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Gravitational spreading ridges on the crystalline basement of the Eastern Alps (Niedere Tauern mountain range, Austria)

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Abstract

The distribution of gravitational spreading and collapsing ridges in the Eastern Alps is shown within crystalline basement units of the Wölzer Tauern mountain chain. In this study, a structural approach furnishes additional information for the subsurface geometry of faults created by gravitational spreading. We demonstrate the anatomy of three spreading ridges involving five sites of the sackung-type spreading. Depending on the bedrock type and fabric, opposite modes of spreading are discerned: Mode 1 spreading occurs on ridges where the main foliation dips roughly parallel to the slope. Examples for this mode of spreading are the sites Schladminger Alm, Großsölk and Weißgulling. Mode 2 spreading occurs on ridges where dip of principal foliation is into the slope. Mode 2 spreading has developed well-regulated morphological structures that are comparable to offset structures of steep normal faults. At the sites Kleinsölk, Schwarzgulling and in parts at the sites Schladminger Alm and Weißgulling we can define individual features of normal faulting. At each site an assemblage of master faults, synthetic and antithetic branch faults, horsts and grabens, halfgrabens, hanging wall roll-over structures and release faults can be documented. At the basal detachment of site Kleinsölk, displacement data reflect a displacement gradient that is characteristic for normal faults. Since we have a detailed picture of (a) the arrangement and asymmetry of faults, (b) the orientation of branches in the hangingwall, and (c) dips and gradients of detachments, we interpret that mode 2 gravitational spreading forms by similar processes as the formation of steep normal faults. Recognizing deep seated extensional structures on spreading ridges is important for both tunnelling activities and water reservoir recognition.

1. Introduction

High mountain ridges may deform under their own weight. They collapse vertically and extend laterally. Characteristic surface features of such collapse include trenches and depressions along ridge crests and approximately vertically opening linear fissures, trenches and scarps. In the Eastern Alps morphological characteristics of such slope deformations are well known for some time and have been called "Sackung" and "Talzuschub" (e. g. HEIM, 1932, AMPFERER, 1939, 1940, STINI, 1941). They may include outward bulging of lower slope portions (ZISCHINSKY, 1966, 1969). Similar features on high slopes had been recognised in various parts of the world and were described by the terms

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"mass rock-creep" and "deep- seated creep" (e. g. MAHR, 1977; RADBRUCH-HALL, 1978; NEMCOK, 1972), "lateral spreading of ridges" (JAHN, 1964; RADBRUCH-HALL et al., 1976; SAVAGE and VARNES, 1987) and "sagging of mountain slopes" (e. g. HUTCHINSON, 1988).

Whereas the study of gravitational spreading of slopes is well established in the community of physical and engineering geologists, the mechanical and kinematic aspects of their formation is not yet fully understood. The kinematics of spreading slopes has been investigated only in a few sites, in particular those sites that are in risk areas for building activities (e. g. TENTSCHERT, 1998, LEOBACHER and LIEGLER, 1998, MOSER and GLAWE, 1994, WEIDNER, 2000). More recently, some additional information came up by means of numerical modelling and geophysical investigations (e. g. BARLA & CHIRIOTTI, 1995, VENGEON et al., 1999; MAURITSCH et al., 2000; BONZANIGO et al., 2001).

1.1 Characteristics of spreading slopes

The term gravitational spreading slope summarizes a group of large scale slow mass-movements developed on natural slopes including phenomena like "sagging of mountain slopes" (HUTCHINSON, 1988), "rock-creep" (MAHR, 1977), "mass rock creep" (RADBRUCH-HALL, 1978), "deep-seated creep" (NEMCOK, 1972) "lateral- or gravitational spreading of ridges" (JAHN, 1964; RADBRUCH-HALL et al., 1976; SAVAGE and VARNES, 1987) and "Sackungen" (ZISCHINSKY, 1966, 1969). Spreading slopes may form as a consequence of valley oversteepening due to glacial erosion (REITNER et al., 1993), rapid river downcutting in response to tectonic uplift (DRAMIS and SORRISO-VALVO, 1994) and seismicity (RADBRUCH-HALL et al., 1976; DRAMIS and SORRISO-VALVO, 1983; HARP and JIPSON, 1995). The principal characteristics of spreading slopes are:

- Spreading slopes have slow displacement rates compared to landslides. They are classified to be of high activity if their displacement rates are of the order of 10^{-8}-10^{-6} m/s (10^{-1}-10 m/year) (BLANC et al., 1987; MANDZIC, 1988; TRAN et al., 1988, VIBERT et al., 1988; MOSER, 1993; WEIDNER, 2000), but many spreading slopes have been documented that they move at much slower rate („dormant").
- The internal deformation style of spreading slopes corresponds to that of tectonic motions, rather than to deformation patterns inside landslides. As such, their deformations style is distinctly different from that of landslides, where acceleration and momentum play a role and their deformation geometry is therefore often chaotic.

