig
161   (Soutadé,1988). The deposits are located approximately 300 meters above the current valley
162   bottom, which indicates the approximate thickness of the glacier as itflowed by the
163   Encampadana massif.
164
165   **Landslides and DSGSDs in the Central & Eastern Pyrenees**
166   Slope failures in the axial Pyrenees are controlled by three mainfeatures (Corominas and
167   Baeza, 1992): (i) The presence of susceptible lithologies. Widespread shallow failures in the

form of shallow slides and debris flows are associated with unconsolidated deposits of glacial and periglacial origin (e.g. till, glacio-lacustrine deposits, colluvium) although the large rock slope deformations and failures involve weak geological units such as the Silurian shales. A synthesis of the most susceptible ones is included in Corominas (1989). (ii) The erosive action of the Pleistocene glaciers and the incision of the present fluvial network, locally exacerbated by the orogenic uplift, have resulted in a steep relief, which constitutes the main predisposing factor for instability; (iii) The geological structure plays a fundamental role in failures that require the contribution of the planes of weakness such as the deep seated gravitational slope deformations (DSGDD). Main fold axes and thrust fronts follow an East-West orientation. River valleys running parallel to these geological structures display large slope failures as observed in some central Pyrenean valleys (Soeters and Rengers, 1983; Bordonau and Vilaplana, 1986) as well as most of the Andorran valleys (Jarman et al. 2014)

3. Methods

Trenching: We excavated three trenches with picks and shovels across sackung troughs near the toe, midslope, and head of the northern slope. Trenches were roughly 60 cm wide, 4.5-6 m long, and 2-2.5 m deep. The eastern wall of each trench was cleaned and gridded with string, after which we drew a field trench log on graph paper at a scale of 1:15. Those logs were then digitized for this paper. Unconsolidated stratigraphic units were defined based on color, texture, and sedimentary structures. Soil horizons developed on deposits (parent materials) were also identified and labelled according to the A/B/C horizon terminology used in the USA (e.g., Soil Survey Staff, 2014).

Geochronology: Our three trenches were sited in parts of sacking troughs that were closed (or nearly closed) topographic depressions, in hopes that trough sediments would contain organics (amenable to radiocarbon dating) or fine-grained deposits (amenable to luminescence dating). Each trench contained both datable organics and silty sediments. Radiocarbon samples were detrital charcoal or in-situ burn layers, dated by AMS. We used the calibration curve of Reimer et al. (2013) to convert radiocarbon years to calendar years. Fine-grained sediments were dated by the infrared-stimulated luminescence (IRSL) method. The multi-aliquot IRSL method was employed by Glenn Berger at the Desert Research Institute, Reno, Nevada. The polymineralic, non-carbonate, detrital 4-11 µm diameter size fraction was prepared. Laboratory sample-preparation procedures have been outlined elsewhere (e.g., Berger, 1990; Wintle and Huntley, 1980). U and Th concentrations were measured by the thick-source-alpha-particle counting (TSAC) technique (Huntley and Wintle, 1981) on dried powders. K was measured by commercial atomic absorption spectrophotometry. Radioactive secular equilibrium is assumed, and assumption apparently valid for luminescence dating of many sediments but not of all alluvial sediments (Olley et al., 1996). The basic sealed-chamber TSAC test (Huntley and Wintle, 1981) indicates no significant radon loss from the dried sample powders used in the study, except for sample OSL3-3, for which an increase-on-sealing of 14±4% in the total TSAC count rate was observed. This increase could indicate that significant radon loss has occurred and is occurring within sediments surrounding this sample.

For IRSL measurements the deep-blue luminescence near the known 410-nm emission from the most K-rich feldspars was chosen for detection (e.g. Aitken, 1998). To convert the sample's fossil light to an absorbed-energy equivalent, calibrated laboratory beta (^{90}Sr-^{90}Y) and alpha (^{241}Am) sources were used. Signal was recorded with an automated, high-capacity Daybreak Nuclear Model 1150 reader using an EMI 9635Q photomultiplier tube. Dose-response curves and other data were processed with software produced by Glenn Berger (e.g., Berger et al, 1987).

4. Results

4.1. Geology and Geomorphology of the Northern Slope
The trimline of the Latest Glacial Maximum (LGM) Valira d'Orient glacier crosses the northern slope from about 2100 m on the upvalley (east) side, to 1850 m on the downvalley side (thin red line on Fig. 3). The trimline is marked by the sudden appearance of rounded erratic boulders of granitic composition, which contrast to the angular, locally-derived clasts of dark Lower Paleozoic phyllite and slate.

The most abundant geomorphic expressions of DSGSD on the northern slope are contour-parallel antislope scarps found from low on the slope to its head at the Solanelles Graben (Fig. 4). Such small scarps have also been referred to in the literature as counter-slope scarps, counterscarps, and uphill-facing scarps. Hurliman et al.(2016) described the slope as follows: "*The field data at Encampadana show the typical morphological features of a DSGSD such as a prominent graben at the top of the slope and many large counterscarps. The structural data measured in the area indicated two important discontinuity sets: a subvertical schistosity parallel to the valley axis* [our Fig. 4]*, which favored the general toppling of large slope-parallel blocks, and a subvertical perpendicularly orientated joint system, which divided these rock blocks.*"

Most scarps on the slope are short (200-400 m), trend east-west, and have a swarm-like pattern in map view. Their east-west strike is about 15° oblique (clockwise) to the SW-NE-trending topographic contours. Scarp orientation is thus similar to the strike of foliation/cleavage in the metamorphic bedrock. The longest antislope scarp zone is 1500 m long and lies on the steepest part of the entire slope, about 120 m above the LGM ice limit (Fig. 5). It consists of three abnormally high antislope scarps each about 500 m long, which form a left-stepping pattern and descend obliquely across the slope from ~2200 m elevation at the east end to 2000 m at the west end. Assuming that the scarps represent displacement on extensional (normal faults), the left-stepping pattern implies a left-oblique sense of displacement (Crider, 2001).
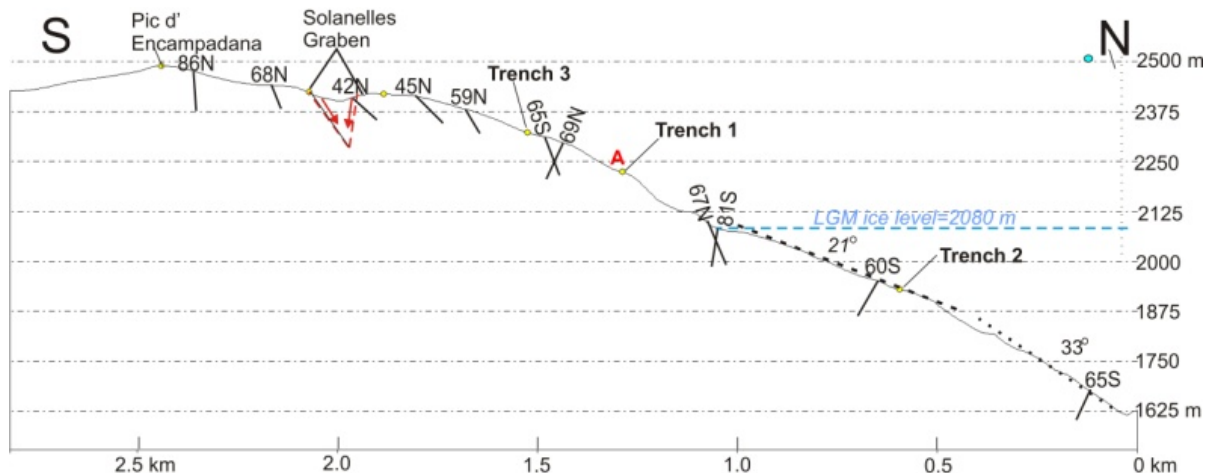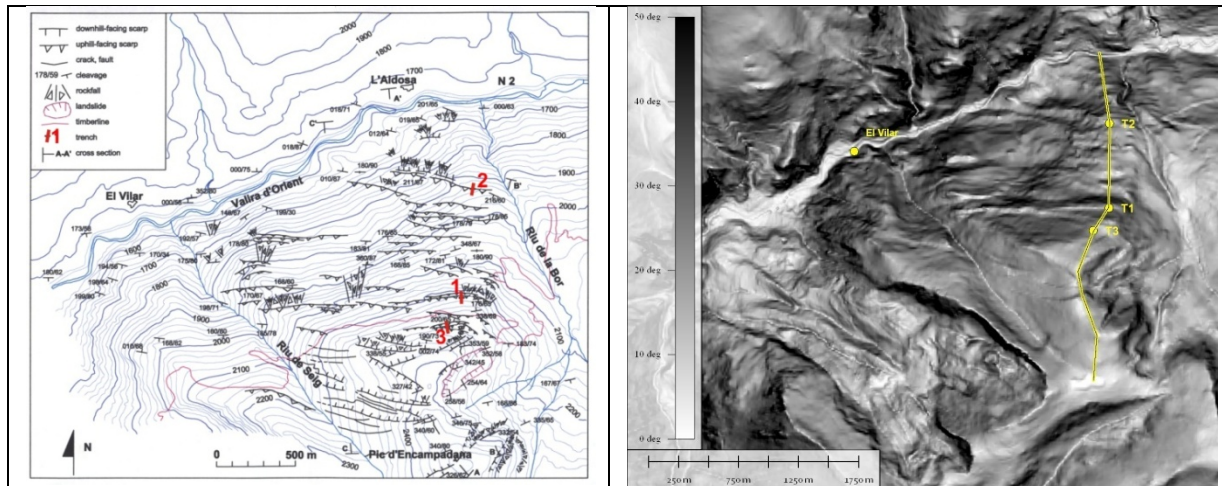

Fig. 4. Topographic profile of the northern slope through our three trench sites (line of section shown in yellow on Figs. 3, 5b). Small black lines with numbers are dip angles of the dominant foliation/cleavage in bedrock. Strike is approximately perpendicular to the section. Red "A" marks the longest (1.5 km) and highest sackung scarp.

