Megafans and outsize fans from catastrophic slope failures in Alpine glacial troughs: the Malser Haide and the Val Venosta cluster, Italy

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Abstract: A cluster of exceptionally large sediment fans occurs in Val Venosta, a glacial trough in the east-central Alps, Italy. Its 59 tributary valleys generate 49 fans with volume:catchment area ratios varying across four orders of magnitude. Geomorphological and statistical analysis distinguish 'allometric' and 'anomalous' fans. Catastrophic massive slope failure origins are suggested for the anomalous cases. They comprise 'outsize fans' and 'megafans', the latter attaining 400 m cone height and 2700 m radius, and dominating the trough. Above most fans, evidence is found for source cavities of comparable volume. Reconstruction of the missing sides and heads of two tributary valleys reveals lost mountains 700 m deep. They are credible sources for the Malser Haide, a globally significant 11 km-long megafan with an estimated volume of 1650 Mm^3, and the St Valentin outsize fans. Generally, anomalous fans occur where landslides are funnelled, comminuted and controlled through 'debouchures' high enough above the trough floor for conoidal deposition. Although sedimentological data are sparse, these fans may represent a new category of catastrophic slope failure outcome, mimicking conventional sediment fans of incremental origin. The Val Venosta cluster is the largest in the Alps, with concentrated glacial erosion in conducive geology among the possible factors explaining anomalous fan incidence.

Sediment fans in glacial troughs

Fan-shaped deposits are common in formerly glaciated mountains, especially where steep tributary valleys join broad troughs; this being a classic locus where high volumes of mobilized sediment suffer a sudden loss of transport power (Harvey 2003). The term 'alluvial fan' now generally embraces both fluvial and debris-flow-dominated deposits (Blair & McPherson 1994; Sorriso-Valvo *et al.* 1998; Iverson 2003). However, Derbyshire & Owen (1990) considered the epithet 'alluvial' clearly inappropriate as the majority of fan deposits in alpine environments are not laid by flowing water, but are partly or wholly composed of debris flows. They propose 'sediment fans' as a process-neutral term.

Fan gradients vary widely, with fluvial fans tending to lower angles, but gradient is not a good discriminant given that deposits are often mixed and in confined topographical settings (Sorriso-Valvo *et al.* 1998; Crosta & Frattini 2004). Thus, Fischer (1965) found trough-wall fans in the Alps (his 'murkegel' type) in the range 7–21%. In the Karakoram, Derbyshire & Owen (1990) recorded considerable overlap between fluvial fans (<17%) and debris-flow fans (<27%) in gradient. They also suggested that extensive (<18%) fans 'imply very wet, fluidized debris, and rapid flow and sedimentation rates' (p. 41). Fluidization can be achieved during transit by incorporation of ice, snow and wet sediments (Hewitt 1999). Legros (2006, p. 233) observed that 'the difference between landslides and debris flows is wholly gradational and related to the water content'.

It is generally assumed that cone-shaped fans in glacial troughs have grown incrementally, as evidenced by layered sections. Eisbacher & Clague (1984) described many incremental fan-building events in the Alps. Most of the contributions to Rachocki & Church (1990) and Harvey *et al.* (2005) follow this paradigm, although Lecce (1990) recognized a uniformitarian v. catastrophist issue in fan formation. The cases he cites for high-magnitude–low-frequency activity are, however, relatively modest, and he views their geomorphic role as still 'controversial'. By contrast, Derbyshire & Owen (1990, pp. 28 and 50) observed that debris-flow landforms may 'mimic closely the form of alluvial fans within high mountain valleys'; they concluded that a subtype of sediment fans can be identified that 'derive essentially from a few large, perhaps catastrophic events'; for example, the 150 m-thick Batkor cone. Hewitt (2001) confirmed a rockwall detachment source for Batkor as a single large rock avalanche deposit, among other similar cases. Watanabe *et al.* (1998) found that the largest debris cones in Langtang Himal came from

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slope failures, while Shang *et al.* (2003) described the deposit from a fresh 3000 Mm^3 rock avalanche in Tibet as a sediment fan. In Tajikistan, Evans *et al.* (2009) documented a sediment fan emplaced by the 1949 Khait 75 Mm^3 rockslide transformed in a rapid flow. Friele *et al.* (1999) identified a paraglacial collapse from the Mt Garibaldi volcano as the prime origin of the Cheekeye megafan, British Columbia, while conoidal deposits related to massive slope failure are documented at Huascaran, Peru (Plafker & Ericksen 1978).

However, an overview of the possible association between large fans and catastrophic slope failures in glaciated mountain ranges remains lacking. An instructive precedent is the reinterpretation of anomalously large 'terminal moraines' in the Karakoram as huge rock avalanche deposits (Hewitt 1999).

The classic model for sediment fans identifies an allometric (power-law) relationship between fan area and catchment area (Harvey 2003), albeit primarily for arid contexts. Crosta & Frattini (2004) reviewed its relevance for humid, deglaciated mountain environments. Their study of 209 'alluvial fans' confirms the negative allometric relationship between fan and catchment areas identified in such environments (Allen & Hovius 1998). Larger catchments are inferred to generate relatively small fans because they are less likely to have completed paraglacial resedimentation, while small catchments generate disproportionately large fans because of their limited sediment storage capacities. But over and above this built-in tendency, Crosta & Frattini (2004) identified 12 'anomalous' (non-allometric) fans, which they suggest may be associated with infrequent high-magnitude events (primarily large landslides).

Exceptionally large fans occur widely across the European Alps (Fig. 1), but none have been interpreted as catastrophic except for Biasca where a 20 Mm^3 outsize fan occurred as a single historical event in 1513, damming a temporary lake (Eisbacher & Clague 1984). Even though the Ponte-Chiuro megafan in Valtellina is located below a bold matching cavity, it was attributed by Crosta & Frattini (2004) to intense debris-flow activity rather than a single massive failure. The densest cluster of fans with areas greater than 3 km^2 occurs in Val Venosta, including the world-ranking Malser Haide at over 16 km^2. Its gross mismatch with a tiny catchment area has been noticed (Fischer 1965; Eisbacher & Clague 1984; Crosta & Zanchi 2000; Agliardi *et al.* 2009*a*) but not analysed, providing initial inspiration for this study. The aims here are:

- to catalogue the Val Venosta fans, identifying and characterizing anomalous cases;
- to reconstruct possible source configurations for the Malser Haide megafan and adjacent St Valentin outsize fans, where gross terrain anomalies suggest they could be the product of catastrophic landslides;
- to discuss the conditions leading to the observed clustering of massive slope failure in the study area in relation to topography, lithology, structure and glacial–paraglacial history;
- to consider, as an example of equifinality, how catastrophic slope failures can lead to the emplacement of conoidal deposits mimicking incremental fans, and thus to explore the possibility of anomalous fans as a new category of large slope failure outcome.

Existing sedimentological and dating information is sparse; geotechnical investigations are essential to verify the interpretations advanced and to explore geohazard implications.

Geomorphological and geological setting

Val Venosta (Vinschgau) is a major glacial trough between the Ötztal and Ortler ranges of the east-central Italian Alps (Fig. 1). Its lower part trends west–east for 42 km, descending from 900 to 500 m asl with its east end above Meran closed by a large fan complex into the Adige (in German the Etsch) gorge. At its west end, the Upper Val Venosta ascends north into the lowest gap in the main Alpine divide west of Brenner, the Reschen Pass (1500 m). The infilled trough floors are 1–2 km wide with a typical local relief of 1500–2000 m.

The terrain character falls into three elevation ranges, reflecting Quaternary glacial impact on an orogenic landscape that had become generally 'mature' and well adjusted to late Tertiary base levels. Below 2400 m asl steep slopes fall to the Venosta glacial trough, without high rockwalls; tributary valleys are more V-shaped than U-shaped because of gravitational and fluvial overprinting. Between 2400 and 2900 m relief is subdued with open ridges and broad upland valleys, with remnants of preglacial relief suggesting rather limited glacial erosion. Only above 2900 m do narrow, periglacially shattered, alpine crests occur, with limited cirque development. This is probably a glacial trimline: at the Last Glacial Maximum, the upper ice limit was approximately 2500 m asl (Van Husen 1987), but may well have been higher in the mid-Quaternary stadials. The present main Alpine divide at the Reschen Pass is only 5 km from the Inn valley. The preglacial divide is inferred to have crossed the Upper Val Venosta at St Valentin (Fig. 1). South-carried erratics (J. Reitner pers. comm.) here suggest the cutting of a major glacial

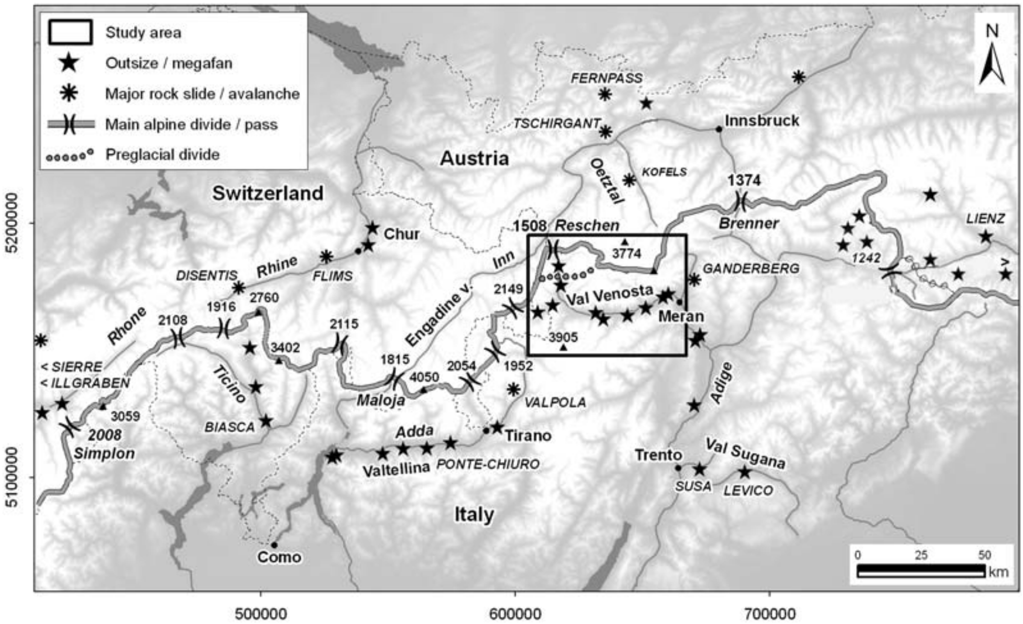

Fig. 1. The Central and Eastern Alps, with the main Alpine divide and passes, the Val Venosta study area, and the most prominent megafans, outsize fans and rockslides identified in the literature and from satellite imagery. The co-ordinate grid is UTM 32.

breach, with post-glacial diversion of former Inn tributaries to the Adige (Etsch).

The geology is predominantly Austro-Alpine metamorphic units (Fig. 2) (Agliardi *et al.* 2009*b*), comprising metapelites and metapsammites, with subordinate orthogneiss, metabasites and calc-schists. Slices of sedimentary Upper Palaeozoic–Mesozoic cover occur around the Upper Val Venosta. Val Venosta exploits the Vinschgau Shear Zone, which separates the Ötztal Unit from the underlying similar Campo Nappe. The entire stack is cut by north-, east-, NE- and SW-trending fractures, strongly constraining the drainage pattern and the strength of rock masses.

Rock slope failure is so extensive here as to be nearly endemic. Susceptibility depends primarily on lithology, fracturing and anisotropy (Hoek & Brown 1997). Where stronger rock masses occur (e.g. orthogneisses in the Plawenn valley, carbonates east of St Valentin), rockfalls and rockslides dominate. Where less strong, anisotropic rock masses occur (e.g. metapelites, paragneiss), deep-seated gravitational slope deformations (DSGSD) (Agliardi *et al.* 2001; Ambrosi & Crosta 2006) affect whole valley sides and interfluves (Agliardi *et al.* 2009*b*). In the Upper Val Venosta area, east-facing slopes tend to slope deformation, while west and NW-facing slopes are more prone to rock-sliding. This tendency is partly influenced by the low-angle Schlinig Fault underlying the west side (Agliardi *et al.* 2009*a*).

Anomalous fans and source cavities in Val Venosta

There are 59 tributary valleys in the 65 km length of Val Venosta plus Val Mustair; 49 have discernible fans at their mouths (Fig. 3, anomalous sites numbered and identified below as #). This indicates that fan production is here the norm across all catchment sizes and types. The equally diverse 'no-fan' group includes some large upper Venosta tributaries where the Malser Haide has either buried their fans or displaced their effective valley mouths down to its own toe, and a sequence at the east end of Val Venosta possibly attributable to damming by the Partschins fans (#12 and #13) and subsequent alluvial burial.