Within the above definition, three types of spreading slopes may be discerned, depending on the geological setting:

(i) Type 1 spreading slopes form on ridges where massive, strong rocks rest upon weaker rocks (e. g. POISEL and EPPENSTEINER, 1988) This mode shows distinctive "mountain splitting" structures which indicate the dismembering of the cap rock.

(ii) Type 2 spreading slopes form on ridges composed of metamorphosed or sedimentary rocks with pronounced anisotropy, for example foliation, cleavage or bedding. The near surface movement leads to an extensive bending of foliated gneisses, schists, phyllites and flysh sequences. This mode has been called in the past "true Sackung" (STINI, 1941; ZISCHINSKY, 1966; 1969).

(iii) Type 3 spreading slopes form on isotropic, but intensely fractured, usually crystalline or igneous rocks (e. g. MAHR, 1977). This mode is characterized by internal sagging and collapse of the mountain ridge as a whole.

The three modes listed above may all be characterized by some or all of the following surface morphological features: "mountain splitting" or "Bergzerreißung" describes morphological features in upper slope portions including both single scarps and double- to multiple crested ridges, ridge-top grabens, trenches and "rock labyrinths" all of which are indicating dilative behaviour in upper most hillslope portions (AMPFERER, 1939; 1940). "Closing-up of the valleys and cambering" (in German: "Talzuschub") defines the contraction of valley floors by the bulging front sector and by repression of the river towards counter slope (STINI, 1941; MOSER, 1993). If the entire slope bulges to form a convex shape, this is called "bulging of the slopes". Finally, the term "up hill facing scarp" (uphill) describes asymmetric trenches parallel to topographic contours that form as the consequence of internal sagging of the uphill side of a fault on a slope. Such trenches often are associated with ephemeral ponds.

Within type 2 spreading slopes two end-members can be distinguished depending on the qualitative relationship between the dip of the slope and that of the foliation (HERMANN et al., 2000):

(a) **Mode 1** spreading develops multiple crested ridges and intense mountain splitting structures on upper slope and a bulging toe on lower slope. A concave-convex slope profile is produced and the average slope inclination has decreased significantly.

(b) **Mode 2** spreading develops with one major offset scarp. If the cut-off line of the fault is in front of the ridge crest a single scarp structure is generated. If the cut-off line is behind the ridge crest a double crested ridge structure is generated. Typically, on upper slope portions uphill facing scarps occur and the slopes profile becomes convex. On contrast to mode 1 spreading the average slope inclination does not decrease.

This classification, that mainly is based on morphological differences but is also employed here to discuss structural differences of spreading slopes.

1.2 Objectives of this work

Formation and development of yielding and dislocation surfaces never have been documented in detail through a structural approach. One impetus to the study of these features comes from the need to know the subsurface geometry of surface morphological features for a variety of construction activities. The scarps observed are technically fault surfaces that resemble from the local adjustment within steep sided ridges. It is the purpose of this paper, to illustrate certain surface features of such faults and to compare them with normal faults. This concept will be discussed for the site Kaponig, where such an gravitational fault was crossed by tunnelling.

To illustrate typical features of gravitational faults, the anatomy of three ridges, involving five sites of gravitational spreading slopes will be presented. The three ridges were selected because of detailed knowledge of the structural