Fig. 5. Maps of slope deformation landforms on the north slope of Pic d'Encampadana. (a) Left, antislope scarps and other landforms related to deep-seated and shallow gravitational deformation. Trench sites are shown in red. Contour interval 20 m. (b) Right, slopeshade image made from a 5 m lidar DEM (Spanish National Inst. of Geography). Prominent east-west bands on Encampadana's lower slopes are antislope scarps and benches (light) and downhill-facing scarps (dark) created by toppling.

4.2. Geochronology of Quaternary Deposits and Paleosols in Trenches

Our age control for deformation events comes from radiocarbon and IRSL dates from sediments deposited in structural depressions (Table 1). This approach to dating deformation events derives from paleoseismic studies of normal faults (e.g. McCalpin, 2009, Chapter 3). Sample locations are shown on the trench logs (Figs. 7, 9, and 12)..

Table 1. Radiocarbon (C-14) and infrared-stimulated luminescence (IRSL) dates from the Andorra trenches (from Berger, 2000).

Trench	Unit	Material	Dating Method and Laboratory[1]	Reported Age (C14 yr BP)	Calendar Age (cal BP), 2σ[2]
1	6A	soil A horizon (organic sandy loam)	AMS/NSF	1130±50	Cal AD 781 to 1003 (1014-1235 cal BP)
1	4	organic silty loam	AMS/NSF	3035±55	Cal BC 1122 to 1419 (3139-3436 cal BP)
2	10a	silt matrix of younger distal colluvium	IRSL		5.51±0.37 ka
2	5a	silt matrix of older distal colluvium	IRSL		15.3±1.1 ka
3	6g	soil A horizon (organic silty loam)	AMS/Beta	1490±40	Cal AD 442 to 499, and 518 to 643 (whole span 1374 to 1575 cal BP)
3	6a	silty younger sag pond deposit	IRSL		8.11±0.74 ka
3	3a	silty older sag pond deposit	IRSL		11.6±2.1 ka

[1]AMS= radiocarbon, accelerator mass spectrometry; NSF= NSF AMS Facility, Tucson, Arizona; Beta= Beta Analytic, Miami, Florida; OSL dates are infrared-stimulated luminescence dates on the 4-11 micron silt fraction from the Desert Research Institute, Reno, Nevada.
[2] Calendar-year Calibration from CALIB Rev 7.0.4 (2017), using the IntCal13 calibration data set; see http://calib.org (accessed 2017-12-28) and Reimer et al., 2013. Assumes dated samples contain a 50-year average of C-14.

IRSL dosimetry data are listed in Table 2. Ages and related luminescence data are listed in Table 3. The Th concentrations seem high, but without additional, detailed data on the spatial distribution of U and Th and without detailed isotopic data, it is necessary to assume that

279 conditions of secular equilibrium have applied throughout the samples' burial history. It is also
280 necessary to assume that the estimated past-water-concentration values are accurate and that
281 the measured U, Th, and K concentrations from a single sample adjacent to the IRSL sample
282 are representative of the sediment surrounding the sample out to a radius of ~30 cm (the
283 approximate range of ambient gamma radiation in soil). The measured present water value was
284 used with the samples, with conservative uncertainty assigned.

285
286 Table 2. Dosimetry data of Andorra IRSL samples.

Sample	Water[1]	K_2O wt.% (±0.05)	C_t[2] $ks^{-1} \times cm^{-2}$	C_{th}[2] $ks^{-1} \times cm^{-2}$	Th ppm	U ppm	b value[3] $pGy \times m^2$	Dose rate[4] Gy/ka
OSL2-3	0.21±0.05	3.22	0.808±0.014	0.385±0.048	10.3±1.3	3.30±0.39	0.899±0.076	4.54±0.23
OSL2-2	0.13±0.05	2.73	0.871±0.016	0.518±0.062	13.9±1.7	2.76±0.50	0.745±0.079	4.58±0.25
OSL3-1	0.34±0.08	3.43	0.907±0.021	0.649±0.084	17.4±2.3	2.01±0.68	0.691±0.081	4.26±0.29
OSL3-3	0.34±0.08	2.65	0.864±0.017	0.544±0.064	14.6±1.7	2.50±0.52	1.08±0.27	3.98±0.34

287 [1] Estimated historic average ratio of weight of water/weight of dry sample. Uncertainties here and elsewhere are ±1σ.
288 [2] Total and thorium count rates from finely powdered samples for thick-source-alpha-particle-counting (TSAC) method
289 [Huntley and Wintle, 1981]. $C_u = C_t - C_{th}$.
290 [3] Alpha effectiveness factor [Huntley et al., 1988; Berger, 1988].
291 [4] Calculated with the conversion factors and equations given by Berger [1988] and includes a cosmic ray component
292 of 0.15±0.03 estimated from the data of Prescott and Hutton [1988].

293
294
295 Table 3. IRSL data and ages for Andorra trench samples.[1]

Sample	Preheat[2]	D_E[3] (Gy)	Time[4]	Age (ka)
OSL2-3	140°C/2d	25.0±1.1	1-40	5.51±0.37
OSL2-2	140°C/2d	69.8±3.5	1-40	15.3±1.1
OSL3-1	130°C/2d	34.6±2.1	1-15	8.11±0.74
OSL3-3	130°C/2d	46.1±7.2	1-40	11.6±2.1

296 [1] Thepolyminerallic 4-11µm size fraction was used for all IRSL measurements. IRSL was detected at the 420±20 nm
297 spectral region (bandpass 390-470 nm at 1% cut). All bleaching was for 2 h with >780 nm solar spectrum passed..
298 [2] The chosen pre-readout heating.
299 [3] Weighted mean equivalent dose plus average error over time interval in next column. A weighted-saturating-
300 exponential regression and error model (Berger et al., 1987) was employed for all samples.
301 [4] The readout (LED-on) time interval for which D_E is calculated.

302
303 *4.3.Trench 1*
304 Trench 1 was located at 2230 m elevation at the eastern end of the longest antislope scarp on
305 the northern slope (Fig. 5). Trench 1 was 4.5 m long and as much as 2.1 m deep. The trench
306 axis was oriented N07°W, perpendicular to the sackung trough.

307
308 *Local Geomorphology:* Trench 1 was located across an asymmetric, contour-parallel trough that
309 occupied the southern half of a 15 m-wide bench. The deepest part of the trough lay up against
310 a very steep slope to the south (Fig. 6, right). We trenched across the topographic low point that
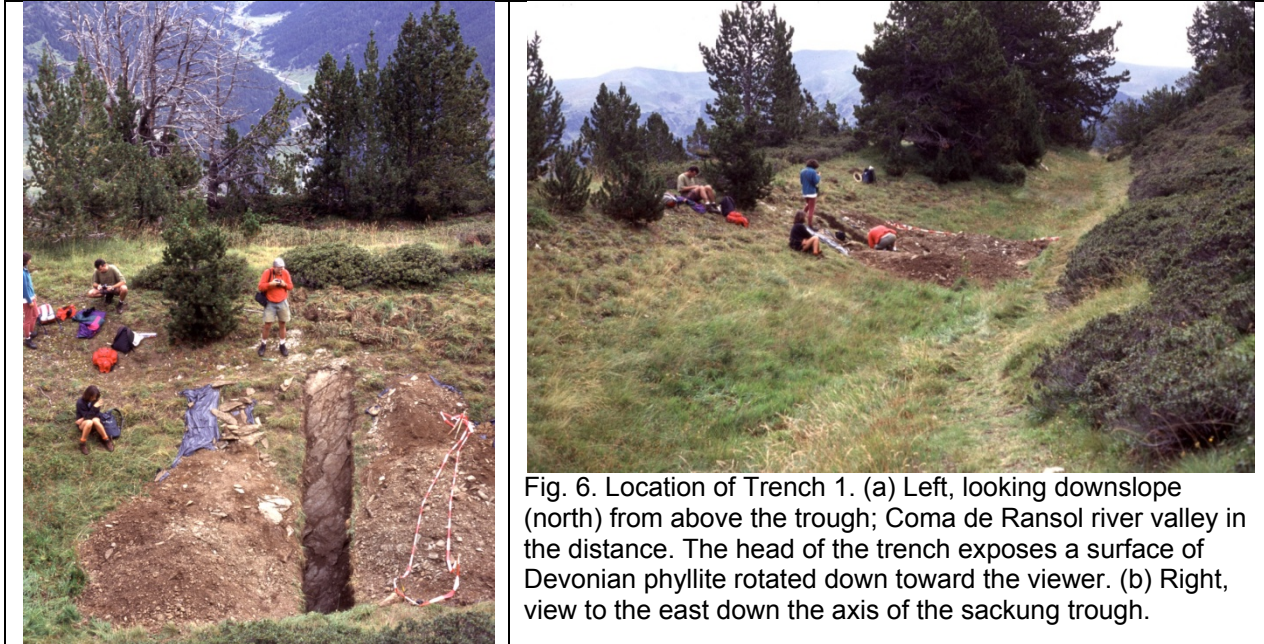311 supported growth of lush green grass, suggesting fine-grained deposits and occasional ponding.
312

Fig. 6. Location of Trench 1. (a) Left, looking downslope (north) from above the trough; Coma de Ransol river valley in the distance. The head of the trench exposes a surface of Devonian phyllite rotated down toward the viewer. (b) Right, view to the east down the axis of the sackung trough.