Preliminary fan assessment by proxy volume

The fans vary enormously in prominence, their scale often bearing little relationship to their catchment area. Adjacent pairs of similar side valleys commonly juxtapose tiny fans with outsize cones. To sort this extreme variation, a simple initial classification was carried out based on estimated volume

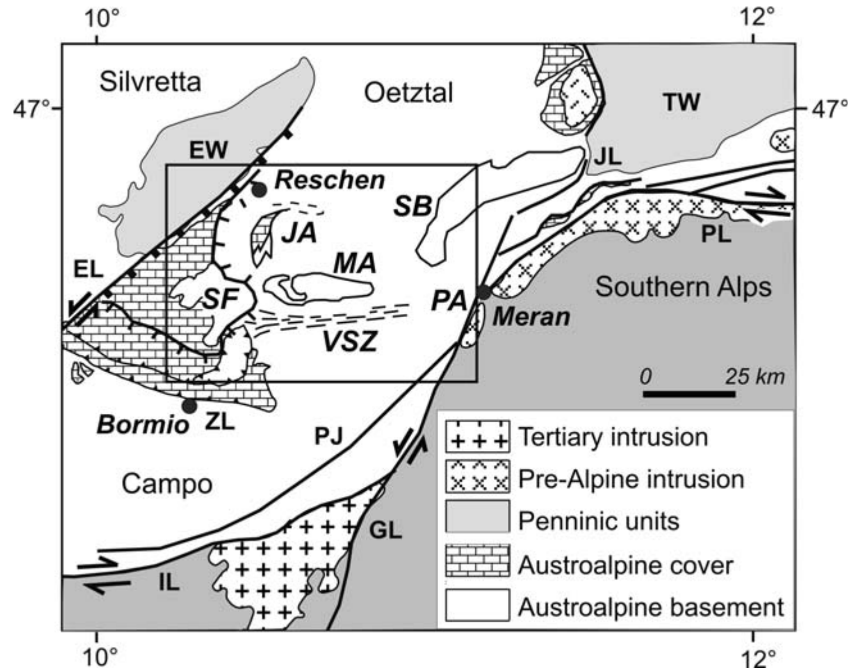

Fig. 2. Geological sketch map of the study area in the context of the eastern Central Alps. EW, Engadine Window; EL, Engadine Line; GL, Giudicarie Line; IL, Insubric Line; JA, Jaggl Permo-Mesozoic; JL, Jaufen Line; MA, Matsch Unit; SB, Schneeberg Unit; PA, Passiria Line; PJ, Pejo Line; PL, Pustertal Line; SF, Schlinig Fault; TW, Tauern Window; VSZ, Vinschgau Shear Zone; ZL, Zebrù Line.

following the method of Fischer (1965). Clearly, actual fan volumes cannot be determined without geotechnical investigation, but area and height can be combined via conoidal geometry to give ‘proxy volumes’. Although these proxy volumes imagine fan deposition on flat floors abutting vertical trough walls, they offer a reasonable basis for preliminary comparison where trough form is consistent. Proxy volume should normally exceed true volume, but at St Valentin (#2 and #3) it is less than half the estimate obtained from borehole-constrained cross-sectioning, illustrating an ‘ice-berg effect’ where fans coalesce or have buried toes.

Proxy volume:catchment area ratios vary across four orders of magnitude, and allow five types of fan to be distinguished in ascending order of visual prominence within the trough (Table 1). These five types fall readily into two broad categories.

- *Allometric fans* are the majority and represent ‘normal’ fan production, not standing out as discordant in the landscape. They are broadly proportionate to their catchment areas, and are inferred to have built incrementally from varying proportions of fluvial and debris-flow input; hence their wide range of gradients. They subdivide naturally into groups with smaller and larger volume:catchment area ratios, which may well correspond with the Type I and Type II fans of Blair & McPherson (1994), the latter having a greater debris-flow input attested by steeper angles.
- *Anomalous fans* stand out conspicuously, whether as ‘outsize fans’ emanating from micro-catchments (<3.7 km^2) or as ‘megafans’ dominating the troughs with huge volumes exceeding 250 Mm^3 (Table 2). In the megafan group, the Malser Haide is exceptional in both scale and character. The excess volume in these anomalous fans, over and above normal production by conventional incremental processes, can be inferred to derive from one or more high-magnitude events (Crosta & Frattini 2004).

Finally, the four very extensive but very low-angle alluvial fans (‘schwemmkegel’ of Fischer 1965) (Fig. 3) are from the five largest catchments. Although they are allometric in respect of fan area, they have extremely low proxy volume:catchment ratios, suggesting that they fall into a separate process domain.

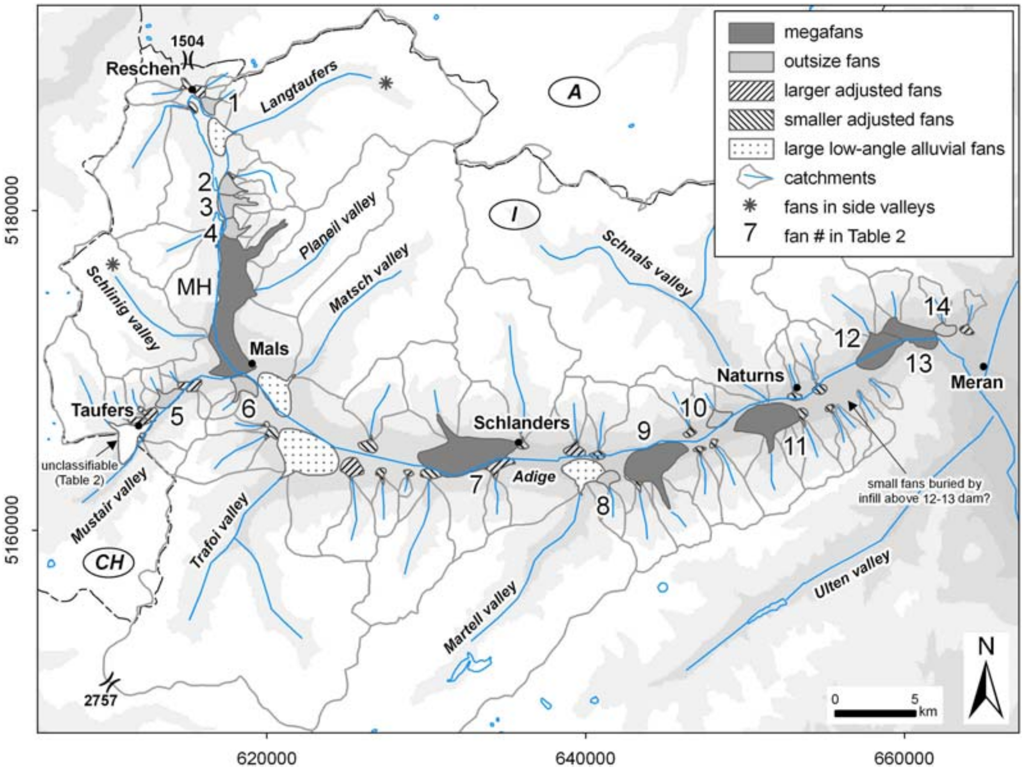

Fig. 3. Sediment fans and related catchment areas in Val Venosta and the Mustair valley. Fans are classified according to the procedure described. Outsize fans and megafans are numbered (Malser Haide marked MH). The co-ordinate grid is UTM 32.

Regression analysis by fan area

Building on this preliminary assessment of fan typology, a statistical analysis was carried out. Detailed measurement of key parameters from high-resolution LiDAR (Light Detection And Ranging) topography (2.5 m cell size) enabled regression analysis to be performed using fan area as the standard size descriptor. While most studies using this parameter deal with pediment fans in arid environments (e.g. Allen & Hovius 1998), it was also used in a study of the neighbouring Valtellina troughs (Crosta & Frattini 2004). Fan area is a more objective measure than proxy volume, although both encounter problems with variable underlying trough topography, and where fans are constrained by neighbours or are partly concealed by lakes or alluviated flood plains; fan area cannot allow for varying gradient. The distorting effect of confinement by neighbouring troughs was identified by Sorriso-Valvo *et al.* (1998) and, to identify a truer relationship, Crosta & Frattini (2004) excluded such constrained cases from their analysis. Larger fans are, of course, more likely to be 'confined', both distally and laterally, with the smaller ones best representing 'normal' or base-load fan production.

Iterative least squares, non-linear regression analysis showed that for the whole of the Venosta fan population ($N = 49$) the classic power-law (i.e. 'allometric') relationship is weak, with correlation coefficient $R = 0.36$. By excluding 15 'distally confined' fans and 12 'laterally confined' fans, a subset of the population comprising the unconfined fans ($N = 22$) gives a much better regression of the fan area–catchment area relationship, with $R = 0.83$. Applying 99.7% confidence bands rigorously identifies 'outlier' fans with respect to allometric assumptions (i.e. fans whose morphometric character has a negligible chance of being explained by the allometric model). The results then compare well with other studies (Table 3), although the dataset includes large low-angle alluvial fans that were excluded by Crosta & Frattini (2004).

The log–log plot of fan area v. catchment area (Fig. 4) clearly distinguishes most of the apparently 'anomalous' fans as lying well outside the

Table 1. *Val Venosta fan types and size:catchment ratios*

Fan type	N	Catchment area (A_c) (km^2)	Fan area (A_f) (km^2)	Fan height (H) (m)	Fan radius (R) (m)	Fan gradient (G_f) (%)	Fan proxy volume (V) (Mm^3)	A_f/A_c ratio	V/A_c ratio (Mm^3 km^2)
Allometric fans	**33**								
Large low-angle alluvial	4	95–167 (133)	2.2–8.6 (4.4)	20–70 (45)	1550–2500 (1840)	4–6 (4)	18–92 **(56)**	0.02–0.05 **(0.03)**	0.2–0.5 **(0.4)**
Smaller	19	2.6–49.6 (10.9)	0.1–0.7 (0.33)	25–150 (70)	280–900 (550)	8–27 (15)	0.4–12 **(5.3)**	0.01–0.09 **(0.05)**	0.1–1.8 **(0.8)**
Larger	10	0.8–10.4 (3.2)	0.2–1.3 (0.64)	75–250 (150)	400–1650 (830)	8–27 (18)	4–55 **(27)**	0.12–0.45 **(0.27)**	4–16 **(9)**
Anomalous fans	**16**								
Outsize	10	1.4–3.7 (2.2)	0.8–1.6 (1.3)	130–350 (195)	800–1500 (1050)	13–23 (17)	35–100 **(69)**	0.24–1.14 **(0.63)**	13–57 **(35)**
Megafans	5	5.3–18.7 (11.0)	3.4–10.6 (6.2)	230–400 (300)	1600–2700 (2100)	11–21 (14)	268–916 **(513)**	0.42–0.64 **(0.56)**	33–67 **(47)**
Malser Haide (MH)	1	9	16.5	–	–	11.5	*1650*	1.83	*200*
Total fans	**49**								
No fan	**10**	2.0–236 (44)	–	–	–	–	–	–	–
Total tributary valleys	**59**								

Notes:
1. Data given as ranges with averages (in parentheses). Figures in bold highlight the marked distinctions between categories.
2. ‘Proxy volume’ data are obtained by conoidal geometry for comparative purposes only, see the text.
3. One unclassifiable fan is included in the outsize fans tally but is excluded from the data tabulation (see Table 2).
4. Malser Haide is shown separately from the more typical megafans. Its volume is a best estimate from cross-sectioning, not comparable with proxy volumes (data in italics).