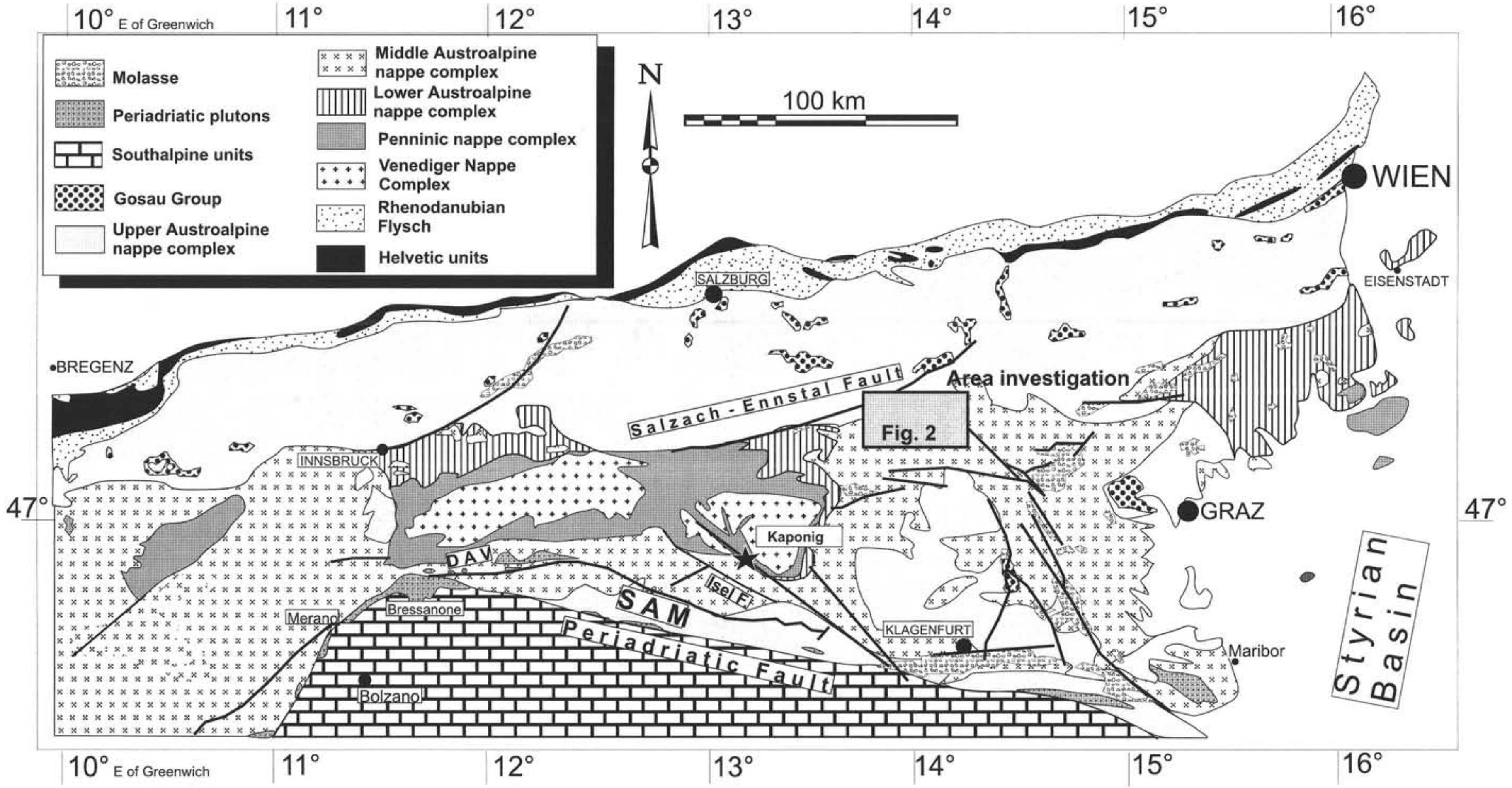


Fig. 1
Tectonic map of the Eastern Alps. Grey rectangle defines the area covered by aerial photography investigations. Black asterisk marks the location of the site Kaponig.