313
314 *Stratigraphy and Soils*: On the east trench wall we define 6 major units, which were further
315 subdivided into 15 subunits (Fig. 7). Unit 1a is the intact phyllite bedrock of the downthrown
316 block (Devonian), and units 1b and 1c are fractured and translocated counterparts of unit 1a.
317 The oldest unconsolidated deposit (unit 2) directly overlies weathered phyllite and is composed
318 of thin, tabular, clays (unit 2b) or clayey loams (unit 2a) that contain very weathered phyllite
319 clasts. The strong weathering and odd (reduced) colors (green-yellow to golden yellow) suggest
320 that unit 2 was deposited in stagnant water in a closed depression. In the deepest part of the
321 trench (between faults F2 and F3a) unit 2 is overlain by a dark brown silty loam (unit 4). Unit 4 is
322 interpreted as the A horizon of a buried paleosol developed on underlying unit 2. However,
323 outside of faults F2 and F3a, there are intermediate deposits (unit 3) between units 2 and 4.
324 North of fault F2 the intermediate unit is 3a, a gravelly sand with yellow-brown matrix. The unit
325 coarsens toward the north and thus resembles scarp-derived colluvium; it is overlain by the unit
326 4 paleosol. South of fault F3a units 2 and 4 are separated by a 1.6 m-thick block of strata (unit
327 3) that has been tilted 30°-40° to the south and faulted (faults F3b through F3d). Based purely
328 on color and texture, unit 3c may correlate with unit 3a in the northern part of the trench.
329 However, that leaves the upper 1.2 m of stratigraphy in the tilted block (units 3d, 3e, 3f) with no
330 counterparts in the rest of the trench. Unit 4 drapes the truncated edges of block stratigraphy in
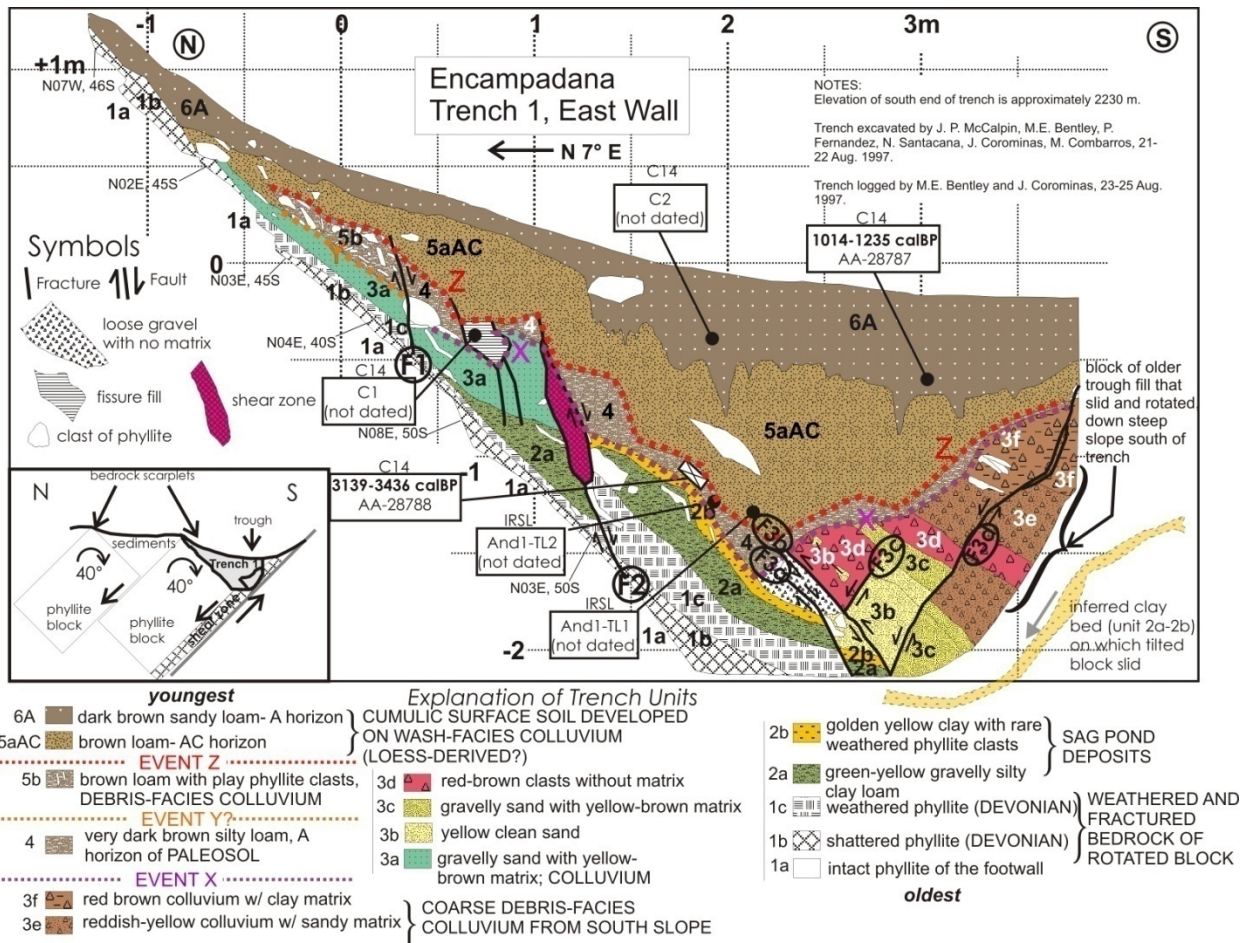331 angular unconformity.
332

Fig. 7. Log of East Wall of Trench 1. Inset at lower left shows structures and kinematics.

Subsequent to its formation, the unit 4 paleosol has been folded into a V-shape. Atop the V are units 5a and 6, which are poorly stratified brown loam to dark brown sandy loam, respectively. Unit 5a yielded an age of 3139-3436 cal BP. We interpret units 5a and 6 as wash-facies colluvium (slopewash) that has filled in the sackung trough over long periods of time subsequent to the latest deformation event. Soil-forming processes have kept pace with trough aggradation, creating a 1.3 m-thick cumulic soil profile composed of an A horizon (unit 6A) and underlying AC horizon (unit 5aAC). North of fault F1 we identified a stone line at the base of unit 5a, which we interpret as debris-facies colluvium (unit 5b).

Structure: The northern end of the trench is composed of a smooth plane of fractured phyllite bedrock (visible in Fig. 6) which dips 40°-50°S. Faults F1 and F2 are normal faults that splay upward off this bedrock surface at steeper angles. F1 dips 80°S and displaces unit 3a about 10 cm down-to-the-south, whereas F2 dips 70°S, has a shear zone about 15 cm wide, and displaces unit 4 50 cm down-to-the-south. However, both faults have inconsistent displacement sense and/or amounts as they are traced up and down dip. For example, on F1 unit 4 exists on the south side of the fault but not on the north side. On F2 unit 4 is displaced 50 cm in a normal sense, but underlying unit 2a is displaced a smaller amount in a reverse sense (down-to-the-north). Similar mismatches of stratal thickness and displacement across faults are observed on faults F3c and F3d. The thickest part of the trough fill lies between faults F2 and F3a and contains thin clayey deposits (units 2a and 2b). These were interpreted as basal sag pond deposits, so should have been deposited subhorizontally. But at present they are tilted down-to-

11

357 the-south as much as 50°-60°. This degree of tilt is even greater than the 30°-40° southward tilt
358 of strata in the rotated block in the south end of the trench.
359
360 Several lines of evidence indicate that the bedrock surface exposed on the north end and floor
361 of the trench is the top of a bedrock block that has been rotated clockwise (down-to-the-south).
362 First, the originally-horizontal sag pond deposits (unit 2) now dip south, which can only have
363 been caused by rotation down-to-the-south (not by outward toppling to the north). Second, with
364 successive rotation the trough deepened, which was accompanied by normal faulting on the
365 south margin of the trough (seen in unit 3) and sliding of blocks of exotic stratigraphy into the
366 trough. Third, the presence of two reverse faults (F2, F3b) is an anomaly in a system of rotating
367 domino blocks, normally associated with extension.
368
369 *Interpreted Sequence of Deformation:* Based on stratigraphic superposition, cross-cutting
370 relationships, and the occurrence of two paleosols, we interpret a sequence of four late
371 Quaternary deformation events at Trench 1, with two more questionable events (Table 1).
372
373 Table 4. Inferred sequence of depositional, pedogenic, and deformational events affecting
374 Trench 1.