Table 2. *Val Venosta outsize fans and megafans*

# ref in Fig. 3	Fan	Note	Catchment area (A_c) (km^2)	Fan area (A_f) (km^2)	Fan gradient (G_f) (%)	Fan height (H) (m)	Debouchure width (W) (m)	Fan proxy volume (V) (Mm^3)	Volume Fischer (Mm^3)	A_f/A_c ratio	V/A_c ratio (Mm^3 km^2)
	Outsize fans										
1	Reschen	1	1.7	1.1	22	350	125	70	67	0.65	30
2	St Valentin North	1	1.4	1.2	15	200	375	80	72	0.86	57
3	St Valentin South	1	2.3	2.0	16	150	450	100		0.87	43
4	Fischerhauser		1.9	1.4	14	140	460	47	–	0.74	25
5	Taufers NE		1.9	1.4	23	200	175	74	–	0.74	39
6	St Martin/Glurns		2.1	1.5	17	150	150	78	80	0.71	37
8	Mareinweisen	2	3.7	0.9	13	160	250	54	–	0.24	15
10	Tschars		1.8	1.1	23	280	230	97	–	0.61	54
14	Algund/Meran	2	2.7	0.8	18	130	–	35	–	0.30	13
–	*Avignatal*	3	21.0*	2.2	14	150	–	90	–	0.10*	4.3*
	Megafans										
7	Allitz/Laas	6	18.6	10.6	13	300	500	916	1350	0.57	49
9	Tarsch/Latsch		9.8	6.9	16	300	600	567	630	0.61	58
11	Tabland		11.4	6.2	11	230	500	385	420	0.54	34
12	Partschins West	4	10.0*	4.2	12	240	450	332	280	0.42*	33*
13	Partschins East	5	5.3	3.4	17	400	–	268*	240	0.64	51*
MH	Malser Haide	5	8.3	16.5	$16 > 11 > 7$	(200)	(650)	1650*	1550	1.99	200*

Notes:
'Volume Fischer' is from Fischer (1966), obtained by conoidal geometry (basis of calculation for #MH unclear).
*Data not comparable, see the numbered notes.
1. Toes in reservoir: proxy volumes taken to former lake shore; true volumes estimated from valley cross-sections with allowance for prior infill (see text) are: (#1) 65 Mm^3; (#2) 200 Mm^3; and (#3) 230 Mm^3.
2. These cases have significantly lower area:volume ratios to catchment, and are on the regression confidence limit (Fig. 4). They are transitional with large allometric fans.
3. This unclassifiable fan has a volume much greater than any allometric fan and a conoidal shape, but debouches into Münstertal from a large catchment giving it very low ratios. It is likely that the deposit emanates from a small part of the outer basin, but a suspected catastrophic source has yet to be verified. Compare #12.
4. The fan emanates from the large Zielbach catchment (32 km^2) but is evidently sourced from a side bay just inside its mouth; the arbitrary catchment area given here is for the outer basin, offering best comparablility, but the specific catchment is only 4 km^2.
5. These fans are not conoidal and proxy volumes cannot be obtained. #13 is estimated assuming overlap onto #12 and infill of a V-valley to 100 m average thickness; for #MH see text.
6. Subsequent field work and valley section calculations indicate that this site has a larger true fan volume and lost mountain source than Malser Haide. This fan is the Gadriamure of Fischer (1966).

Table 3. *Values of coefficient* c *and exponent* k *in the power-law relationship ($A_f = cA_b^k$) between fan area and catchment area in humid mountain ranges*

Location		Sample	*c*	*k*	*R*
Present study	All fans	49	0.93	0.33	0.36
	Unconfined fans	22	0.25	0.52	0.83
Valtellina area (Crosta & Frattini 2004)	All fans	209	0.29	0.33	0.35
	Unconfined fans	64	0.15	0.65	0.81
Banff, Alberta*	Fluvial fans		0.48	0.32	
	Debris-flow fans		0.17	0.48	
Roan Mt, North Carolina*			0.38	0.76	
Dellwood, North Carolina*			0.23	0.53	

*North American data from Crosta & Frattini (2004, table 1).
R, coefficient of correlation.

regression confidence limit, with only a few borderline cases. They are grossly disproportionate to catchment area, with the two distinct clusters of 'outsize fans' and 'megafans' almost an order of magnitude apart, suggesting responses to different scales of terrain in the study area. Both point to catastrophic events for which sources can be sought.

Anomalous sources for anomalous fans

Recognizing anomalous cavities as possible sources for problematic deposits (e.g. Hewitt 2001), let alone reconstructing them to determine comparability of volume (e.g. Jarman 2002), is not yet common practice in geomorphology. Thus, in the Central

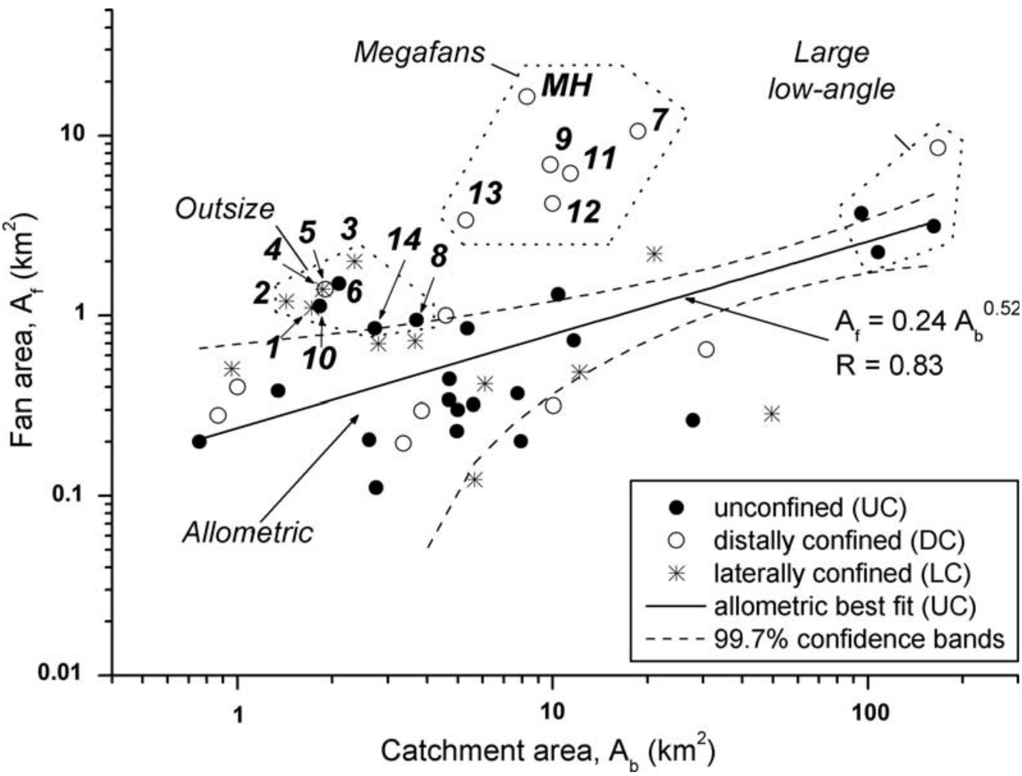

Fig. 4. Log–log plot of fan area v. catchment area for the 49 sediment fans mapped in Val Venosta. Fans are classified according to confinement. The solid line represents the allometric best fit for the unconfined (UC) data subset ($N = 22$). The dashed lines represent 99.7% confidence bands. Different groups of fans are identified (see Table 1); anomalous fans are numbered as per Table 2.

Alps, Fischer (1966) simply regarded the whole catchment valley space ('hohlraum') as the anomalous fan source: for 12 cases he found fan:hohlraum ratios averaging 1:1.8 (excluding Tabland (#11) as exceptional at 1:6). However, in Val Venosta most of the 15 megafans and outsize fans have specific source cavities or broader anomalous landform configurations identifiable from topographical maps, LiDAR topography and satellite imagery. These candidate sources often appear to be sharply bounded landslide scars, and usually occupy more than a quarter of the catchment area (Fig. 5).

These anomalous cavities are generally not just simple voids in the open trough wall, but are linked to the trough floor by somewhat narrower 'debouchures' of measurable width (Table 2); their significance is discussed below.

Evidence for the most striking cases is now examined:

- #1–Reschen (Fig. 5a): a remarkably steep cone debouches from a broad chute below an embayment only 1.7 km^2 in catchment area. The cirque bowl beneath the 2981 m summit appears well adjusted. Below 2500 m, a subarcuate cavity bites roughly 150 m into the trough wall, faceted by scars controlled by NW–SE- and NE–SW-trending fractures, and yielding a volume broadly equivalent to the fan. Intense post-collapse debris flows may have steepened the cone. The boldest wedge facet cuts into a broad paragneiss ridge on the SE flank where incipient retrogressive scarps indicate deep-seated deformation.
- #2–#4, #MH. see detailed reconstructions in the following sections on 'The Malser Haide megafan' and 'The St Valentin outsize fans'.
- #5–Taufers NE: at the foot of the Mustair valley, a sequence of contiguous fans of different types suggests intermeshing of catastrophic and incremental processes. The boldest outsize cone debouches from an open chute beneath an evident cavity that sharpens the deforming orthogneiss crest. Two adjacent bays have even wider debouchures above bajada-like debris banks; the smaller retains bulky slip-masses, the larger appears evacuated.
- #6–St Martin, Glurns (Fig. 5b): a steep cone emanates from an open chute below a sharply defined wedge cavity biting into the end of a broad split-crested ridge; residual slipped material lies in the apex and an arrested rockslide occurs on the left side just upslope from the debouchure. The scar in mylonitic orthogneiss and mica-schist is controlled by north–south and NE–SW fractures. Extrapolating a pre-cavity hill form yields a volume of 96 Mm^3, equal to the cone if it extends below the toe of the Malser Haide. This is a particularly good candidate for a single catastrophic event, given that the adjacent bay of similar catchment area produces only a tiny fan (Lichtenburg). In this extreme case, virtually the entire catchment is the inferred source cavity.
- #7–Allitz/Laas (Fig. 5c): one of the largest symmetrical fans in the Alps deflects the Adige (Etsch) river to the opposite slope foot and dominates Val Venosta as an extraordinary half-barrier. The upper catchment has an open valley floor and north side well adjusted to the *c.* 2500 m asl trough rim topography. It hangs above a more rectilinear lower V-basin, cut into mylonitic paragneiss and mica-schist, and sharply delimited by NE–SW structural controls. This inferred slope failure cavity has rendered the upper basin highly asymmetric, and beheaded the adjacent valley (cf. the Vivana valley, Fig. 5d discussed below. Reconstructing these anomalies identifies a lost slice between the upper and lower basins of some 4 km^2 and averaging 200 m in depth, which yields a volume comparable to the *c.* 900 Mm^3 proxy volume calculated for the fan (but see Table 2, note 6).
- #9–Tarsch/Latsch: although resembling #7 in its remarkable cone height, gradient and ratios to catchment, a single source cavity is less evident here. Several mid-slope gully bays carved in orthogneiss and metapelites would yield a volume comparable to the fan if reinstated by an average depth of only 75 m. This could point to multiple event origins for this cone. The debouchure is unusually wide (600 m). The adjacent valley to the west, which is of similar catchment area and topographical character, has no significant fan. The broad summit ridge from here eastwards is lower relief (*c.* 2500 m) and much deformed.
- #11–Tabland: this is similar to #9 except that a single large cavity could be reconstructed more readily across the lower half of the valley side. Tree logs near the toe have only been buried to a depth of 7 m since 2600 BP (Staffler & Nicolussi 2004). None of the six similar conventionally gullied catchments to the east display fans, although they may have been concealed by alluvium.
- #12 and #13–Partschins West/East: these fans overlap, with the west one (Zielbach) being conoidal and rather dissected, and the east one (Töll) confined by and funnelled down the Adige (Etsch) gorge. The trough is cut into metagranitoids and paragneiss, with a thick cover of slope and glacial debris. Widespread east–west- and NE–SW-trending gravitational deformation morphostructures behead a series of glaciated upland basins at the 2500–3000 m rim.

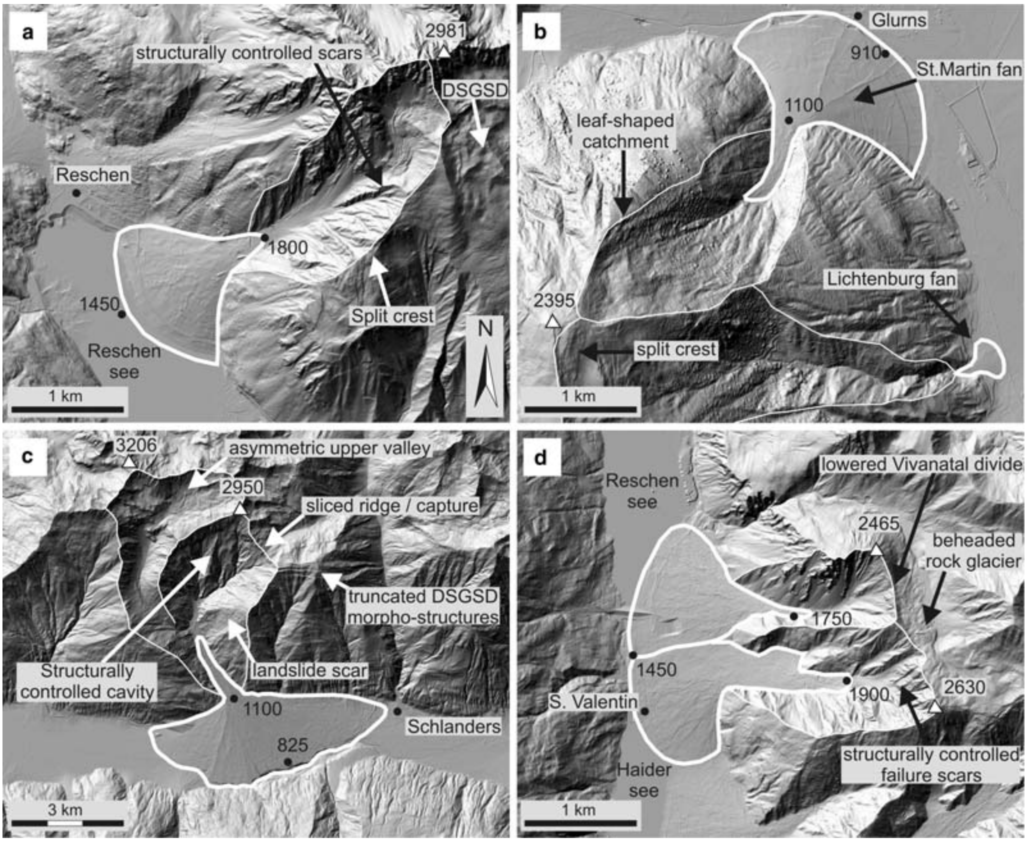

Fig. 5. Anomalous cavity–fan systems in Val Venosta. Thick and thin solid white lines represent fan and cavity boundaries, respectively. (**a**) Reschen outsize fan (#1 in Fig. 3). (**b**) St Martin outsize fan (#6) and the adjacent Lichtenburg Valley with minimal fan. (**c**) Allitz/Laas megafan (#7). (**d**) St Valentin outsize fans (#2 and #3). Note the widespread slope deformation (DSGSD) indications. Basemaps: LiDAR topography at 2.5 m resolution.