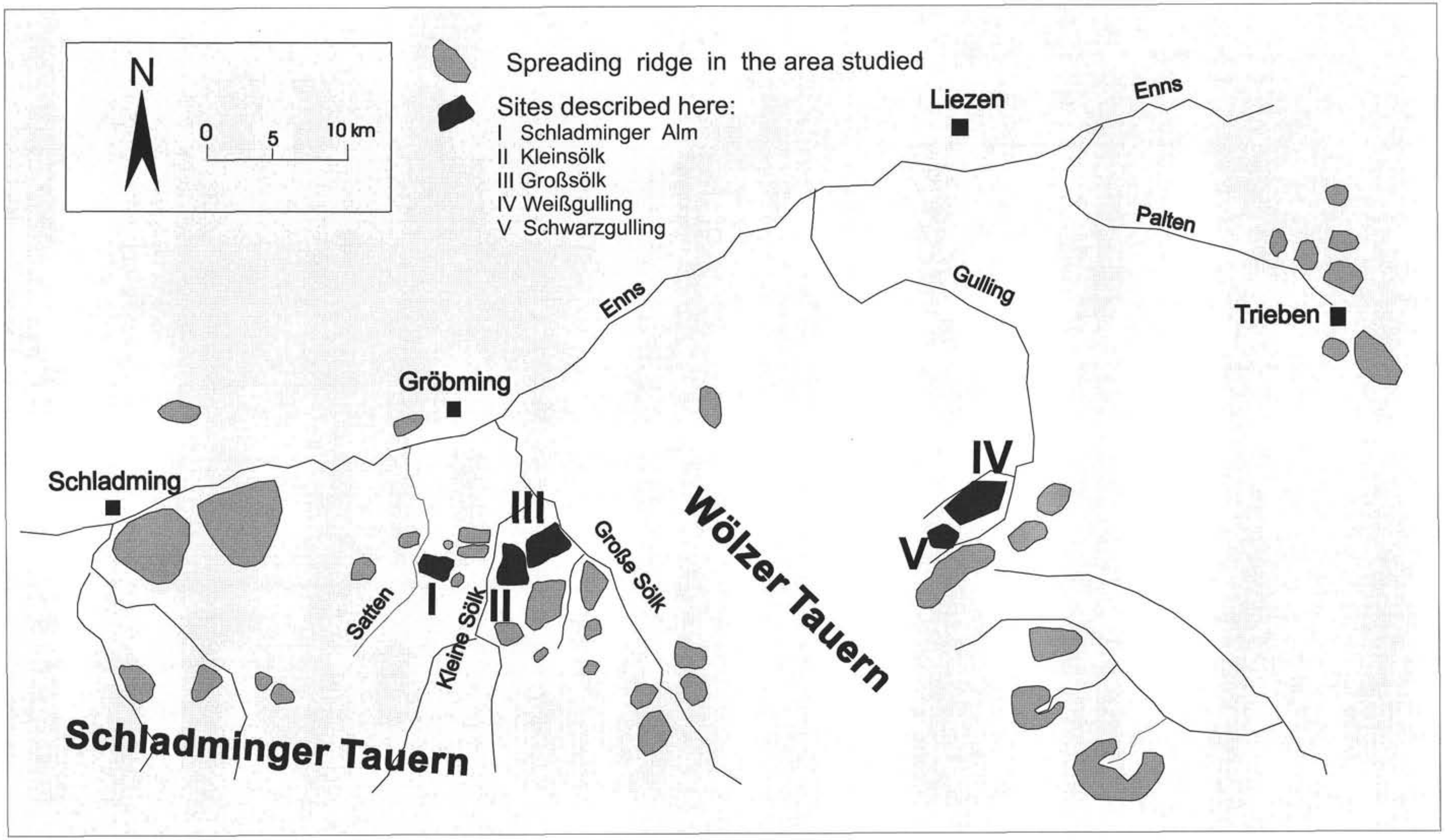


Fig. 2
Location of gravitational spreading slopes in the studied area. Source data from FAHRNBERGER, 2001, HERMANN, 1997, MADRITSCH, 1999 and RAUTH, 1996.

inventory. Therefore we may explain pronounced differences by physical-morphological and mechanical variations. In addition the sites selected represent spreading slopes, that are larger than 1.0 square kilometer and have some relevance for high mountain processes such as slope and valley floor development, catchment area of torrents and settlement properties (HERMANN et al., 1999).

The examples presented here were selected from more than 40 sites detected during research on the frequency and distribution of spreading events in the Eastern Alps. This study expands on previous work (HERMANN et al., 2000). Those studies were based on (i) regional mapping in the course of MSc theses (RAUTH, 1996, MADRITSCH, 1999, FAHRNBERGER, 2000) and Ph.D. theses (HERMANN, 1997), (ii) mapping on the regional scale (approximately 800 km^2) by a detailed evaluation of aerial photography and (iii) the study of digital orthophotography (ÖLK 10, resolution 0.5 m) on the local scale (HERMANN, 2001). Location of sites may be seen in Fig. 2.