| Event (oldest at bottom)	Evidence
11-Deposit units 5b, 5aAC, 6A	A 1.3 m-thick fining-upward sequence (5b-5a-6) is deposited as wash-facies colluvium (slopewash), on which is developed a thickcumulic surface soil (horizons6A, 5aAC). Lower unit 6A yields charcoal age of**1014-1235 calBP.**
10-Deformation EVENT Z	Youngest event faults unit 5b against unit 4 on fault F1; faults unit 4 on faults F1 and F3d. Fault F2 faults unit 4 up to N, but offsets unit 2a down-to-N
9-Deposit unit 4	Followed by accumulation of organic material in an A horizon Paleosol; ; **3139-3436 cal BP**
5-Deformation EVENT Y	Unit 3 is faulted. Between faults F2 and F3a all of unit 3 is translated away, either westward by oblique faulting, or it all slides southward to its present location.
4-Deposit unit 3	Fine-grained units 2a-2b are abruptly buried by coarser colluvial units 3a (derived from the north) and 3b-3f (derived from the south).
3-Deformation EVENT X	Trough deepens due to faulting and clockwise block rotation.
2-Deposit units 2a, 2b	Thin sag pond silts and clays (2a, 2b) accumulate in trough; reduced conditions.
1-Deformation EVENT W	Normal faulting creates the initial topographic trough

375
376
377 *4.4 Trench 2*
378 Trench 2 was located at 1935 m elevation on the lowest-elevation antislope scarp in the
379 Encampadana complex, only 300 m above the modern valley floor (Fig. 5). Trench 2 was the
380 longest (6 m) and deepest (3 m of stratigraphic section) of our three hand-dug trenches. The
381 trench axis was oriented N10°W, perpendicular to the sackung trough.
382
383 *Local Geomorphology:*The trenched antislope scarp/trough is a roughly 500 m long and follows
384 foliation to the WNW, cutting obliquely across contours that trend WSW. Downslope of this
385 scarp all the mapped scarps face downslope and appear to be part of a late Holocene landslide
386 on the oversteepened lower valley wall.
387
388 *Stratigraphy and Soils:* On the east wall we define 10 major units, which were further subdivided
389 into 23 subunits (Fig. 9). The oldest units (1-5) maintain a tabular geometry throughout the
390 trench, suggesting that they were either: (1) deposited on a uniform slope unaffected by
391 development of a sackung trough and scarp ("Pre-Faulting Units" on Fig. 8), or (2) deposited in
392 a trough much wider and shallower than the present trough. In contrast, units 6-10 are lenticular
393 and are restricted to the northern half of the trench. Each of these five units is located above the

axis of maximum displacement on faults that were active before its deposition. Thus we interpret units 6-10 as deposits that accumulated between successive deformation events.
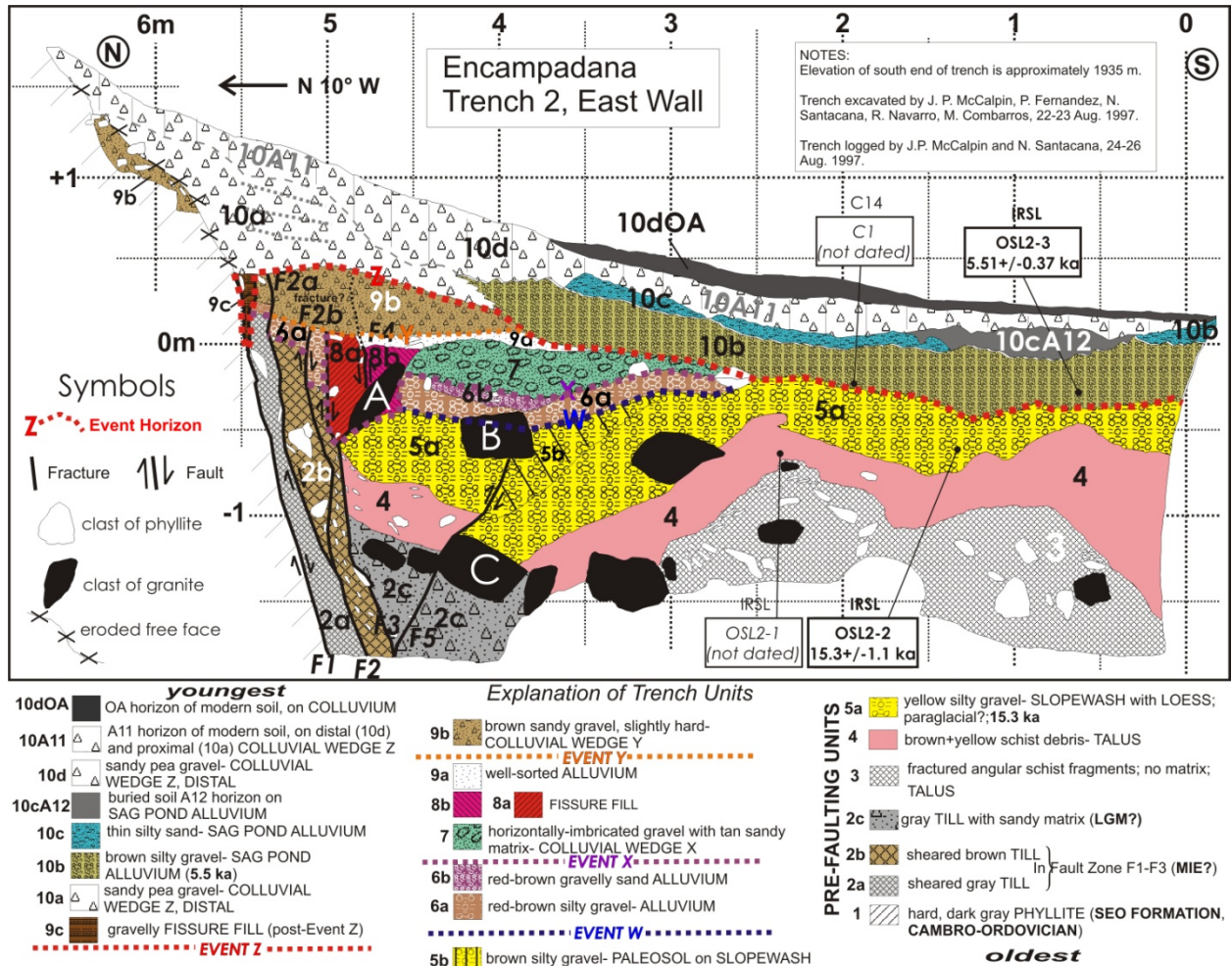
Fig. 8. Log of the east wall of Trench 2.

The oldest deposit exposed in the trench (unit 1) is the hard, dark gray phyllite of the Seo Formation (Cambro-Ordovician) that underlies the lower half of the Encampadana slope. This bedrock unit is only exposed on the footwall of the main south-dipping normal fault beneath the sackung scarp. The oldest in-situ unconsolidated deposit (unit 2c) is a gray, unoxidized till exposed in the deepest part of the trench. The till contains exotic subrounded clasts of granite derived from far upvalley of the Encampadana slope, indicating it was deposited here by the Valira d'Orient glacier. Material derived from this till has been drug up along the main fault zone (units 2a, 2b). In the southern half of the trench the oldest deposit (unit 3) is composed of angular schist and phyllite fragments with no matrix. This deposit contains no granite and appears to be a locally-derived talus deposit, age equivalent to (or slightly younger than) the gray till. Overlying units 2c and 3 is a brown, oxidized talus deposit (unit 4) similar in lithology to unit 3. This talus fines upward into a poorly-sorted yellow silty gravel (unit 5a), the upper part of which has been turned brown by soil formation (unit 5b, and paleosol). The base of unit 5a yielded an IRSL age of 15.3±1.1 ka, suggesting it was deposited shortly after the retreat of the LGM glacier. The silt content may be loess deflated from the retreating outwash plain.

Units 6 through 10 comprise 15 subunits comprised of one of these facies: (1) thin, tabular, well-sorted alluvium, (2) coarser lenses or wedges of poorly-sorted colluvium, and (3) downward-tapering wedges of poorly sorted fissure fill. These facies are all located above deformation structures in the trench, and are interpreted as alluvial and colluvial deposits, respectively, that accumulated episodically in the sackung trough. Unit 10 is the largest of these deposits and contains scarp-derived colluvium (10a) and correlative sag-pond alluvium (10b; basal age 5.51±0.37 ka), overlain by thin alluvium and a paleosol (units 10c and 10cA12, respectively), distal wash-facies colluvium (10d) and its two soil horizons (10A11 and 10dOA). None of these subunits are deformed, indicating that all deformation occurred after 15.3 ka but before 5.5 ka.