Immediately below this rim, sharp breaks may define the sources of the two failed masses that have generated the cones.

- #14–Algund: the catchment is within the same paragneiss slope affected by extensive deep-seated deformation, suggesting a source of fractured material. It emanates from a dog-leg ravine that may be a debouchure closed in by subsequent rock slope failure. Despite intense gullying of the high scarp, there has only been 5 m of debris overlay to the main gravelly deposit since 5200 BP (Spindler 1994).

Key diagnostic landforms for anomalous source cavities thus include: interruption of the continuity of topographical features; beheaded valleys; and bold planar/wedge/subarcuate forms with unusually clean-cut boundaries. These are often associated with regional structural orientations, split ridges, and other evidence of deep-seated deformation and slope failure. Distinct or probable source configurations are discernible in 11 cases, with Tarsch, Tabland and Partschins requiring closer investigation. All except Partschins have distinct debouchures ranging from broad gullies and wider recesses to hanging bays and short tributaries.

The secondary Venosta valleys generally lack significant fans, except at Melag in Langtaufers (similar to #6 St Martin), and one in Schlinigertal beneath a distinct source bay. At these locations (Fig. 3) the secondary valleys are broad troughs; elsewhere their narrowness, V-shape and gradient are inimical to fan development.

There is little evidence for fan ages. They presumably post-date final deglaciation, with the destabilized mountain sources either collapsing soon after withdrawal of glacier buttressing or delayed until progressive failure and/or trigger events

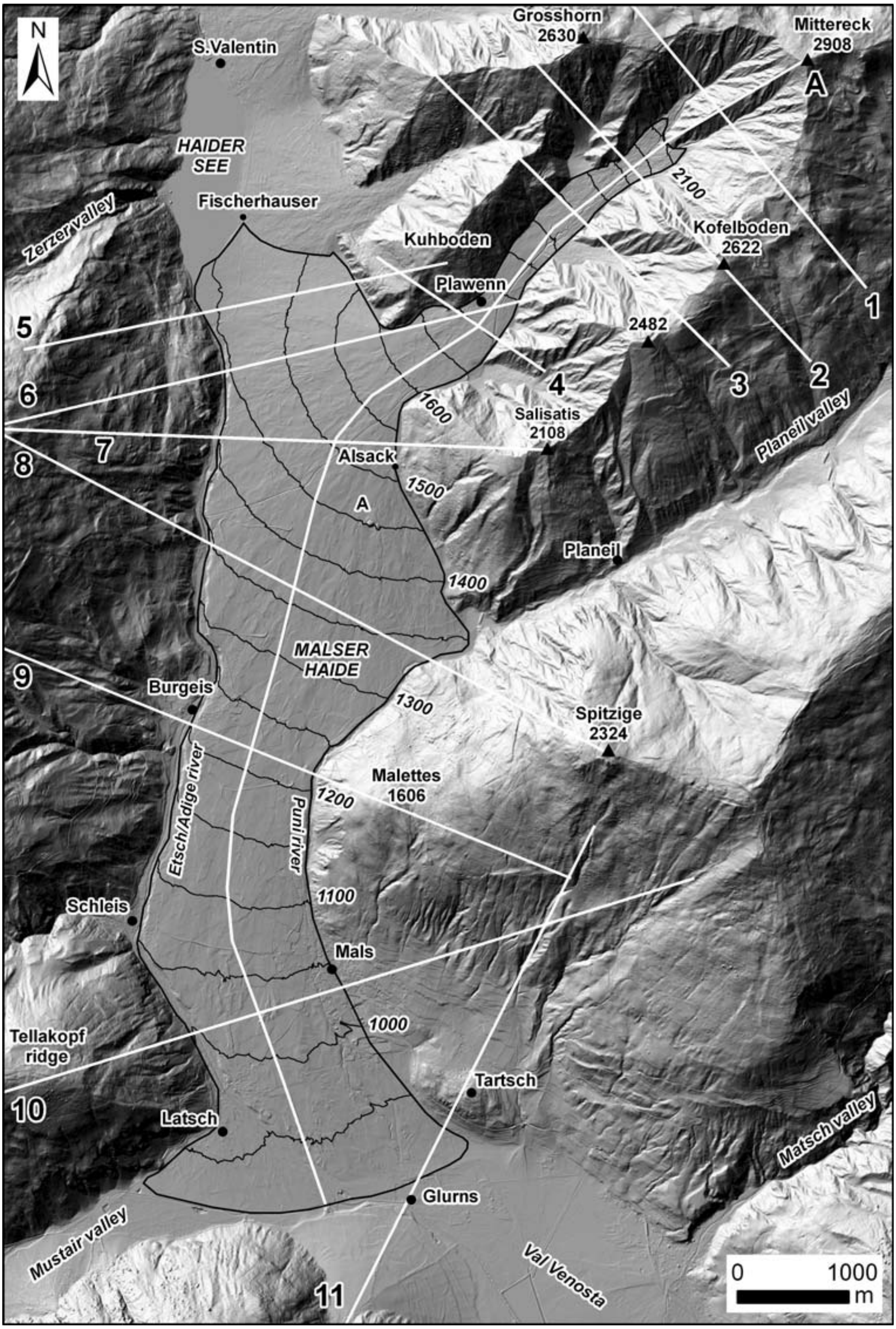

Fig. 6. The Malser Haide megafan and source area (Plawenntal), within the upper Val Venosta. Contour lines of the Malser Haide are at 50 m intervals. Traces of the long section of Figure 8 and cross-sections of Figure 9 are shown. Note the splitting crests of main ridges indicating slope deformation. Basemap: LiDAR topography at 2.5 m resolution.

exceeded critical thresholds (Prager *et al.* 2008). At Allitz/Laas (#7) the fan toe overlies Adige (Etsch) valley-floor sediments, with logs dated to around 7300 BP (Fischer 1990). Most fans have undergone remarkably little fluvial dissection of their surfaces or erosion of their toes, possibly suggesting recency or continuing aggradation, but alternatively it could be that they are so large and massive that Holocene processes have had little impact on them.

The Malser Haide megafan

The Malser Haide has long been celebrated as the largest 'alluvial fan' in the Alps (Penck & Brückner 1909; Taylor 1940; Eisbacher & Clague 1984). With an area exceeding 16 km^2 (Table 3), it is one of only three fans with Allitz/Laas (#7) and Illgraben (Fig. 1) noted by Fischer (1966) that exceeds 10 km^2. It is remarkable for its exceptional overall height (900 m) and length (11 km), extending far beyond the main cone both headwards and down-valley.

The Malser Haide occupies much of upper Val Venosta (Fig. 6). It emanates from the small Plawenn side valley, which has a catchment area of 8.3 km^2 and unexceptional available relief (summit: Mittereck 2908 m; Fig. 7a). At its oblique point of entry into the upper Venosta trough (1600 m) it fans out in a conventional smooth conoid of 'distally confined' form (Sorriso-Valvo *et al.* 1998) to dam the small Haidersee (1450 m). It then continues on down the 1–2 km-wide main trough, with a progressively more planar surface to the confluence with Val Mustair at Glurns (910 m). The head of the cone retrogresses more steeply 3 km into the Plawenn source valley. The deposit dramatically overfills the trough (Fig. 7b), displacing the Adige (Etsch) and Puni rivers against their respective valley sides. Its notably smooth overall surface (Fig. 6) may partly reflect extensive boulder clearance and cultivation. It being named as a heath and its irrigation attest to its porosity. There are numerous shallow dry channels, with floods and superficial debris flows recorded in recent centuries (Eisbacher & Clague 1984).

The exceptional length of the Malser Haide is attributable to its topographical context. Most megafans in the Alps debouch into broad, low-gradient glacial troughs (eg. Rhône, Valtellina). The upper Venosta trough is a glacial breach and, therefore, descends relatively steeply (450 m in 8 km, or 5.6%) into the main low-gradient trough (400 m in 42 km, or 1%). The Plawenn valley enters the upper Venosta trough at a 17% gradient at an oblique angle that is conducive to onward travel: if it debouched into a typical trough a more

Fig. 7. The Malser Haide megafan. (**a**) Cone debouching from Plawenntal into the upper Val Venosta; the inferred lost mountain 'Plawennspitz' location is above the head. View NE from Mt Watles ski lift base station.

conventional fan form would have resulted. Nevertheless, the Malser Haide has a 250 m cross-trough cone height and a gradient profile (16% at the head, 10–12% on the cone, declining to 7% at the toe: Fig. 8), which are within the typical range of Alpine megafans (Fischer 1965). There is no information on the age of the Malser Haide, but it clearly post-dates final local deglaciation.

Quantifying the Malser Haide

There is no available borehole or geophysical evidence on the thickness of the Malser Haide fan. Although mathematical procedures exist to obtain glacial trough bedrock profiles (Schrott *et al.* 2003; Jaboyedoff & Derron 2005), the possible form of the atypical upper Venosta breach trough is more naturally obtained by graphically extrapolating cross-sections at *c.* 1 km intervals (Figs 6 & 9). The profiles assume a gently parabolic form that can be projected and reasonably constrained from the extant valley side slopes, which vary between 35 and 70%. A relatively continuous long profile of the bedrock valley floor is obtained (Fig. 8), although its varying width may suggest a more stepped long profile. The marked widening at the Planeil valley mouth may be illusory, if the rock 'island' near Alsack (Fig. 6) is bedrock and indicates the trough margin proper.

In estimating a volume for the Malser Haide fan, the key assumption is the depth of prior infill by glacial, glacifluvial, debris-flow and alluvial deposits. Major Alpine glacial troughs can have kilometric infill depths, but this is implausible here. A conservative prior infill depth of 100–125 m has, therefore, been adopted for the core 7 km (Plawenn–Mals). The long section (Fig. 8) shows total sediment thickness as fairly constant, but has the prior infill thinning back to zero in the Plawenn valley, and likewise the Malser Haide debris layer thinning out to zero at Glurns. Applying the cross-sectional areas net of prior infill to the relevant approximately 1 km lengths gives a best estimate megafan volume of 1650 Mm^3.

Simple robustness checks on this volume address three variables:

- Bedrock floor shape – this is well constrained because the width of the Malser Haide surface is fixed, and the considerable taper in the cross-section even above the prior infill reduces the effect of any deviation. Deepening the floor by 100 m increases the fan volume by 80 Mm^3 over a typical 1 km length or 600 Mm^3 over

Fig. 7. (*Continued*) (**b**) Sediment infilling upper Val Venosta and tapering into the main Val Venosta trough head. Asymmetrical cross-profile is real – compare Figure 9, sections 6 and 7. View north from St Martin above Glurns.

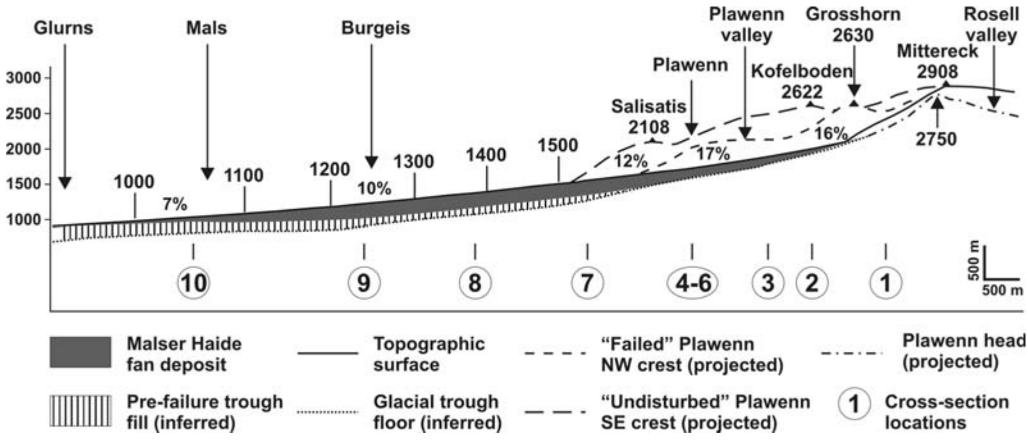

Fig. 8. Longitudinal section of the Malser Haide megafan (profile trace in Fig. 6), showing the inferred depths of the catastrophic failure deposit and prior infill. Asymmetry of Plawenntal is demonstrated by profiles of its NW and SE crests. The cross-section locations (Fig. 9) are shown.

the core 7 km. The precise shape of the Plawenn valley itself is less material because it contributes only about 100 Mm^3 of the volume.