2. Structure and lithology of the host rock

The sites of gravitational slope deformation we present here, belong to the crystalline basement of the Eastern Alps (Fig. 1). In the studied area upper structural units of the Middle Austroalpine Nappe Complex (Wölz micaschist complex) forms the Wölzer Tauern mountain chain. That unit mainly is made up of metamorphic siliciclastics and subordinate marbles that may be derived from a shelf environment of suggested Silurian to Devonian age (BECKER, 1981). The complex is intruded by swarms of Permian pegmatites (SCHUSTER et al., 1998), postdating Variscan deformation and metamorphism. A second metamorphic overprint occurred during Eoalpine times (e. g. HEJL, 1984, ABART and MARTINELLI, 1991). These events resulted in the development of a penetrative foliation. A second foliation, a transversal crenulation cleavage, forms the dominant fabric element at the northernmost portions of the Wölz micaschist complex.

Several sets of steeply dipping, brittle fabrics elements control the principle drainage network of the Niedere Tauern mountain range (enclosing the Schladminger Tauern and the Wölzer Tauern range). Those include NW-SE to NNW-SSW trending cataclastic faults, that locally are traced by gullies and chutes (see Fig. 3) and, on a larger scale straight valleys (e. g. the Großsölk valley, see Fig. 2). Shear sense indictors always display dextral strike slip movement. Orientation and kinematic of those faults is best interpreted as antiriedl faults with respect to the ENE-WSW trending sinistral Salzachtal-Ennstal fault system (HERMANN, 1997, WANG and NEUBAUER, 1998, Fig. 1). Additionally, consistently NNE-SSW striking sets of master joints locally control the orientation of several valley segments, e. g. the Kleinsölk valley (Fig. 2). Main valleys are glacially sculpted and characterised by symmetrical U-shaped cross sections, if not modified by gravitational spreading.

3. Morphological characteristics of studied sites

Among the five sites discussed below, site II and site IV belong to mode 1 spreading, site I and site V belong to mode 2 spreading. Site III morphologic features are characteristic for both modes. For location of studied areas see Fig. 2.

3.1 Site I, Schladminger Alm

The spreading slope of site I deforms the east facing slope into the Satten valley of the ridge between the Kleinsölk valley and the Satten valley (Fig. 2). A detailed map is displayed in Fig. 3, the slope profile is given in Fig. 9 C.

The width of the valley floor in the vicinity of the pasture of Kleinreiter Alm has reduced significantly by a bulging toe of mode 1 spreading. Here, that valley segment does not exhibit any glacial forms and contrasts the glacially modelled segments of upper and lower Sattental. Downstream the pasture of Kleinreiter Alm, the Satten brook runs through a creek section, upstream the pasture of Kleinreiter Alm the Satten brook forms a 1 km long division of a braided river system. Such circumstances indicate ongoing closing up of the valley nearby the pasture Kleinreiter Alm as a consequence of a slope failure by the single scarp offset nearby Mt. Dromeispitz (Fig. 3). The following morphological characteristics document a gravitational spreading slope:

The lower slope portions between the pasture of Kleinreiter Alm and the alpine pasture of Schladminger Alm has a significant bulging slope portion that is limited by a series of concentrically aligned scarps at 1400 m to 1550 m altitude. The open spread of the main foliation indicates complete perturbation of the main fabric (see Fig. 3). That slope portion also developed an individual surface drainage network and performed restrained (hopper like) erosion.

Middle to upper slope portions delineate substantial gravitational faulting. Here, several sets of uphill-facing scarps indicate downslope displacement of the current upper slope portions. Two sets of uphill facing structures occur: (i) A set of closely spaced rather short uphills (they may be traced up to 150 m distance). They are always oriented in en- echelon mode and mainly strike NW-SE. (ii) A set of singular NE-SW trending uphills (perpendicular to the set of short uphills) can be traced up to distance of several hundreds of meters. Many of that uphills are traced by ephemeral ponds (Figs. 3 and 7). In central portions, curt above the alpine pasture of Schladminger Alm, these two sets of uphills intersect. Exactly at this position the network of uphills and associated graben structures (HERMANN, 1997) is related to some profitable run over springs.

The upper slope portion is limited by a scarp structure, that can be traced over a distance of 1100 m between Mt. Lafenberg to the north and Mt. Dromeispitz to the south. Here, the offset is faced by a single scarp segment in central portions, a multiple scarp segment at the southern branch and at the northern segment the offset is determined by two main scarps. In the vicinity of Mt. Lafenberg minor scarps occur (see Fig. 3). Their position with respect to the scarp structure of Mt. Dromeispitz is not clarified up to now.