Structure: Trench 2 structures are mainly normal faults, numbered from the footwall to the hanging wall as F1, F2 (F2a, F2b), F3, F4, and F5. Faults F1 through F3 are steeply south-dipping normal faults in the main fault zone that underlies (and created) the south-facing sackung scarp (Fig. 9). The fault sliver between F1 and F2 is filled with unoxidized gray sheared till, clearly derived from unit 2c. The sliver between F2 and F3 is filled with an oxidized brown sheared till. F4 is a subvertical fault that splays upward from F3 and bounds the south edge of a fissure fill (unit 8a). F5 is a north-dipping fault that displaces the hanging-wall sequence down-to-the-south in an apparent reverse sense. We suspect that some local horizontal compression was generated here by the down-to-the-north rotation of units 3-6 between 2.5 m and 4 m on the horizontal grid. As in Trench 1, the down-to-the-north rotation of those units tends to push them northward into their correlatives on the north side of the fault, putting that area into compression.
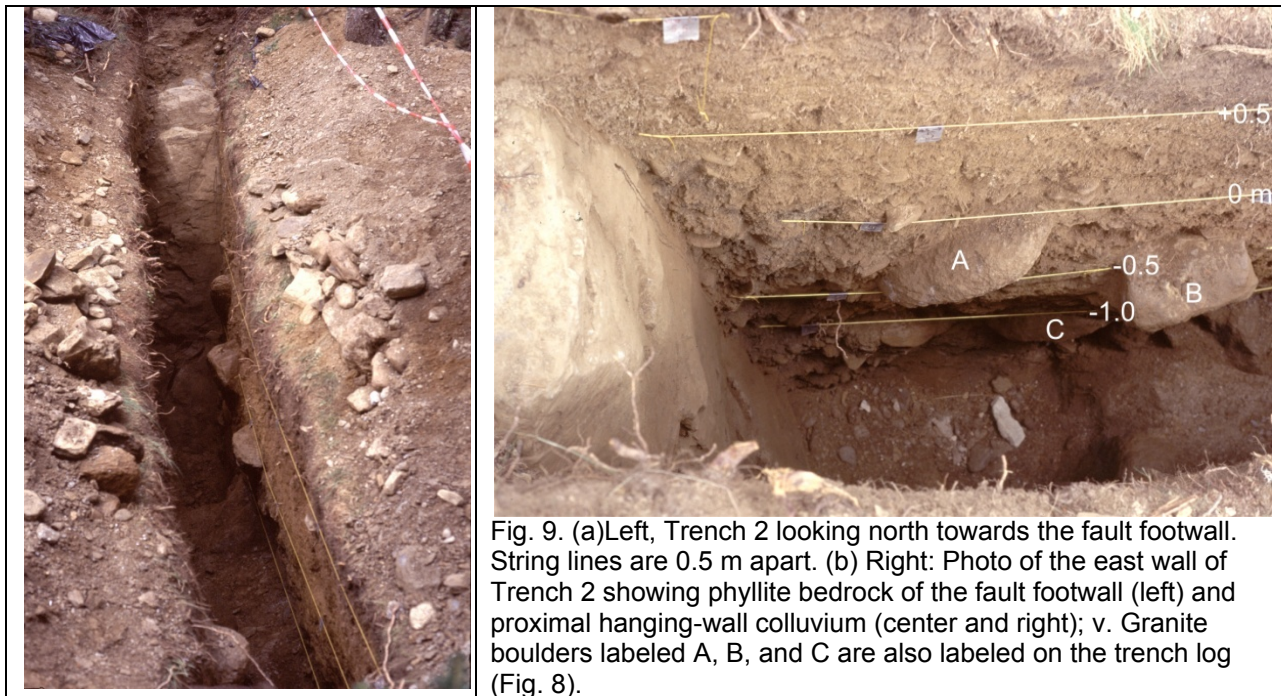

Fig. 9. (a)Left, Trench 2 looking north towards the fault footwall. String lines are 0.5 m apart. (b) Right: Photo of the east wall of Trench 2 showing phyllite bedrock of the fault footwall (left) and proximal hanging-wall colluvium (center and right); v. Granite boulders labeled A, B, and C are also labeled on the trench log (Fig. 8).

Interpreted Sequence of Deformation: The number of deformation events at Trench 2 is evaluated via a retrodeformation sequence (Fig. 10). The sequence starts (Stage A) with the present trench wall geometry and proceeds backwards in time, by a stepwise: (1) removal of any unfaulted deposits, and (2) reversing the fault movement such that the youngest underlying faulted deposits are restored to their continuous (pre-faulting) geometry. Then these deposits

14

446   are removed, and so on to Stage G (geometry of Quaternary deposits before trough formation).
447   This procedure recognizes all upward fault terminations in the stratigraphic sequence, which
448   occur at unconformities separating faulted from unfaulted strata. In paleoseismic investigations
449   such unconformities created by coseismic faulting events are termed "event horizons", a term
450   which we will use in this paper, but not implying in any way that the deformation events are
451   related to earthquakes.
452
453   We recognize four event horizons in Trench 2, labeled from Z (youngest) to W (oldest). Event
454   horizons Z, Y, and X coincide with scarp-derived colluvial wedges (cwZ, cwY, and cwX
455   respectively) overlying either older wedges or inter-faulting alluvium. The next older event
456   horizon (W) resulted from downwarping of units 3-5 into a narrow trough, quickly followed by
457   alluvial erosion then deposition (units 6a, 6b) in the trough axis. The lack of a colluvial wedge
458   following Event W suggests that no high scarp was formed in this event, but only an extensional
459   fissure. Event W occurred long enough after 15.3±1.1 ka that a weak paleosol (unit 5b) had
460   formed on the pre-faulting colluvium. Subsequent downwarping of units 6a and 6b beneath unit
461   7 (colluvial wedge X) suggest further sagging occurred in Event X. The latest deformation event
462   (Z) occurred immediately before deposition of unfaulted unit 10b at 5.51±0.37 ka. Thus, all four
463   deformation events occurred in a time span of <10 ka (<15.3 to 5.5 ka). In addition, it is possible
464   that units 2 through 5 were deposited in a pre-existing depression, rather than on a uniform
465   erosional slope. However, our trench exposure was too limited in size to distinguish these two
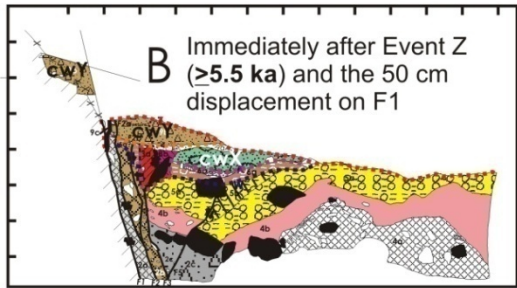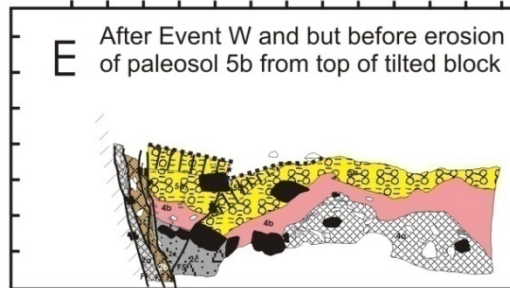466   possibilities.
467
468
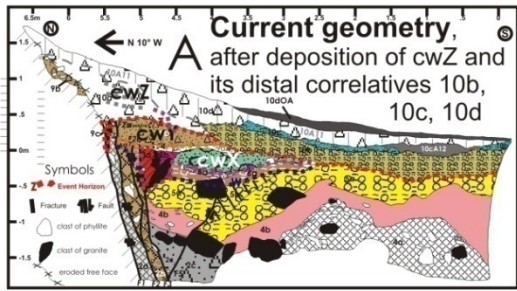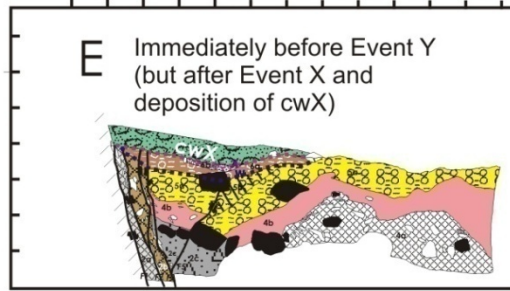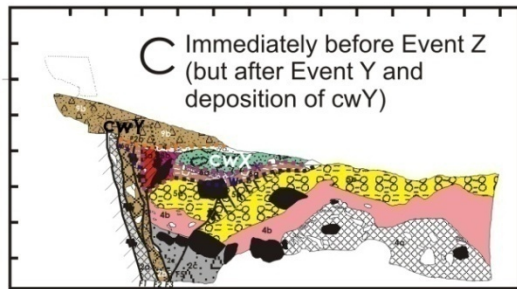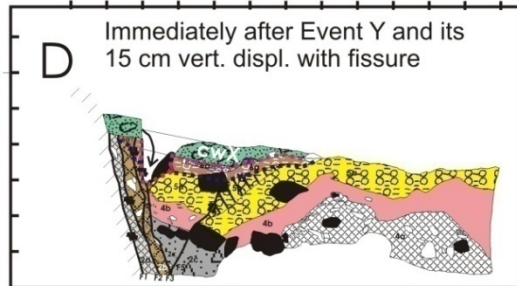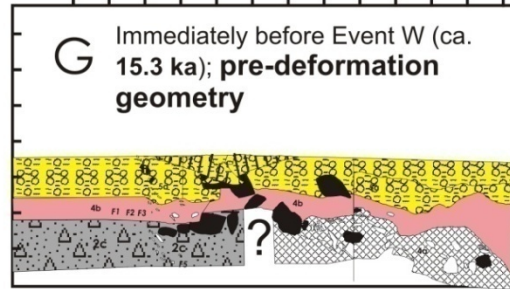
Fig. 10. Retrodeformation sequence of the East Wall of Trench 2. Stage A represents the present trench wall geometry, Stage G the geometry prior to Event W. There may have been additional sackung events prior to Event W, but our trench was not long enough or deep enough to permit reconstruction of the topography of that time.

4.5 Trench 3

Trench 3 was located at 2320 m elevation on the highest-elevation antislope scarp/trough pair in the Encampadana complex (Fig. 5). The trench was 5 m long and up to 2 m deep, oriented toward N10°E (perpendicular to the trough axis).