- Depth of prior infill–as this is in the tapering floor and its width is only about half that of the Malser Haide surface, varying it by ± 50 m alters volume over the core length by 200 Mm^3 per 50 m depth, maximally ± 500 Mm^3.
- Toe concealment by alluvial deposits–debris layer extension by 2 km at 100 m thickness increases the volume by 200 Mm^3.

Until geophysical depth profiles are available, a broad range for the estimated fan volume is appropriate. These robustness checks suggest a volume of 1150–2450 Mm^3, assuming that a deeper floor is unlikely to have shallower prior infill.

Problems with reinterpreting the Malser Haide origin as catastrophic

Eisbacher & Clague (1984, Appendix A86) observed that the Malser Haide 'drops off from an astonishingly small catchment basin, forcing the Etsch river against the west side of the valley for almost 10 km'. Viewed from any vantage point (Fig. 7a), it seems improbable that the small Plawenn valley could yield sufficient debris to build such a megafan by episodic debris flows and floods. However, unlike the other Venosta cases reviewed earlier, there is no obvious cavity of sufficient size within the Plawenn valley. Yet, the area around the valley head displays many large-scale terrain anomalies, especially the obviously beheaded Vivana valley, and extensive evidence of slope failure (Fig. 10).

The possibility of a catastrophic mass movement origin for the Malser Haide has been noted previously (Crosta & Zanchi 2000). Fischer (1966) recognized its exceptional scale but, as with all Venosta fans, attributed it to numerous fluvial events, including glacial melting, ice-dammed lake bursts and 'catastrophic' rainstorms, with 'piles of rubble driven by water like lavaflows'. He treated the entire Plawenn valley space or 'hohlraum' as the source cavity, obtaining his closest fan volume: hohlraum ratio (1:1.1). Despite this close coincidence, it is an implausible origin. By reference to valley spacing in the surrounding area, a short side valley would naturally have pre-existed here; the two dendritic gully complexes on the SE side of the valley are inconsistent with a rockslide scar, by comparison with the smoother valley-head gullies; the terrain form achieved by extrapolating perimeter ridge contours across the present valley is incongruous; and the anomalous terrain around the valley head cannot be reconciled with it.

Nonetheless, a catastrophic interpretation must address three principal difficulties.

- Can a plausible source for such a large deposit be identified, given that it must be substantially above the rims of the present Plawenn valley if the hohlraum-source explanation is rejected? At the Köfels catastrophic rockslide (Fig. 1), the failure plane daylighted well behind and sheared off the crest of the Fundus ridge, which flanks the west side of Ötztal (Heuberger 1994), leaving no measurable cavity. The lost ridge is inferred to have been some 300–400 m higher (Sørensen & Bauer 2003; Prager *et al.* 2009*b*). A similar 'lost mountain ridge' is proposed here.

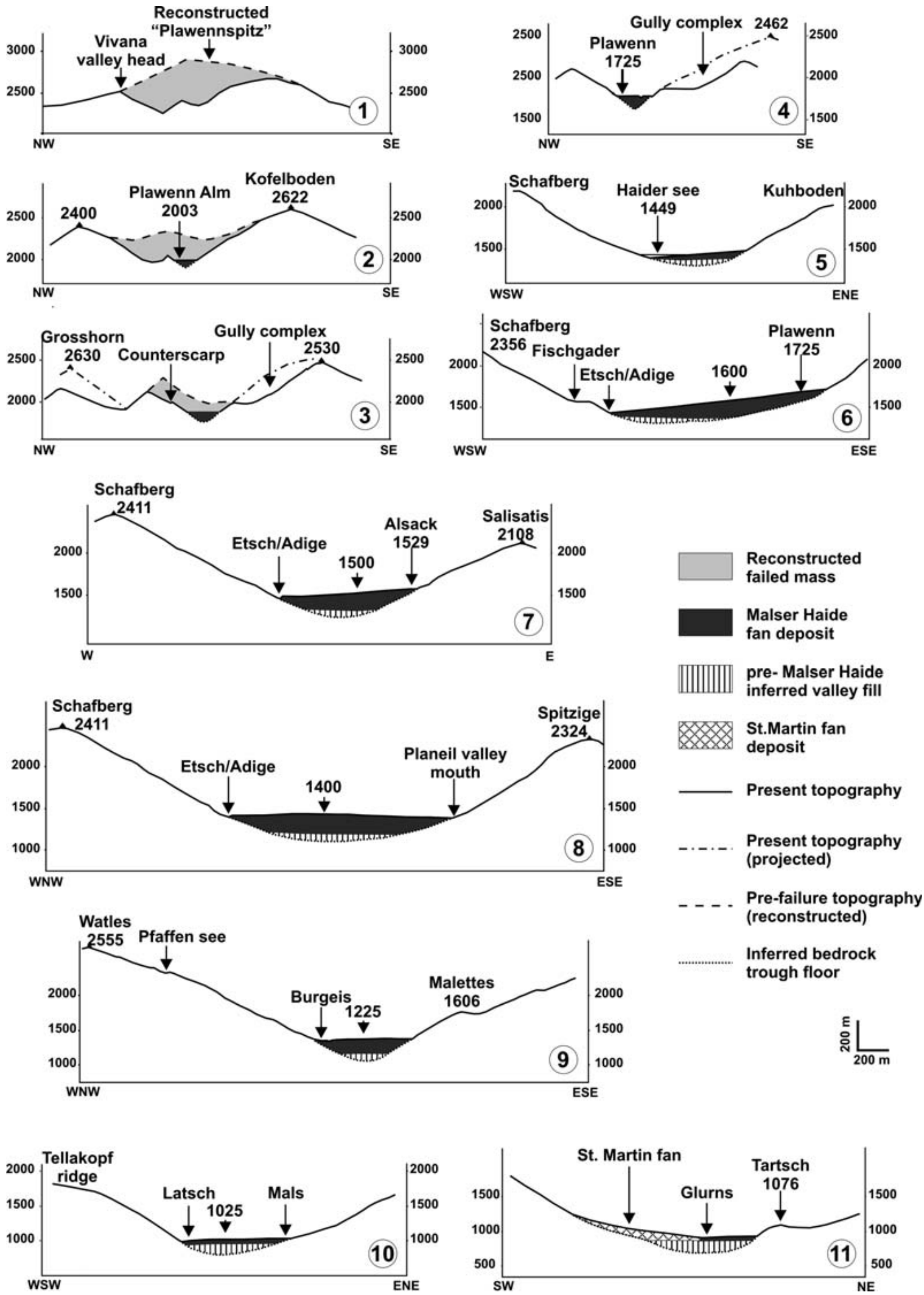

Fig. 9. Schematic cross-sections of the Malser Haide megafan (profile traces in Fig. 6), showing their parabolic extrapolation from existing valley side slopes. Section 8 appears flat floored because it extends into the mouth of Planeiltal; it overstates the deposit if the main trough is narrower at Alsack island ('A' in Fig. 6). Sections 1–3 include the 'Plawennspitz' lost mountain and the Plawenntal lost NW ridge (Fig. 13).

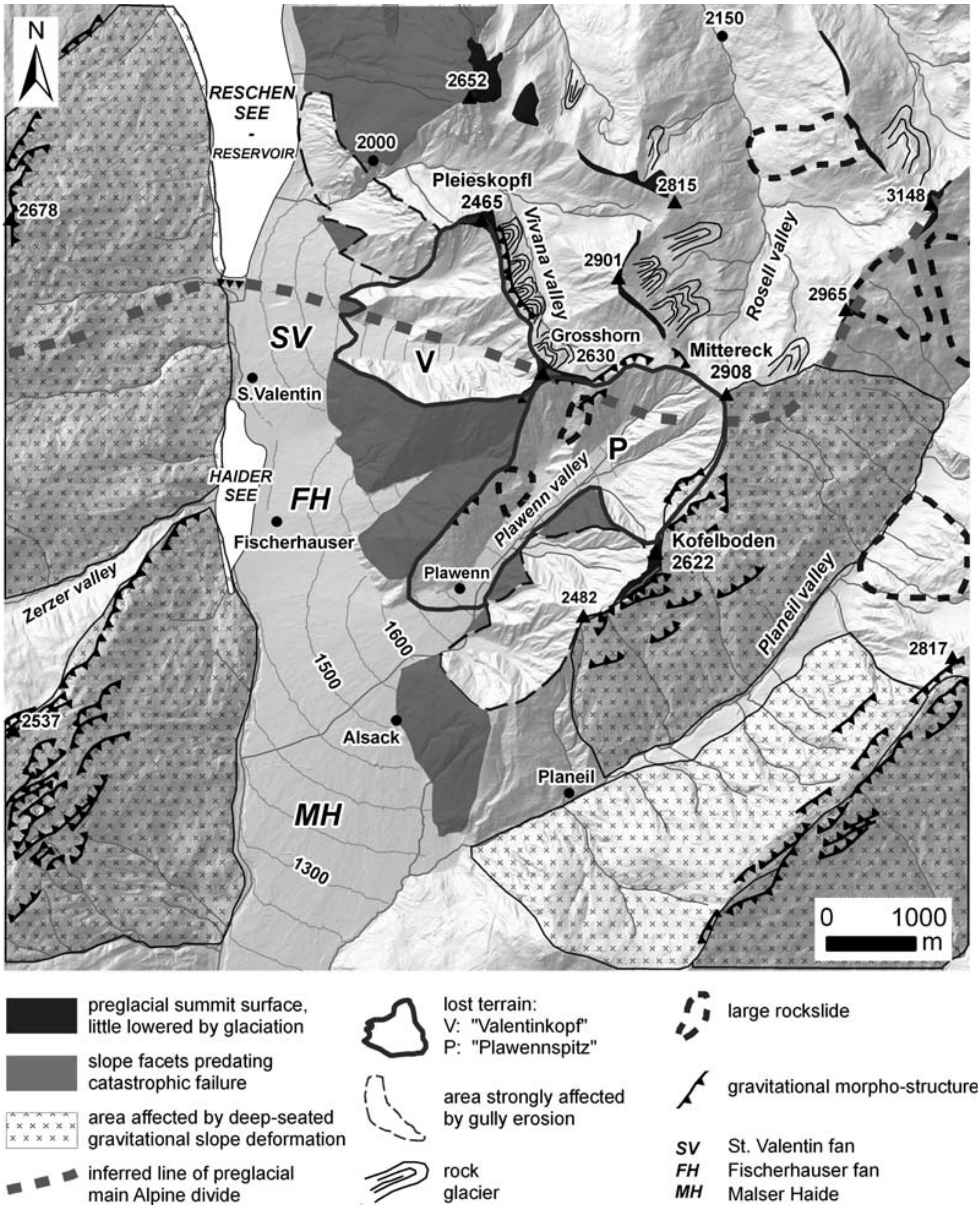

Fig. 10. Geomorphological sketch of the source areas for the Malser Haide megafan and the St Valentin outsize fans. Note the well-adjusted terrain character of adjacent valleys used for 'clone-stamping'. Intact or near-intact terrain elements define perimeters of inferred catastrophic slope failure events at 'Plawennspitz' (P) and 'Valentinkopf' (V). Basemap: LiDAR topography.

- How can catastrophic failure be asserted when it is not yet known whether the Malser Haide is a homogenous diamict of disintegrated bedrock, and not a layered structure of incremental flows and outwashes? In the absence of quarries or deep river cuts, this must await geotechnical investigations. However, at St Valentin (#2 and #3), eight closely-spaced boreholes near the fan margins up to 100 m deep show chaotically intermixed sediment grades with no consistent layering (Fischer 1966), while at Allitz/Laas (#7) the 40 m-thick megafan toe is a massive unstratified diamict with plurimetric blocks (Fischer 1990).

- If a lost mountain comparable with the Fundus ridge at Köfels is identifiable here, how could its catastrophic collapse and discharge have been mobilized so as to settle out into the smooth form of a fan? Does the smooth surface indicate a high degree of comminution of mobilized debris or an overlay by subsequent debris flows and alluvial deposition? If the latter, how could such relatively low-energy processes extend smooth deposition for 11 km? This is addressed in the Discussion below.