The map view of the gravitational spreading slope around the pasture of Schladminger Alm reveals asymmetry of displacement. The lateral limitations of the spreading slope run parallel to a regional, steeply dipping regular dextral fault system and/or joint system that strikes in NW-SE direction. On stable slope portions, e. g. at the east facing slope of Mt. Dromeispitz such cross joints (with respect to schistosi-

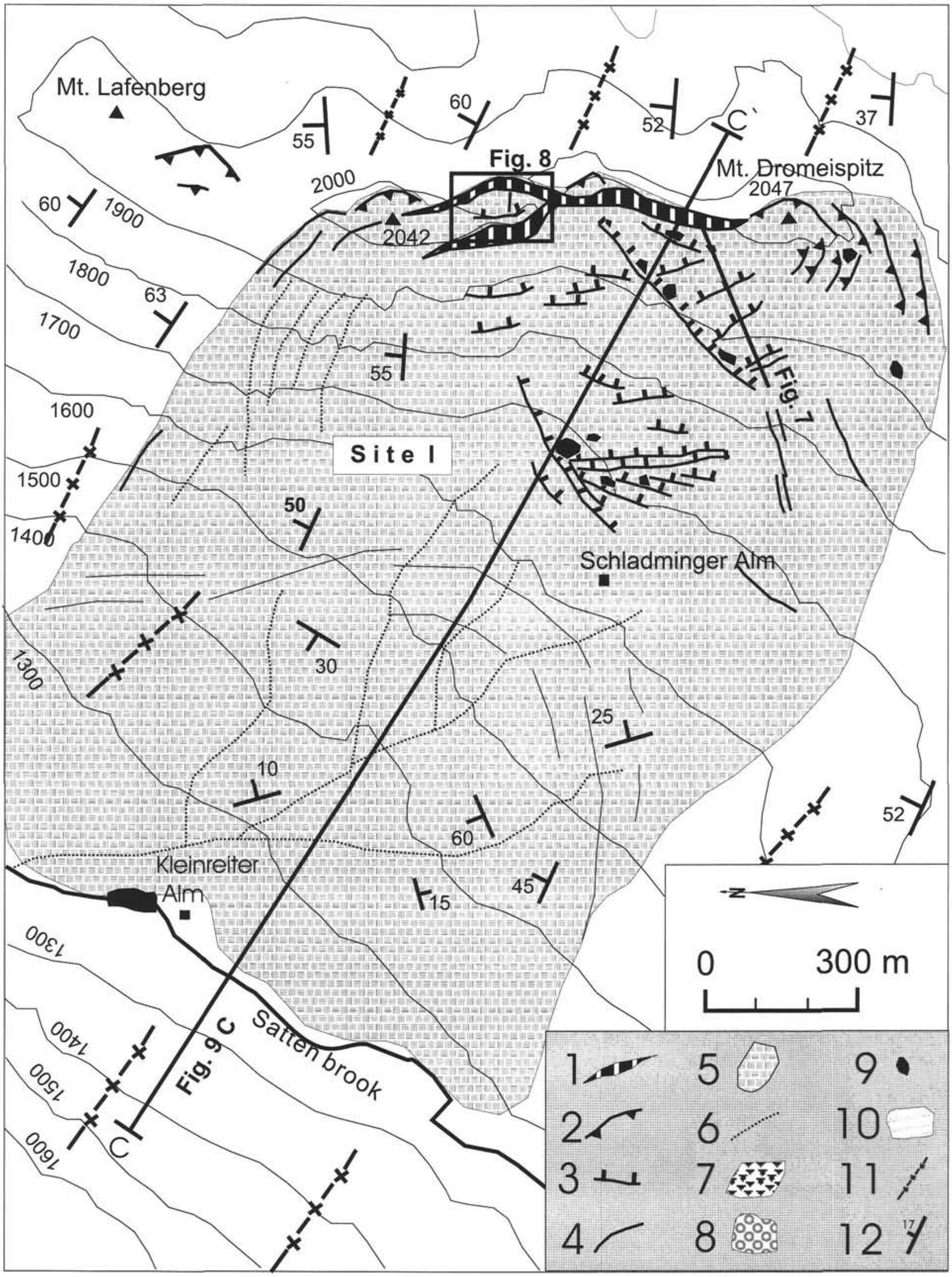


Fig. 3

Map of site I, Schladminger Alm. This site to a great extend represents a mode 1 spreading slope determined by a bulging lower slope portion. Exceptionally the northernmost segment of the main offset scarp features mode 2 spreading.