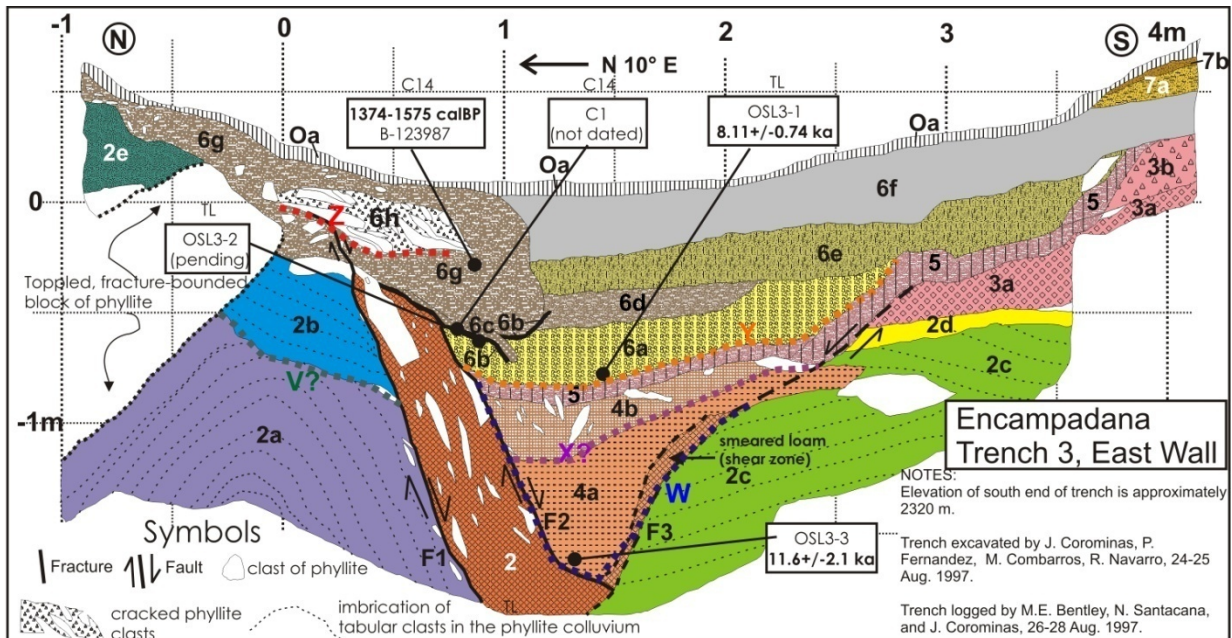*Local Geomorphology:* Trench 3 crosses the axis of a ~5 m-wide trough which is topographically closed at the trench site (Fig. 11). We chose the site hoping to expose fine sag-pond sediments beneath the center of the closed trough, which might be suitable for C-14 and/or IRSL dating. The trough margins are asymmetrical, with the northern boundary being formed by a 2 m-high near-vertical outcrop of Devonian phyllite, while the southern boundary is a gentler grassy slope underlain by inactive talus.

Fig. 11. Site of trench 3. (a) Left, site before trenching, view to NE. Trench was dug between two red arrows. (b) Right, view of trench 3 looking N.

Stratigraphy and Soils: On the east wall we define 7 major units, which were further subdivided into 22 subunits (Fig. 12). The oldest unit (1) is phyllite bedrock (Devonian) of the fault footwall. The oldest unconsolidated deposit exposed is unit 2, mainly a talus deposit composed of angular fragments of phyllite, either without any matrix (unit 2a) or with a finer sandy matrix (2b, 2c). The geometry of these deposits does not conform to any of the present structures of topography of the sackung scarp or trough, so we interpret it as pre-trough talus. The shear zone that truncates units 2a and 2b is labeled unit 2. Younger talus of the hanging wall comprises unit 3. Unit 4a is a fine-grained deposit (silty clay) that fills a paleo-depression against the shear zone and is the oldest unit with sedimentology consistent with deposition in a closed depression. The base of unit 4a yielded an IRSL age of 11.6±2.1 ka, a close minimum age estimate for inception of the sackung trough. Unit 4a is unconformably overlain by a southward-tapering wedge of much coarser silty clay loam with angular clasts (unit 4b), interpreted as scarp-derived colluvium. Unit 5 is a paleosol developed on unit 4b, and to the south, on units 2d, 3a, and 3b. On the latter units it appears to be developed in a separate, silty (loess-rich?) parent material. [Unit 5 strongly resembles the unit 4 paleosol exposed in Trench 1, which is also a thin dark grown silty loam that blankets multiple units]. The unit 5 paleosol is unconformably overlain by a second fining-upward of fine-grained sag pond deposits (units 6a through 6f) capped by a paleosol. The bottom of unit 6 yielded an IRSL age of 8.11±0.74 ka. In the center of the topographic trough the A horizon of this soil (unit 6f) is the surface soil. But on the northern and southern flanks of the trough unit 6f is overlain by younger deposits (6g and 6h on the north, 7a and 7b on the south). The center of unit 6g yielded a radiocarbon age of 1374-1575 cal BP.

513

Fig. 12. Log of the east wall of Trench 3. As at Trench 2, the oldest deposits here (unit 2, talus) may have been deposited in an older sackung trough rather than on an undeformed slope. But our limited exposure precludes testing such a hypothesis.

Structure: The trough margins are underlain by inward-dipping normal faults. The northern faults (F1, F2) bracket a 20 cm-thick shear zone (unit 2) containing fault-parallel, tabular clasts of phyllite in a matrix of reddish-brown silty clay loam. Based on color and texture, this matrix was derived mainly units 4a and 4b, although there may have a small component from units 5 and 6a. The southern fault (F3) has a narrower shear zone (10 cm) and less overall vertical displacement (28 cm) than faults F1+F2. The youngest deformation in the trench occurred where fault F1 propagated upward and displaced the lower half of unit 6g.

In addition to these major extensional structures, there are minor compressional structures. The northern end of the trench exposes an isolated block of phyllite that has toppled southward toward the trough axis. Toppling opened a small void space on the north side of the block, into which unit 2e was deposited. However, on the south side of the block, stratified talus of unit 2a has been folded into an anticline, indicating local compression. Likewise, the antithetic normal fault F3 now has a rather serpentine shape, as if the originally planar fault was bent by unit 2c pushing northward toward the trough axis.

536 *Interpreted Sequence of Deformation:* Based on stratigraphic superposition, cross-cutting
537 relationships, and the occurrence of two paleosols, we interpret a sequence of three late
538 Quaternary deformation events at Trench 3, with a questionable 4th event (Table 5).
539
540 Table 5. Inferred sequence of depositional, pedogenic, and deformational events affecting
541 Trench 3.

Event (oldest at bottom)	Evidence
10-Deformation EVENT Z	On fault F2, the north margin of unit 6a is sheared against unit 2. On fault F1, a small-displacement fault propagates upward through the lower half of unit 6g.
9-Deposit unit 6	A 0.9 m-thick fining-upward sequence (6a-6d) with a 0.25- m surface soil (A horizon, unit 6f; B horizon, unit 6e). On north side of trough all subunits are intruded by a solifluction (?) lobe with a basal burn layer.
8-Deformation EVENT Y	Displaces unit 5 paleosol up 0.5 m to south; forms shear zone at unit 4a/2c contact; deepens trough.
7-Deposit units 4b, 5	Unit 4b has a sharp contact with underlying unit 4a and is much coarser; but could be either a colluvial wedge (tapers to south) or debris flow. In contrast, unit 5 is a paleosol (represents hiatus) on slope-mantling loess.
6-Deformation EVENT X?	Questionable deformation event. Depends on whether stony unit 4b is a scarp-derived colluvial wedge, or a debris flow.
5-Deposit sag pond silt in trough	Sag pond silt (unit 4a) has no correlatives outside of the inner trough (i.e., south of fault F3).
4-Deformation EVENT W	Extensional faulting/fissuring on faults F1-2-3 creates a narrow topographic trough.
3-Deposit units 2b, 2c, 2d, 3a, 3b	Talus sourced from the south
2-Deformation EVENT V?	Unconformity on footwall; unit 2a talus is folded into an anticline, but overlying unit 2b talus is not folded. Possibly not due to deformation; could be depositional?
1-Deposit unit 2a TALUS	Source is upslope to the South

542
543
6. Discussion
544
545 Our three trenches sampled only three of the ~50 antislope scarps on the northern slope, so our
546 interpretation of the larger pattern of slope kinematics may be viewed as preliminary. However,
547 we do see some trends that we believe can be generalized over the entire deforming slope.
548
549 *6.1 Reconciling Extensional and Compressional Structures in a Single Trench*
550 The conventional explanation of DSGSD is that it accommodates valleyward movement mainly
551 by toppling (need References), which is essentially an extensional process. Our trenches show
552 dominantly extensional structures, but each one also contains minor compressional structures
553 (reverse faults and folds). Does this mean that the entire gravitational stress field on the
554 mountain slope is switching from extension to compression and back to extension? Or does it
555 reflect a very local response to changing subsurface geometry as the sackung slope elements
556 rotate and evolve? We believe the latter, for reasons explained below.
557
558 Trench 1: This trench shows some small-displacement reverse faults in the lower part of the
559 trough fill, as well as horizontal 'squeezing' of the unit 4 paleosol to attain slopes exceeding the
560 angle of repose. Our first thought was that horizontal compression was caused by slump blocks
561 (unit 3) sliding into the trough from upslope. The toes of such slump blocks would press against
562 the sediments already deposited in the trough, causing local compression. However, such
563 compression should also deform the toe of the slide block, and strata in the supposed slide
564 block (unit 3) are not so deformed. Another possible source of compression would arise if
565 adjacent bedrock blocks rotated a different amount, which would cause compression in the back
566 edge of the sediment wedge. As long as two adjacent 'domino blocks' rotate the same amount,
567 the fault movement along their boundary fault will be purely translational (i.e., a normal fault;
568 Fig. 13A). However, if the downhill block rotates more than the uphill block, the sediment wedge