Reconstructing a lost mountain source for the Malser Haide

A lost mountain can be reconstructed above the present head of the Plawenn valley of sufficient scale to support a catastrophic origin for the Malser Haide. Its former existence is apparent from extensive anomalous upland terrain (Fig. 10). Reconstruction of a geomorphologically authentic pre-failure landscape is possible by an iterative process for which published exemplars appear lacking. This process recognizes the typically sharp boundaries between pre- and post-failure terrain, and rebuilds a reasonably constrained proto-relief by reference to intact landform 'templates' in the vicinity ('clone-stamping'). The methodology comprises:

- preparing a geomorphological map based on terrain character (Fig. 10);
- identifying slope facets and ridge lengths that appear little modified by post-glacial mass movements;
- identifying landscape elements that may have been truncated or displaced, for example, valley heads, rock glaciers (Figs 11 & 12);
- identifying large landslips and slope deformations, and reinstating them to former elevations;
- defining the boundary of the pre-catastrophe terrain form around the inferred cavity;

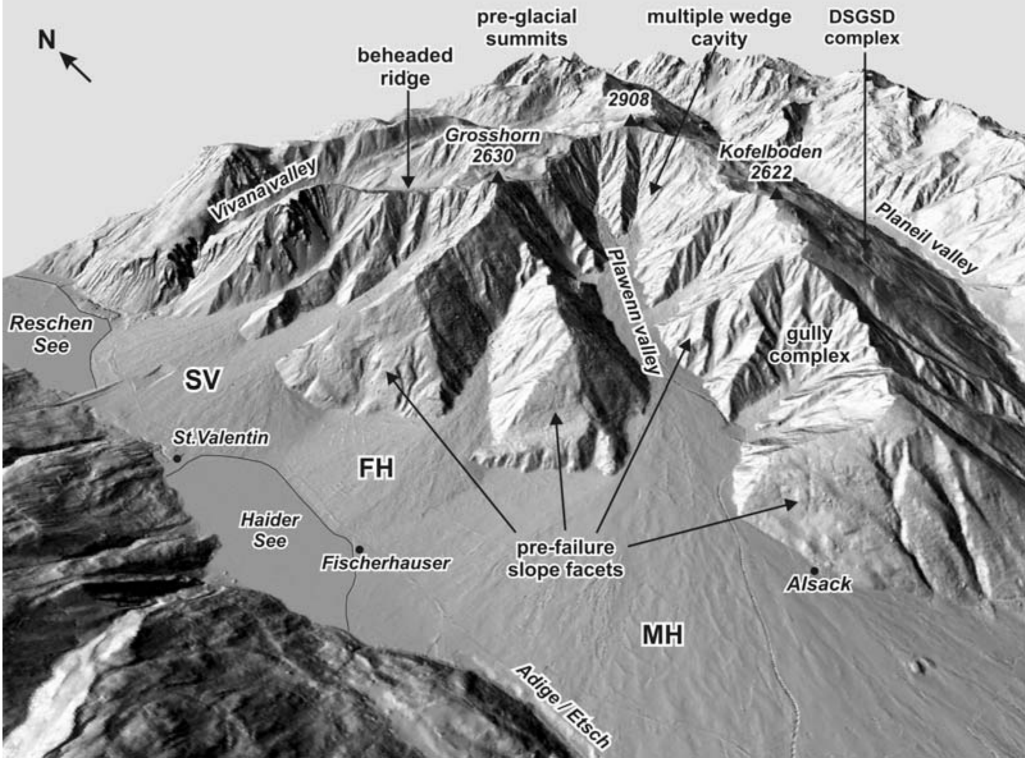

Fig. 11. Source areas for the St Valentin outsize fans and the Malser Haide megafan, with the dismembered Vivana valley. The Plawenn valley head displays bold wedge structures fresher than adjacent gully complexes, inferred to have assisted detachment of the failed mass. Oblique view from SW (3D rendering of LiDAR topography).

Fig. 12. Anomalous morphological features indicative of the lost mountains 'Plawennspitz' and 'Valentinkopf'. (**a**) The Vivana valley remnant west rim, looking north from the foot of Grosshorn: a beheaded rock glacier drapes back over the headwall of the St Valentin south fan cavity. Note the anomalous 'crater' at the far end of the ridge, source of north fan. (**b**) The Vivana valley with beheaded rock glacier complex, looking west from the Habicherkopf ridge, the St Valentin breach shown beyond: the far side of the valley is the inferred site of the lost mountain 'Valentinkopf'. (**c**) View from Kofelboden north across the head of the Plawenn valley into the dismembered head of the Vivana valley, through the location of the inferred lost mountain 'Plawennspitz'. (**d**) The Vivana valley grossly asymmetrical cross-section and missing head, looking south along the decapitated west-side ridge from Pleiskopfl. (**e**) and (**f**) Hectometric gravitational morphostructures indicating structural propensity for large-scale slope instability. (e) Rim of the Plawenn valley at the head of the Vivana valley; note the remnant NE flank of Grosshorn from which the lost mountain contours and summit trend were extrapolated; (f) the Vivana valley west-side ridge viewed from the NE.

- extrapolating contours from this boundary across the cavity so far as their initial trend is clear;
- taking the form beyond the limits of contour extrapolation by 'clone-stamping' suitable slope angles and curvatures from non-failed topography in the vicinity. These templates take into account local rock-type variations, structural grain, valley asymmetry, etc.;
- governing the lost mountain form by iterating the process, converging from its perimeters, until a well-integrated proto-landscape is achieved.

Implementing this procedure reveals that most of the pre-failure boundary can readily be fixed and extrapolated from Figure 10; only the SW boundary within the Plawenn valley is problematic. The position and steepness of a pre-catastrophe headwall across the valley between Grosshorn and Kofelboden has to be fixed. While the position is somewhat arbitrary, its form can be clone-stamped from the mature gully complexes in the SE Plawenn valley, interpreted as outside the failure. It may also have been supported by a higher NW Plawenn ridge, the present one being anomalously low and deformed.

The lost mountain (here named 'Plawennspitz') reconstructed by this procedure has a summit above 3100 m (Fig. 13). This is about 200 m higher than the remnant Mittereck, and is consistent with other summit elevations along the inferred preglacial main watershed (Fig. 1). Plawennspitz emerges as the natural culminating peak at the convergence of several ridges and valley heads. Its upper slopes and summit ridge have been kept relatively broad and the encroaching cirques gentle, consistent with the subdued character of this watershed section. The failed mass is located predominantly above the head of the Plawenn valley, attaining a maximum thickness of 700 m (Fig. 13c). It almost completely beheads the Vivana valley (Fig. 12c), where incipient gravitational scarps 150 m behind the rim indicate the propensity for failure (Fig. 12e). It slightly beheads the Planeil and Rosell valleys, both of which display broad splitting and sagging crests.

The volume of the failed mass obtained by digital elevation model (DEM) calculation is 1500 Mm^3. This excludes a small sector east of the present Mittereck south ridge, where the present broad bay is inferred to be the cavity of a sliding failure into the Planeil valley, which is widely affected by slope deformation and rockslides (Fig. 10). Because it is not known whether this Planeil valley failure pre- or post-dated the main event, an arbitrary vertical separation is placed between them, attaining 200 m in height; the difference to the volume is minor. It is assumed that all of the failed mass within the present Plawenn catchment contributed to the Malser Haide, except for *c*. 50 Mm^3 exported down the adjacent valley to the west to build the contiguous and, also outsized, Fischerhauser fan (#4).

Simple robustness checks on this result indicate:

- retreating the arbitrarily-positioned pre-failure Plawenn valley headwall by 100 m shrinks Plawennspitz by 65 m in height and 130 Mm^3 in volume. A maximal retreating of 250 m reduces volume by 300 Mm^3;
- lowering the summit by 100 m cuts the volume by 100 Mm^3;
- conversely, steepening the headwall and building a sharper summit, consistent with others above 3000 m along the divide, increases volume by 300 Mm^3. An elevation of 3200 m is feasible for a summit here;
- excluding the Plawenn valley, NW ridge reconstruction cuts the total by 100 Mm^3.

The lost mountain volume could thus be in the range of 1000–1800 Mm^3. Applying a bulking-up factor to the deposit, conventionally 25–33% (Rapp 1960; Crosta *et al.* 2007) but possibly less (say 15%) with comminuted and well-consolidated debris, yields a range of 1150–2400 Mm^3 for the evacuated debris.

Relating source and deposit

At this preliminary level of quantification, the source and deposit volumes match well (Table 4). Note that the reconstruction of 'Plawennspitz' was made purely on geomorphological criteria, prior to calculating the volume of the Malser Haide and with no attempt to equal it.

The two anomalous landscapes require further investigation to determine whether they constitute a catastrophic event. Nonetheless, to deliver such a deposit volume from the 8.3 km^2 catchment of the Plawenn valley by episodic processes would require erosion of the whole catchment by an average of 200 m over the Holocene, a scale for which there are no precedents in deglaciated mountains (Hinderer 2001). In the Alps, some of the highest post-glacial erosion rates occur in the upper Rhine tributary catchment areas in debris-flow- and landslide-prone weak Bündner schist and flysch: 4 mm per annum or *c*. 40 m over the Holocene (Korup & Schlunegger 2009).

If verified as catastrophic slope failure, Plawennspitz–Malser Haide would be among the five largest landslides in the Alps, after Flims, and similar to Sierre, Engelberg, and Köfels (von Poschinger 2002). It would be exceptional (with Köfels) in occurring in crystalline rather than carbonate rocks. It would be in the top 60 recorded globally (Korup *et al.* 2007).

The St Valentin outsize fans

The reconstruction also identifies a second lost mountain ('Valentinkopf') on the west side of the Vivana valley (Fig. 13). This valley is grossly asymmetrical (Figs 11 & 12) and, with its lost crest parallel to the upper Venosta trough, it closely resembles the Fundus Valley above Köfels. Clear evidence of catastrophic collapse is

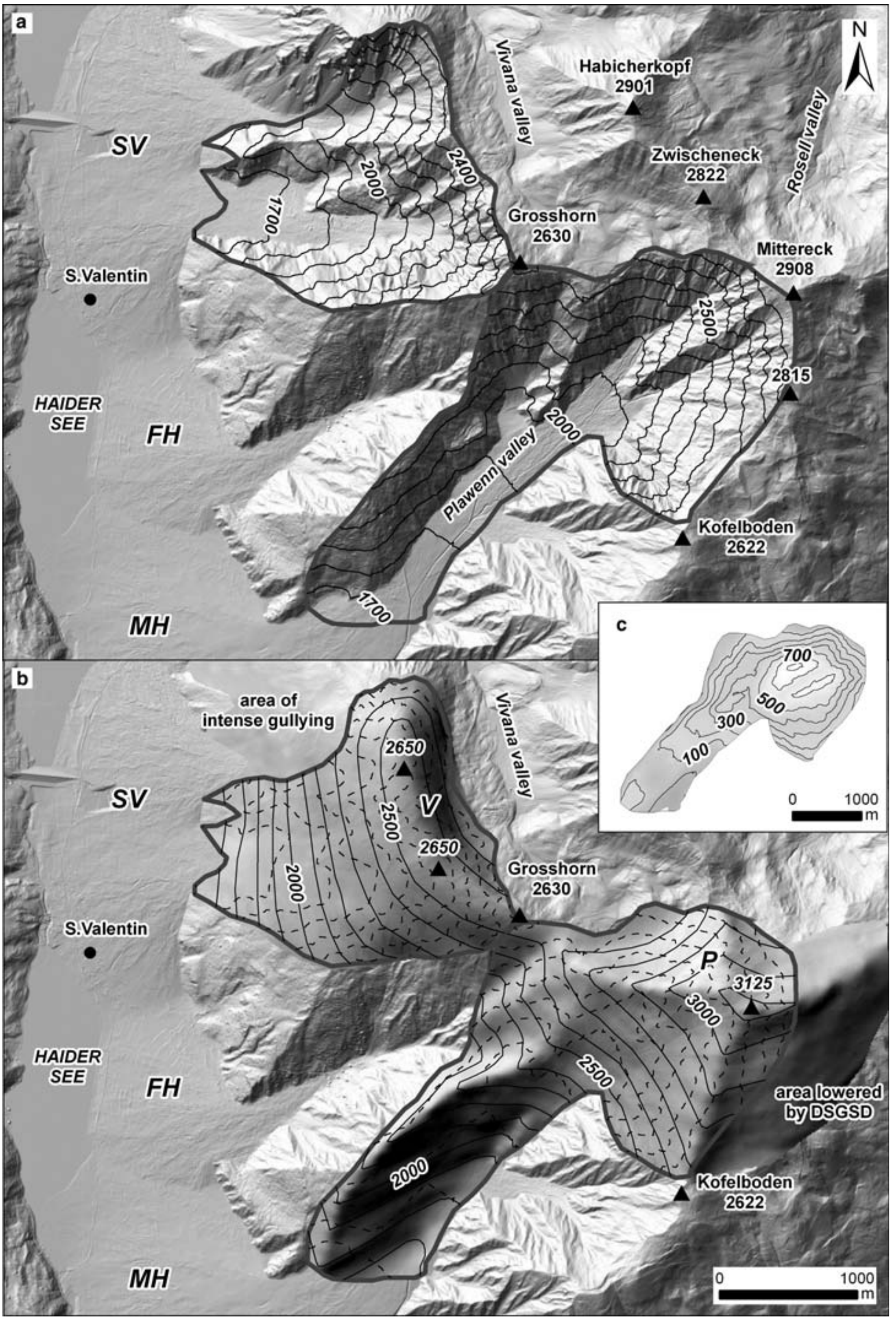

Fig. 13. Reconstruction of the lost mountains 'Plawennspitz' (P) and 'Valentinkopf' (V) by contour extrapolation and the 'clone-stamping' procedure. (**a**) Present-day topography (LiDAR), with cavities of areas lost by catastrophic failure outlined and contoured. (**b**) Reconstructed topography (DEM at 10 m resolution), with 100 m contours (solid) superimposed on present-day ones (dashed). Plawennspitz has a pyramidal form typical of an apex location; Valentinkopf has a more rounded form, comparable to adjacent mid-level terrain (Fig. 7). (**c**) The thickness of the Plawennspitz failed mass by 100 m contours.