Legend (for Fig. 3, 4, 5): 1 Yielding and dislocation surfaces, 2 main scarps, 3 uphill facing scarps, 4 minor scarps and trenches, 5 limitation of spreading slope, 6 avalanche tracks and torrent gullies, 7 rock falls, 8 rotational landslide, 9 ephemeral pond, 10 glacial terrace, 11 brittle fault, 12 strike and tip of schistosity.

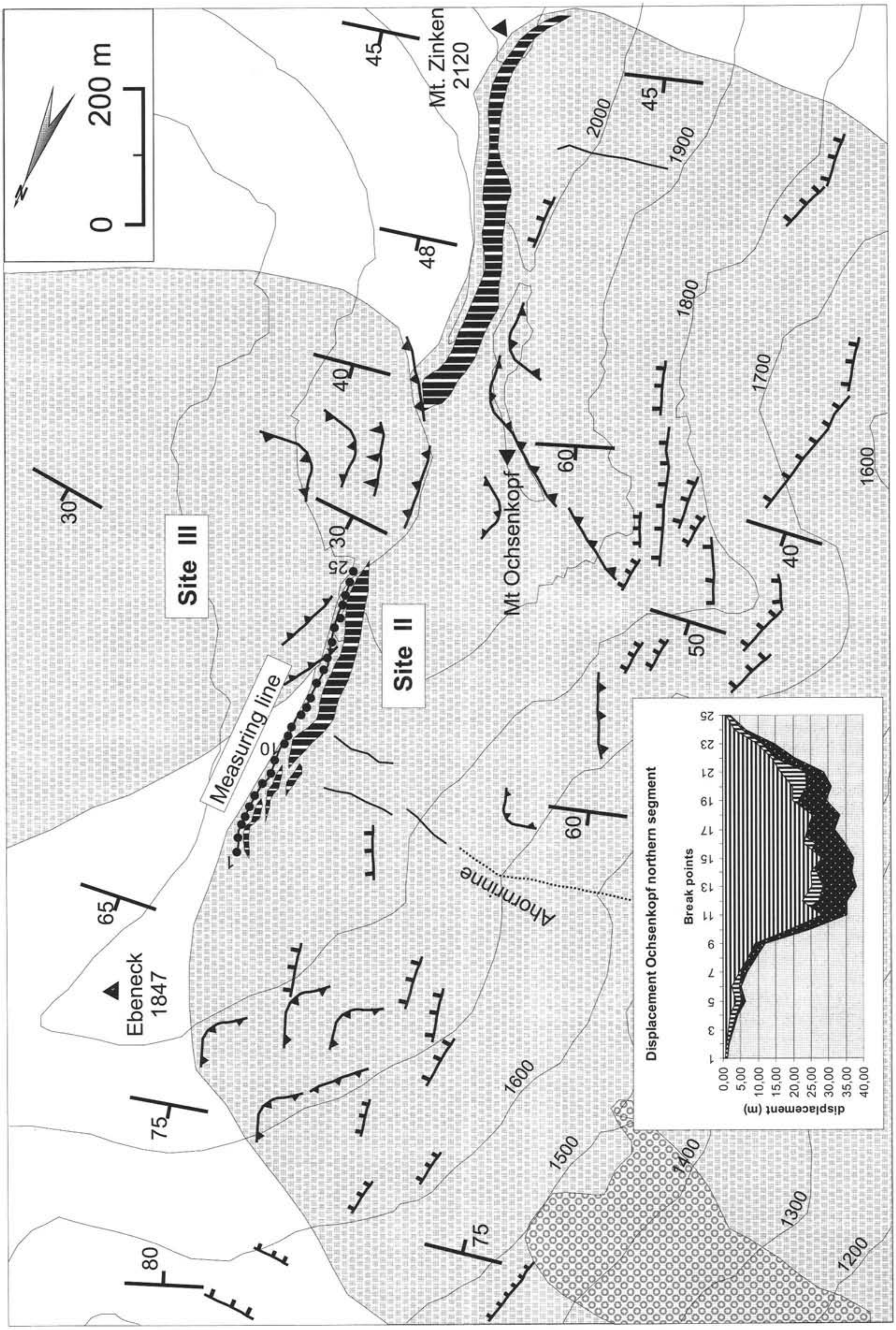


Fig. 4
Map of the spreading ridge including site II (Kleinsölk) and site III (Großsölk). The insert displays offset values of the mode II scarp of site II (displacement: black field, horizontal offset: horizontally hatched field, vertical offset: vertically hatched field). For legend see Fig. 3.

ty) control wedge-form valley on upper slopes and chutes that terminate in debris cones at the base of the ridge (HERMANN, 1996). Within the spreading slope portions, these faults and joint sets are not detectable. An exception is the northern limit where several scarps run into NW-SE directed avalanche tracks and rock avalanche tongues (see Fig. 3).