569 (which sits atop the downhill block) will also be rotated (Fig. 13B). That rotation, even across a
570 pivot point located on the fault, will pivot the sediment wedge into the uphill block, such that the
571 back edge of the wedge will be forced into the uphill block, trying to occupy the same space.
572 The result will be compressional deformation of the softer trough sediments, and this will
573 increase as the difference in rotation angle increases.
574
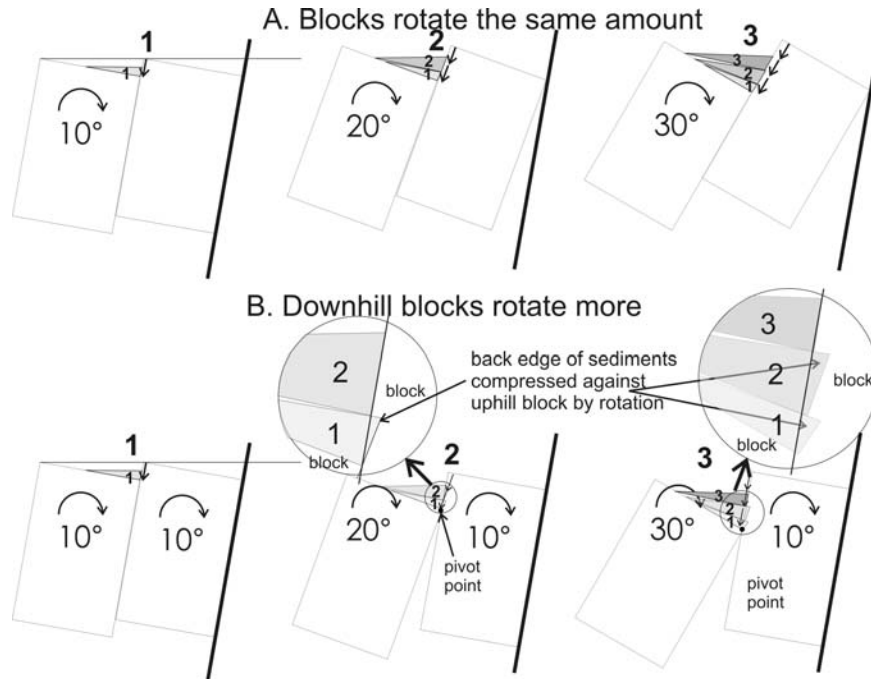
575
576 Fig. 13. Schematic diagrams of a pair of gravitationally-rotated bedrock blocks where sediments fill the
577 trough created by rotation. (A), both blocks rotate the same amount through time; sediment wedges 1, 2,
578 and 3 (gray shades) accumulate. (B), the downhill block rotates more than the uphill block, using a pivot
579 point on the fault plane where the two blocks touch (small black circle). As the difference in rotation
580 increases, the back edge of the earlier sediment wedges gets pushed horizontally into the uphill bedrock
581 block, inducing compression in the trough sediments.
582
583 <u>Trench 2</u>: Trench 2 contains a master south-dipping normal fault with a smaller north-dipping
584 reverse fault splaying upward into the hanging wall sediments (Fig.8). Secondary reverse faults
585 have been documented in the hanging wall of historic normal fault scarps (e.g., Crone et al.,
586 1987) and observed in many paleoseismic trenches across tectonic normal faults (McCalpin,
587 2009, p. 215-219). The causes may range from upward fault refraction (in response to
588 decreasing confining pressures near the surface, to a piece of the hanging wall sediments
589 getting cemented to the fault plane, and thus attached to the footwall in succeeding
590 displacements. Neither explanation seems applicable to the reverse fault in Trench 2. Instead,
591 the reverse fault is contiguous with a section of hanging-wall sediments that were rotated down
592 toward the master normal fault. Units 3 (?), 4 and 5a appear to compose a domino block that
593 has rotated down-to-the-north, toward the reverse fault. As at Trench 1, this rotation would force
594 the north-dipping units 3-5a to try to occupy the same space as their south-dipping correlative
595 farther north, leading to compression. An alternative explanation would invoke localized
596 collapse into a void space to explain the northward dip of units 3-5a. In that scenario units 3-5a
597 between 2.5-4 m on the grid are sagging downward into a subsurface void, perhaps created by
598 fault refraction of the master normal fault in Event W. But for some reason the northernmost
599 parts of units 3-5a have been cemented to the main shear zone, so they have moved upward as
600 part of the footwall, at the same time that their counterparts farther south have collapsed

downward into the void space. This differential movement has created a fault with the sense of a reverse fault, but with no horizontal compression involved.

Trench 3: During logging of Trench 3 we assumed that the anticlinal folding of unit 2a was entirely caused by slow forward toppling of the phyllite block. However, the upper part of the toppled block lies against unit 2b, which is not folded. So it seems that, in this trench, a more far-field source of compression may be required. In the southern half of the trench, normal fault F3 contains an anomalous northward bulge, a very odd shape for a tensional fault. Northward slippage along bedding planes in unit 2c could explain that bulge, but such slippage would require compression coming from outside of the trench, somewhere up the slope to the south. Both deformation structures appear to be plastic deformation of coarse-grained sediments, which suggests slow, creep-style deformation, rather than rapid, episodic (brittle) deformation. As shown in Fig. 14, upslope of trench 3 there is a large downhill facing scarp. A rock wedge is located between this scarp and the footwall of trench 3. So a possible source of far-field compression is that this rock wedge has slid down and compressed the entire area around Trench 3.
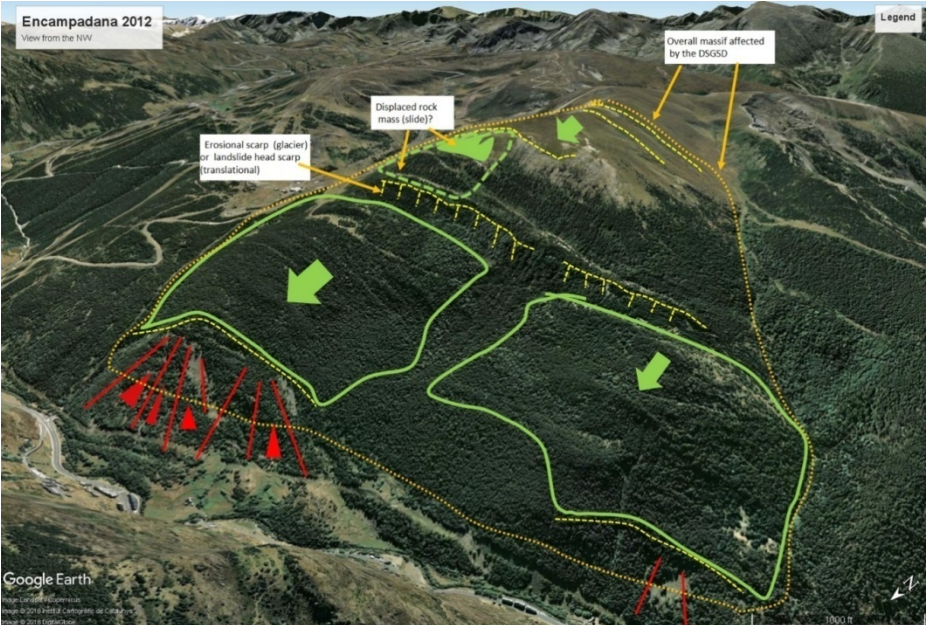
Fig. 14. Overall view of the Encampadana massif. In the foreground (red color) scree deposits (the local place name here is El Tarter, meaning "scree"). The longest scarp at mid-slope (yellow dashed line) suggests that in addition to toppling some translational movement has occurred (green arrows). Upslope of the long scarp lies a smaller, inferred displaced rock mass. Trench 3 lies in the downslope half of this rock mass.

The timing of compressional deformation is also different among the trenches. In Trench 1 reverse faulting and folding accompanied the youngest displacement (Event Z), affecting units at least as young as 3.2-3.4 ka. In Trench 2 the reverse fault is much older, moving only in the oldest of the four recognized displacement events (Event W, slightly younger than 15.3 ka). Compressional deformation in Trench 3 is also old, affecting only units older than 6a, which is 8.1 ka. The cessation of compressional deformation thus varies widely among the trenches, so much that it cannot represent a mountain-wide change in the stress field, but rather some more localized phenomenon.