Table 4. *Estimates of the Malser Haide source and deposit volumes*

		Volume (Mm^3)
Source	First estimate from reconstruction	1500
	applying robustness checks	1000–1800
	with robustness checks and bulking-up	1150–2400
Deposit	First estimate from cross-sections	1650
	plus Fischerhauser (#4) fan	1700
	applying robustness checks	1100–2500
	Fischer (1966) 'murkegel' deposit	*1550*

$1000\ Mm^3 = 10^9\ m^3 = 1\ km^3$.

provided by the extensive rock glaciers that could not have developed beneath the present low to negligible slopes (Figs 10 & 12b); the head of one rock glacier actually drapes back over the remnant crest (Fig. 12a). This crest also displays splits indicating extensive structural weaknesses (Fig. 12f). 'Valentinkopf' is the inferred source for the St Valentin outsize fans (#2 and #3: Figs 5d & 11).

A maximal reconstruction, restoring a continuous Venosta trough wall, yields a broad ridge at over 2650 m, some 2–300 m higher than the present Vivana valley rim, although still 250 m short of full symmetry. This is consistent with the chain of mid-level hills preserving rounded preglacial forms along this rim of the trough, reflecting its incision as a major breach (Fig. 10). Maximum thickness of the lost mountain here is 550 m. However, a gross cavity volume at 1100 Mm^3 vastly exceeds the volume of the St Valentin fans, estimated using the same procedure as the Malser Haide at 430 Mm^3 and constrained by borehole evidence. Even with deep gullying and a cliffed summit factored in, as elsewhere along this trough wall, the cavity volume remains excessive at 680 Mm^3. The south fan appears to be overlapped by the north, and its source bay is more maturely dissected by gullying, suggesting that 'Valentinkopf' may have collapsed in several phases, with earlier ones possibly removed by the last glacier.

Discussion

In proposing a new category of catastrophic slope failure outcome, many vexed questions are raised, including source rock-mass character and flow dynamics. The key issue discussed here is why similar mountain relief should yield such contrasting catastrophic collapse forms as hilly rock avalanche deposits and smooth fan-mimicking cones. The character of catastrophic slope failure deposits is conditioned by: the source geometry; the failure mechanism; the degree of fragmentation (Crosta *et al.* 2007); the wetness of the failed mass and any materials incorporated in transit, for example colluvium, glacial debris, ice (Crosta *et al.* 2009); the trajectory resulting from the interaction of moving debris and topography; and whether the emplacement zone permits unconstrained run-out or induces deflection (Hewitt *et al.* 2008). Here, the source → trajectory → run-out configuration appears to be especially significant.

Topographical controls on fan-mimicking deposits – the 'debouchure'

Most large catastrophic failures in the Alps are on open trough walls and have produced hilly deposits with substantial preservation of source-area fabric, for example Sierre (Burri 1997), Köfels (Sørensen & Bauer 2003), Flims (Ivy-Ochs *et al.* 2009), Fernpass (Prager *et al.* 2009*a*), Tschirgant, and Disentis (Fig. 1). A key difference between these hilly deposits and the Venosta anomalous fans is that the former have laterally unconstrained descent trajectories, whereas the latter have been funnelled through constricted 'debouchures' between the source and the slope foot (Fig. 5).

We thus propose that conoidal deposits mimicking incremental sedimentary fans may originate from catastrophic slope failure if:

- the exposure of the source area above a main glacial trough is high and steep enough to allow rapid movements to originate;
- an open mouth or 'debouchure' exists on the trough wall, greater in width than the typical deeply incised ravine or hanging V-shaped tributary, but narrow enough to funnel the sliding mass through a chute.
- the debris is originally, or becomes, sufficiently comminuted to discharge through the constriction as a freely flowing mass or stream, rather than remaining so blocky as to form a hilly deposit or be arrested as a choke;
- the debouchure is sufficiently elevated above a wide, flat trough floor for a cone to form.

We suggest that the conoidal form is a product of rapid flow-energy dissipation achieved: (a) by constriction as the debris mass passes through the debouchure; (b) by fragmentation during transit, an energy-consuming process (Hungr 2006); and (c) by sudden reduction of gradient as the debris mass enters the proximal run-out zone. The momentum-starved flow decelerates abruptly and is deposited in an efficient conoidal form. The absence of opposite slope run-up in all of the Venosta cases, despite several being distally confined, supports this interpretation. The absence of prominent levées (except possibly at the Malser Haide debouchure, see later) is more surprising.

Debouchure origination is clearly significant. Some may pre-exist as small side valleys, but others might result from initial lower-slope failure of more conventional scale, either propagating rapidly upslope or setting in train progressive weakening above. The main Venosta trough displays classic alpine mid-slope benches, often with signs of slope deformation: failure biting into them would magnify the effective relief exposure of the upper slopes.

There are 18 such debouchures in Val Venosta. They occur above all except two of the anomalous fans; the five not above such fans may indicate evacuated or latent large events. They range between 150 and 600 m in width (Table 2). Significantly, they are proportionate to cone size, averaging 275 and 540 m in width above outsize fans and megafans, respectively, implying that broader openings destabilize larger source areas. Fans often retrogress up the chutes, obscuring their profiles, but these bold trough-wall openings are anomalous landforms in their own right.

Single or multiple events – the unified Malser Haide

A single catastrophic event issuing from a debouchure will experimentally produce a smooth conoidal form if the material is uniformly granular. The greater the extent to which a source area is 'pre-failed' or 'pre-disintegrated', clearly the greater is the potential for comminution to a rapidly flowing fine debris stream. In reality, heterogenous debris might be expected to generate more irregular forms. Equifinality allows that fans of Venosta type may be attained via various combinations of circumstances. One scenario emplaces a subconoidal core deposit, whether by one or a few events, which is either rapidly or gradually smoothed by debris-flow and fluvial processes as the unstable source area re-equilibrates. Subsequent overlays were observed by Blair (1987), Derbyshire & Owen (1990) and Watanabe *et al.* (1998). In the Alps they are have been located at St Barthelémy and Corberier-Yvorne (Eisbacher & Clague 1984), and notably at Illgraben (Fig. 1), where the megafan is concentrically layered, most recently by a 5.4 Mm^3 event in 1961 (Oppikofer *et al.* 2006). These examples suggest that slope instability propagates headwards to trigger successive catastrophic (but relatively small-scale) events.

However, the remarkable smoothness of the entire length of the Malser Haide (Figs 6 & 7) can hardly be accounted for by multiple-event and incremental-overlay models. Multiple large events would tend to increase the cone thickness at the debouchure, not extend it; overlays from conventional debris flows could not travel as thin veneers over such a distance. Even so, clear evidence for a single event is lacking, although Fischer (1965) described anomalous 'kegelimse' terraces sloping outwards from 1750 m asl above down to 1550 m on either side of the Plawenn valley mouth about 100 m above the fan. They bear morainic deposits from sources north of St Valentin, and may resemble the levées often found parallel to catastrophic rock avalanches (Abele 1974).

The steeper gradient within the Plawenn valley (Fig. 8) suggests that subsequent debris-flow activity has retrogressed up it, while the concave gradient in the Upper Val Venosta suggests that alluvial and debris-flow overlay deposition has been limited to the proximal part of the fan. This is consistent with the historical record: debris flows have swept across the conoidal part of the fan in recent centuries, destroying the village of Plawenn three times (Eisbacher & Clague 1984).

Applying Occam's razor suggests that the simplest explanation for the remarkably unified form of the Malser Haide is that it was emplaced by a single catastrophic event of fluidized character funnelled through a debouchure, with relatively minor smoothing by subsequent processes including human activity. This is consistent with inferences of rapid fluidized flow elsewhere (Derbyshire & Owen 1990). The Flims mega-failure also has an exceptionally long run-out: dating confirms that it was most probably a single event, although multiple events within a short period are not ruled out (Ivy-Ochs *et al.* 2009).

Clustered incidence of anomalous fans

The propensity for large slope instabilities to cluster has been noted in Scotland (Jarman 2006), and in the Central Alps (Agliardi *et al.* 2009*b*), where it applies equally to the spatial incidence of anomalous fans (Fig. 1). The occurrence of the largest fan cluster in Val Venosta has no immediately obvious explanation, and may reflect a complex interaction of bedrock type, structure, active tectonic processes and paraglacial slope evolution. But this area has a varied geology, prone to both slope deformation and rockslides, and intensely dissected by tectonic lineaments (Agliardi *et al.* 2009*a*, *b*); while tectonic damage is an important predisposing factor to slope failure (Brideau *et al.* 2009), it is no more prevalent here than in many other parts of the Alps.

In the Upper Val Venosta all of the anomalous fans emanate from east-side sources carved into varied resistant rock types (e.g. carbonates, orthogneiss) with extensive fracturing of brittle fabric. Even though the west side is affected by widespread slope deformation, it is not a fan source; unlike Val Mustair where the fan sequence is below a sagging ridge. The physical asymmetry of the Upper Val Venosta, with much of its east side a cliff wall, may be a factor. By contrast, anomalous fans occur on both sides of the main Venosta trough, as does extensive slope deformation. All of the megafans, except for the Malser Haide, are in this main trough, a not unreasonable scale effect. Throughout the area, arrested rockslides are fairly small while large rock avalanches are absent, suggesting that here they develop into fans.

The main Venosta trough is unusually large and overdeepened, possibly exploiting the Vinschgau shear zone (Fig. 2). The glacier was augmented by transfluent input of ice from the Engadine ice centre (Florineth & Schlüchter 1998) through several glacial breaches of the main Alpine divide, among which Reschen Pass–St Valentin is exceptionally large (Fig. 1). An association between large slope failures and breaches has also been identified in Scotland (Jarman 2006).

Glacial debuttressing, post-glacial unloading, topographical stress rotation, regional seismicity, permafrost, meltwaters, climatic variation and progressive weakening conventionally explain slope failure in the Alps. However, these are endemic factors operating along all glacial troughs, and cannot explain local clusters such as the Val Venosta fans (cf. Jarman 2006). Geology and structure are clearly influential, but only enabling factors. Proximity of these fans to the St Valentin breach, which entailed the removal of more than 1000 m of bedrock (Fig. 10), and to the overdeepened main Venosta trough could suggest that concentrated erosion has induced high rebound stresses akin to quarry-floor bursting (Hutchinson 1988; Ustaszewski *et al.* 2008). Such rebound breakouts could also have provoked higher magnitude seismicity around deglaciation (Persaud & Pfiffner 2004). Topographical amplification of seismic shaking may favour large failures at or near summits (Murphy 2006), possibly contributing to the catastrophic 'Plawennspitz' and 'Valentinkopf' collapses.

Conclusions

This study has explored for the first time the possibility that oversized sediment cones in glacial troughs are not conventional alluvial or debris-flow fans but have primarily catastrophic origins. It identifies a cluster of anomalous fans in Val Venosta that are grossly disproportionate in scale relative to catchment area. These 'outsize fans' and 'megafans' emanate from a quarter of the side valleys, with similar valleys yielding allometric or no fans. This suggests that they are the product of one or more high-magnitude low-frequency events. If non-stratified constitution can be demonstrated by sedimentological and geotechnical investigation then these 'catastrophic fans' would represent a new category of slope failure deposit. They appear to be generated where the topography funnels a fast-flowing comminuted debris mass through a relatively confined 'debouchure' well above a wide trough floor, with rapid deceleration in the proximal run-out zone producing an efficient conoidal form.

The exceptionally large Malser Haide would, if verified, be one of the largest landslide deposits in the Alps, estimated at 1650 Mm^3. For it to have been emplaced incrementally by floods and debris flows would have required erosion of the entire source valley catchment by an average of 200 m during the Holocene, an unprecedented scale and process rate. Instead, its unified form sustained over 11 km suggests a single catastrophic event, for which reconstruction of anomalous terrain at the source valley head yields a lost mountain of comparable volume.

Anomalous fans of catastrophic provenance are identified widely across the Alps, with the Venosta cluster being the most numerous. Their incidence here cannot be explained by generic factors, such as glacial unloading, and while favourable geology is clearly important, locally concentrated glacial trough erosion and rebound stresses may be involved. This new category also embraces certain fans reported in the Himalaya (prehistoric), British Columbia (Cheekye) and the Andes (Huascaran, Peru in 1970), where active tectonics, vulcanicity and seismicity are more relevant.

This geomorphological study addresses the catastrophism v. uniformitarianism controversy via a specific dataset that provides evidence for both. As anomalous fans mimic allometric fans on all criteria other than scale, equifinality is once again a caution against monogenetic interpretations.

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References

Abele, G. 1974. *Bergstürze in den Alpen, ihre Verbreitung, Morphologie, und Folgeerscheinungen*. Wissenschaftliche Alpenvereinshefte, **25**.

Agliardi, F., Crosta, G. & Zanchi, A. 2001. Structural constraints on deep-seated slope deformation kinematics. *Engineering Geology*, **59**, 83–102.

Agliardi, F., Crosta, G., Zanchi, A. & Ravazzi, C. 2009*a*. Onset and timing of deep-seated gravitational slope deformations in the eastern Alps, Italy. *Geomorphology*, **103**, 113–129.

Agliardi, F., Zanchi, A. & Crosta, G. B. 2009*b*. Tectonic vs. gravitational morphostructures in the central Eastern Alps (Italy): constraints on the recent evolution of the mountain range. *Tectonophysics*, **474**, 250–270.

Allen, P. A. & Hovius, N. 1998. Sediment supply from landslide-dominated catchments: implications for basin-margin fans. *Basin Research*, **10**, 19–35.

Ambrosi, C. & Crosta, G. 2006. Large sackung along major tectonic features in the Central Italian Alps. *Engineering Geology*, **83**, 183–200.

Blair, T. C. 1987. Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan. *Journal of Sedimentary Petrology*, **57**, 1–18.

Blair, T. C. & Mcpherson, J. G. 1994. Alluvial fan processes and forms. *In*: Abrahams, A. D. & Parson, A. J. (eds) *Geomorphology of Desert Environments*. Chapman & Hall, London, 354–402.

Brideau, M.-A., Yan, M. & Stead, D. 2009. The role of tectonic damage and brittle rock fracture in the development of large rock slope failures. *Geomorphology*, **103**, 30–49.

Burri, M. 1997. Géologie récente de Finges et de ses environs (VS). *Bulletin Murithienne*, **155**, 5–27.

Crosta, G. B. & Frattini, P. 2004. Controls on modern alluvial fan processes in the Central Alps, Northern Italy. *Earth Surface Processes and Landforms*, **29**, 267–293.

Crosta, G. B., Frattini, P. & Fusi, N. 2007. Fragmentation in the Val Pola rock avalanche, Italian Alps. *Journal of Geophysical Research*, **112**, F01006; doi: 10.1029/2005JF000455.

Crosta, G. B., Imposimato, S. & Roddeman, D. 2009. Numerical modelling of entrainment/deposition in rock and debris-avalanches. *Engineering Geology*, **29**, 135–145.

Crosta, G. B. & Zanchi, A. 2000. Deep seated slope deformations–huge, extraordinary, enigmatic phenomena. *In*: Bromhead, E., Dixon, N. & Ibsen, M. (eds) *Landslides in Research, Theory and Practice. Proceedings of the 8th International Symposium on Landslides, Cardiff, June 2000*. Thomas Telford, London, 351–358.

Derbyshire, E. & Owen, L. A. 1990. Quaternary alluvial fans in the Karakoram Mountains. *In*: Rachocki, A. H. & Church, M. (eds) *Alluvial Fans: A Field Approach*. Wiley, Chichester.

Eisbacher, G. H. & Clague, J. J. 1984. *Destructive mass movements in high mountains: hazard and management*. Geological Survey of Canada, Professional Paper, **84-16**.

Evans, S. G., Roberts, N. J., Ischuk, A., Delaney, K. B., Morozova, G. S. & Tutubalina, O. 2009. Landslides triggered by the 1949 Khait Earthquake, Tajikistan, and associated loss of life. *Engineering Geology*, **109**, 195–212; doi: 10.1016/j.enggeo.2009.08.007.

Fischer, K. 1965. Murkegel, Schwemmkegel und Kegelimse in den Alpentälern. *Mitteilungen der Geographischer Gesellschaft in München*, **56**, 127–159.

Fischer, K. 1966. Die Murkegel des Vinschgaues. *Der Schlern*, **40**, 24–34.

Fischer, K. 1990. Entwicklunggsgeschichte der Murkegel im Vinschgau. *Der Schlern*, **64**, 93–96.

Florineth, D. & Schlüchter, C. 1998. Reconstructing the Last Glacial Maximum (LGM) ice surface geometry and flowlines in the Central Swiss Alps. *Eclogae Geologicae Helvetiae*, **91**, 391–407.

Friele, P. A., Ekes, C. & Hickin, E. J. 1999. Evolution of Cheekeye fan, Squamish, British Columbia: Holocene sedimentation and implications for hazard assessment. *Canadian Journal of Earth Sciences*, **36**, 2023–2031.

Harvey, A. M. 2003. Alluvial fan. *In*: Goudie, A. S. (ed.) *Encyclopedia of Geomorphology*. Routledge, London.

Harvey, A. M., Mather, A. E. & Stokes, M. (eds) 2005. *Alluvial Fans: Geomorphology, Sedimentology, Dynamics*. Geological Society, London, Special Publications, **251**.

Heuberger, H. 1994. The giant landslide of Köfels, Ötztal, Tyrol. *Mountain Research and Development*, **14**, 290–294.

Hewitt, K. 1999. Quaternary moraines v. catastrophic rock avalanches in the Karakoram Himalaya, Northern Pakistan. *Quaternary Research*, **51**, 220–237.

Hewitt, K. 2001. Catastrophic rockslides and the geomorphology of the Hunza and Gilgit River valleys, Karakoram Himalaya. *Erdkunde*, **55**, 72–93.

Hewitt, K., Clague, J. J. & Orwin, J. F. 2008. Legacies of catastrophic rock slope failures in mountain landscapes. *Earth-Science Reviews*, **87**, 1–38.

Hinderer, M. 2001. Late Quaternary denudation of the Alps, valley and lake fillings and modern river loads. *Geodinamica Acta*, **14**, 231–263.

Hoek, E. & Brown, E. T. 1997. Practical estimates or rock mass strength. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, **34**, 1165–1186.

Hungr, O. 2006. Rock avalanche occurrence, process and modelling. *In*: Evans, S. G., Scarascia Mugnozza, G. S., Strom, A. & Hermanns, R. L. (eds) *Landslides from Massive Slope Failure*. Springer, Dordrecht, 243–266.

Hutchinson, J. N. 1988. General report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. *In*: *Proceedings of the 5th International Symposium on Landslides*, *Lausanne*, Volume 1. Balkema, Rotterdam, 3–35.

Iverson, R. 2003. Debris flow. *In*: Goudie, A. S. (ed.) *Encyclopedia of Geomorphology*. Routledge, London.

Ivy-Ochs, S., Von Poschinger, A., Synal, H.-A. & Maisch, M. 2009. Surface exposure dating of the

Flims Landslide, Graubünden, Switzerland. *Geomorphology*, **103**, 104–112.

Jaboyedoff, M. & Derron, M.-H. 2005. A new method to estimate the infilling of alluvial sediment of glacial valleys using a sloping local base level. *Geografia Fisica e Dinamica Quaternaris*, **28**, 37–46.

Jarman, D. 2002. Rock slope failure and landscape evolution in the Caledonian Mountains, as exemplified in the Abisko area, northern Sweden. *Geografiska Annaler*, **84A**, 213–224.

Jarman, D. 2006. Large rock slope failures in the Highlands of Scotland: characterisation, causes and spatial distribution. *Engineering Geology*, **83**, 161–182.

Korup, O., Clague, J. J., Hermanns, R. L., Hewitt, K., Strom, A. L. & Weidinger, J. T. 2007. Giant landslides, topography, and erosion. *Earth and Planetary Science Letters*, **261**, 578–589.

Korup, O. & Schlunegger, F. 2009. Rock-type control on erosion-induced uplift, eastern Swiss Alps. *Earth and Planetary Science Letters*, **278**, 278–285.

Lecce, S. 1990. The alluvial fan problem. *In*: Rachocki, A. H. & Church, M. (eds) *Alluvial Fans: A Field Approach*. Wiley, Chichester, 3–24.

Legros, F. 2006. Landslide mobility and the role of water. *In*: Evans, S. G., Scarascia Mugnozza, G. S., Strom, A. & Hermanns, R. L. (eds) *Landslides from Massive Slope Failure*. Springer, Dordrecht, 233–242.

Murphy, W. 2006. The role of topographic amplification on the initiation of Rock Slope Failures during earthquakes. *In*: Evans, S. G., Scarascia Mugnozza, G. S., Strom, A. & Hermanns, R. L. (eds) *Landslides from Massive Slope Failure*. Springer, Dordrecht, 139–154.

Oppikofer, T., Bardou, E & Jaboyedoff, M. 2006. DTM analysis of the 1961 rock avalanche, Illgraben creek (Switzerland). *Geophysical Research Abstracts*, **8**, SRef-ID: 1607-7962/gra/EGU06-A-02291.

Penck, A. & Brückner, E. 1909. *Die Alpen im Eiszeitalter*. Tauchnitz, Leipzig.

Persaud, M. & Pfiffner, O. A. 2004. Active deformation in the eastern Swiss Alps: Post-glacial faults, seismicity and surface uplift. *Tectonophysics*, **385**, 59–84.

Plafker, G. & Ericksen, G. E. 1978. Nevados Huascaran avalanches, Peru. *In*: Voight, B. (ed.) *Rockslides and Avalanches Natural Phenomena*. Elsevier, Amsterdam, 277–314.

Prager, C., Zangerl, C., Patzelt, G. & Brandner, R. 2008. Age distribution of fossil landslides in the Tyrol (Austria) and its surrounding areas. *Natural Hazards and Earth System Sciences*, **8**, 377–407.

Prager, C., Ivy-Ochs, S., Ostermann, M., Synal, H.-A. & Patzelt, G. 2009*a*. Geology and radiometric ^{14}C, ^{36}Cl and Th/U-dating of the Fernpass rockslide (Tyrol, Austria). *Geomorphology*, **103**, 93–103.

Prager, C., Zangerl, C. & Nagler, T. 2009*b*. Geological controls on slope deformations in the Köfels rockslide area (Tyrol, Austria). *Austrian Journal of Earth Sciences*, **102**, 4–19.

Rachocki, A. H. & Church, M. (eds) 1990. *Alluvial Fans: A Field Approach*. Wiley, Chichester.

Rapp, A. 1960. Recent development of mountain slopes in Kärkevagge and surroundings, northern Scandinavia. *Geografiska Annaler*, **42**, 71–200.

Schrott, L., Hufschmidt, G., Hankammer, M., Hoffmann, T. & Dikau, R. 2003. Spatial distribution of sediment storage types and quantification of valley fill deposits in an alpine basin, Reintal, Bavarian Alps, Germany. *Geomorphology*, **55**, 45–63.

Shang, Y., Yang, Z., Lihui, L., Liu, D., Liao, Q. & Wang, Y. 2003. A super-large landslide in Tibet in 2000: background, occurrence, disaster, and origin. *Geomorphology*, **54**, 225–243.

Sørensen, S. A. & Bauer, B. 2003. On the dynamics of the Köfels sturzstrom. *Geomorphology*, **54**, 11–19.

Sorriso-Valvo, M., Antronico, L. & La Pera, E. 1998. Controls on fan morphology in Calabria, southern Italy. *Geomorphology*, **124**, 169–187.

Spindler, K. 1994. *The Man in the Ice*. Weidenfeld & Nicolson, London.

Staffler, H. & Nicolussi, K. 2004. Fund subfossiler Holzstämme in Naturns. *Der Schlern*, **78**, 4–9.

Taylor, G. 1940. Trento to the Reschen pass: a cultural traverse of the Adige corridor. *Geographical Review*, **30**, 215–237.

Ustaszewski, M. E., Hampel, A. & Pfiffner, O. 2008. Composite faults in the Swiss Alps formed by the interplay of tectonics, gravitation and postglacial rebound: an integrated field and modelling study. *Swiss Journal of Geosciences*, **101**, 223–235.

Van Husen, D. 1987. *Die Ostalpen in den Eiszeiten*. Geologische Bundesamstalt Österreichs, Wien.

Von Poschinger, A. 2002. Large rockslides in the Alps: a commentary on the contribution of G. Abele (1937–1994) and a review of some recent developments. *In*: Evans, S. G. & de Graaff, J. V. (eds) *Catastrophic Landslides: Effects, Occurrence and Mechanisms. Geological Society of America, Reviews in Engineering Geology*, **15**, 237–255.

Watanabe, T., Dali, L. & Shiraiwa, T. 1998. Slope denudation and the supply of debris to cones in Langtang Himal, central Nepal Himalaya. *Geomorphology*, **26**, 185–197.