6.2 Evolution of Deformation over the Whole Slope at Encampadana

Our trench geochronologies indicate that antislope scarps and troughs first formed low on the slope (Trench 2) by 15.3 ka, but deformation there had stopped prior to 5.5 ka. At the midslope position (Trench 1) deformation continued until later, with the latest event (Z) just after 3139-3436 cal BP. Farther up the slope (Trench 3) the latest event (Z) was even younger, occurring after 1374-1575 cal BP. In addition, there are morphologic indicators of displaced rock masses and downhill-facing scarps farther upslope of Trench 3. Taking into account the structural style of deformation in each trench and the timing of deformation events, we have constructed a schematic cross-section through the northern slope of Encampadana (Fig. 15). This cross-section makes several assumptions:

(1) the pervasive antislope scarps in the downhill half of the section were created by bedrock blocks, bounded by subvertical foliation planes, that have toppled valleyward;

(2) the top of each toppled block is parallel to today's ground surface;

(3) the resulting amount of toppling is greater toward the toe of the slope. This could be because slope deformation started earlier there (as indicated by trench geochronolgies);

(4) the steep, long scarps in the midslope position reflect an area of localized maximum extension;
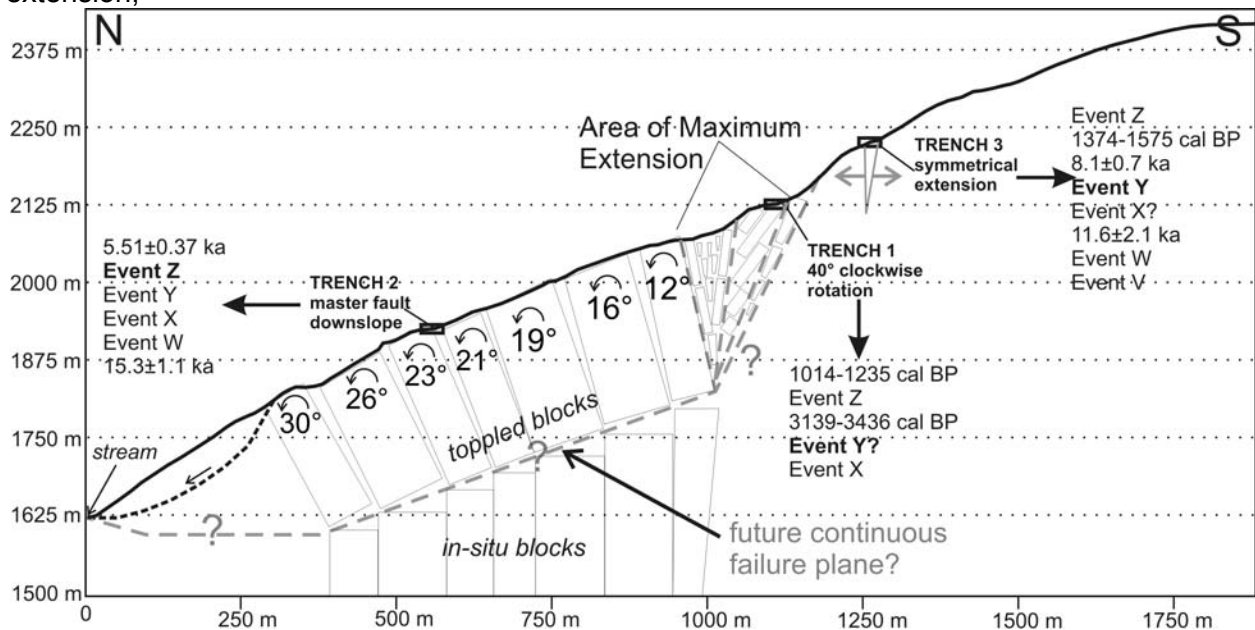
Fig. 15. Interpretive cross-section through the northern slope passing through trenches 1, 2, and 3. Thick arrows point to the chronology of deformation Events interpreted for each trench, and numerical ages from each trench. The Event with the largest vertical displacement is shown in bold.

(5) this extension has created the severely-back-rotated blocks seen in Trench 1;

(6) in order to achieve such large extensions at the surface, there must be at least an incipient discontinuity between the bottom of the toppled blocks and in-situ bedrock;

(7) the depth of that discontinuity can be approximated at its uphill end by projecting downward the bounding faults in the area of maximum extension;

(8) the downhill end of the potential discontinuity should not be too far below the present (post-glacial) valley floor; and

(9) the relatively small, asymmetrical extension seen in Trench 3 suggests it lies outside of the main zone of slope deformation, but perhaps responding to extension from the major gravitational unloading just downslope.

22

668   Other authors have documented similar spatial-temporal trends in DSGSD. In one of the earliest
669   sackung trenching studies McCalpin and Irvine (1995) speculated that antislope scarps would
670   be younger the higher above the glacial trimline, based on the ~2.5-4 kyr lag time between
671   deglaciation and initiation of the highest scarp at the ridge crest. Hippolyte et al., 2009
672   concluded: "*This decrease of the age of the scarps with elevation much probably reflects the*
673   *propagation of the deformation toward the crest (from elevation 2190 m to 2419 m)... This*
674   *chronology agrees with the proposed mechanism of flexural toppling. The migration of the slope*
675   *deformation from the valley flank to the crest also supports the model of glacial debuttressing for*
676   *the origin of the Arcs sackung.*" El Bedoui et al. (2009, 2011) observed a similar trend on the La
677   Clapiere slope in the French Alps. Panek et al. (2017) concluded "*In general, we observe a*
678   *statistically significant correlation showing a progressive decrease of sackung scarp ages with*
679   *their increasing altitudinal position... Such a relationship might indicate linkage of (delayed)*
680   *sackung genesis to overall thinning and retreat of glaciers since the LGM… Therefore, slow*
681   *upslope migration of stress release after glacier withdrawal… could partly explain substantial*
682   *time lag of a number of sackung scarps.*" Panek et al. (2017, their Fig. 5) showed a cross-
683   section similar to our Fig. 15, with age control coming from [10]Be dating of rock exposed on the
684   sackung scarp face. Their oldest dated antislope scarp was the lowest one, as at
685   Encampadana. However, the next-youngest scarp was at the head of the slope (analogous to
686   the Solanelles graben at Encampadana), and the youngest scarps were in the midslope
687   position. Thus, in hindsight, it appears should have also trenched the margin scarps of the
688   Solanelles graben in order to capture the entire span of slope deformation. We considered this
689   in our initial field reconnaissance, but the graben surface there showed no discrete sediment
690   traps and did not look promising for dating fine-grained deposits. Instead, the entire surface was
691   covered with large-diameter frost-shattered slabs and rubble of phyllite.
692
693   **7. Conclusions**
694   Sackung troughs formed at Encampadana have acted as sediment traps since formation, and
695   are underlain by distinctive postfaulting strata that permit reconstructing the evolution of the
696   antislope scarp and adjacent trough. The oldest strata exposed in our 2-2.5 m-deep trenches
697   are coarse, angular talus deposited as either slope-mantling sediments that predate the modern
698   sackung scarp and trough, or as sediments trapped in a very wide and shallow trough of
699   unknown origin. These deposits have been disrupted by normal and reverse faulting, with the
700   largest fault zone underlying the antislope scarp and dipping south at 40°-80°. Each trench
701   contains subsidiary north-dipping normal faults beneath the southern edge of the trough, giving
702   the appearance of a graben. However, in two of three trenches post-faulting deposits have
703   subsequently been tilted or folded down toward the main fault, as if sagging into a void space
704   created by horizontal extension and/or outward toppling of the footwall. The trough fill is
705   generally dominated by poorly-sorted sandy slopewash, but does contain two other important
706   facies: (1) thin clay and silt deposits deposited in standing water, found beneath the center of
707   the trough, and (2) gravelly scarp-derived colluvial wedges, found beneath the edges of the
708   trough. Paleosols have formed on the top of fining-upward sequences of strata, permitting
709   interpretation of several cycles of: (1) episodic downdropping along graben faults and
710   deepening of the topographic trough, (2) filling the trough with marginal colluvial and axial sag-
711   pond sediments, followed by (3) a hiatus of soil profile development. The structures and inter-
712   faulting sedimentation patterns are very similar to those exposed in trenches across active
713   normal faults (e.g. McCalpin, 2009, Chapter 3).
714
715   Despite their shallow depths, each trench preserves evidence of multiple unconformities and 3
716   to 5 deformation events. Deformation events were recognized by upward termination of faults at
717   various stratigraphic levels, by angular unconformities between trough infill units or fining-
718   upward packages, and by coarse, angular colluvial deposits that thin away from the footwall

719 (scarp-derived colluvial wedges). The average time span between deformation events in any
720 one trench in the past 12-15 ka is about 3-3.5 ka (e.g., in Trench 2, four events between 15.3 ka
721 and 5.5 ka; in Trench 3, successive events at 11.6 ka and 8.1 ka). Deformation seems to have
722 begun first in the lower part of the northern slope (vicinity of Trench 2) about 15.3 ka, and had
723 spread to the upper parts of the slope (Trench 3) by 11.6 ka. However, deformation in the lower
724 slope ceased after 5.5 ka, but still continued higher on the slope in the mid-late Holocene. The
725 youngest deformation dated (ca. 1.4-1.6 cal ka) occurred in the highest trench on the slope
726 (Trench 3). This pattern of younger deformation with increasing elevation has been documented
727 at several other sites (e.g., Panek and Klimes, 2016) and has been ascribed to an upslope-
728 migrating extensional stress field which originated at the base of the slope from glacial
729 oversteepening and end-glacial debuttressing.
730
731 Subsequent to our field campaign, there have been many published studies in which sackung
732 bedrock scarps were dated by cosmogenic radionuclides (CRN). That type of dating study does
733 not require trenching, which is admittedly difficult in many alpine environments. Although such
734 studies do result in an emergence and exposure history of the bedrock scarps, they do not
735 reveal the various sediment facies within the trough nor their deformation structures, and these
736 are necessary to reconstruct the (at least local) kinematics of DSGD deformation.
737

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