3.2 Site II, Kleinsölk and site III, Großsölk

The NNE-SSW trending longitudinal ridge between the Kleinsölk valley to the west and the Großsölk valley to the east is on both flanks affected by gravitational spreading slopes (Fig. 2). The spreading slope of site II deforms the west facing slope towards the Kleinsölk valley and the spreading slope of site III deforms the slope towards the Großsölk valley. A detailed morphological map of site II and the fabric of the ridge is shown in Fig. 4. The slope profile of site II is outlined in Fig. 9 A. Ridge spreading occurs only at that segment of the ridge, where dip of schistosity is between 45° and 65° (HERMANN and BECKER, 2001). Northern areas with dip angles from 70° to 85° and southern portions with dip angles between 15° to 25° show no gravitational spreading phenomena.

Site III is developed on a slope, where foliation runs out of the slope and consequently delineates a mode 1 spreading, whereas the slope deformation in site II is characterised by one simple offset forming an impressive double crested ridge (Fig. 6) between Mount Zinken and the anticline near Ebeneck. A typical mode 2 spreading developed. The double crested ridge structure of site II can be traced over a distance of 1700 m, externally passing over single scarps (Fig. 4). Within the slope of site II a glacially modelled landscape is missing. The average slope angle (36,5°) did not decrease compared to slopes that were not destabilized by a slope deformation. However, the slope profile has become convex and in upper slope portions, several uphill facing structures are detectable. In lateral extension of the scarp of site II an enhanced mobility of the slope surface talus may be observed. At the northern portion an active rotational landslide is linked to a rock labyrinth within a "drunken wood" portion in the region west of Ebeneck (see Fig. 4). To the southern branch of the offset scarp a restrained hopper like erosion represents the source area of an rock avalanche tongue called "Bröckelgraben" (HERMANN, 1996).

3.3 Site IV, Weißgulling and site V, Schwarzgulling

The spreading slopes of site IV and site V deform an ENE trending ridge in uppermost portions of the Gulling valley (Fig. 2). Scarp development and the fabric of the ridge are outlined in Fig. 5, the slope profile of site V can be seen in Fig. 9 B.

The uppermost portion of the Gulling valley splits into two parallel valley segments (see Fig. 2), the Schwarzgulling valley to the south and the Weißgulling valley to the north. The ridge in between contains strongly foliated phyllonitic schists and garnet bearing mica schists, gently and consistently dipping to the north. Straight-lined mountain splitting structures between Mt. Hintergullingspitz and Mt. Brennkogel, including double crested ridges, multiple crested ridges and ridge top grabens. These features indicate large scale gravitational spreading slopes in both directions, to the south and to the north (RAUTH, 1996). The overall topography of both sites is different: The spreading slope into the Weißgulling valley to the north displays a concave upper slope and a convex bulging lower slope as well as a complex mountain splitting structure on the upper slope. The glacial morphometric constitution totally has been destroyed. By contrast, the spreading slope into the Schwarzgulling valley to the south is characterised by an offset that produces one single scarp structure only. At site V a glacially modelled bedrock terrace has been preserved to a great extent. Therefore site V is attributed as mode 2 spreading, site IV as mode 1 spreading.

The eastern branch of the scarp of site V overlaps the western branch of the scarp of site IV and consequently forms an area of expressive mountain splitting in the region of the peak at 1.848 m above see level. At the position where branches overlap the ridge shows bilateral spreading as described by JAHN (1964) and HUTCHINSON (1988). Downslope cote 1848 m into the Schwargulling valley, numerous avalanche tracks arise and terminate in abundant debris cones between the pasture of Mittergulling and the pasture of Hintergulling (Fig. 5). In close proximity of Mt. Hintergullingspitz, the western branch of the scarp site IV abruptly expires at a brittle fault that was formed by a set of closely spaced NNW-SSE oriented, steeply dipping shears (RAUTH, 1996).

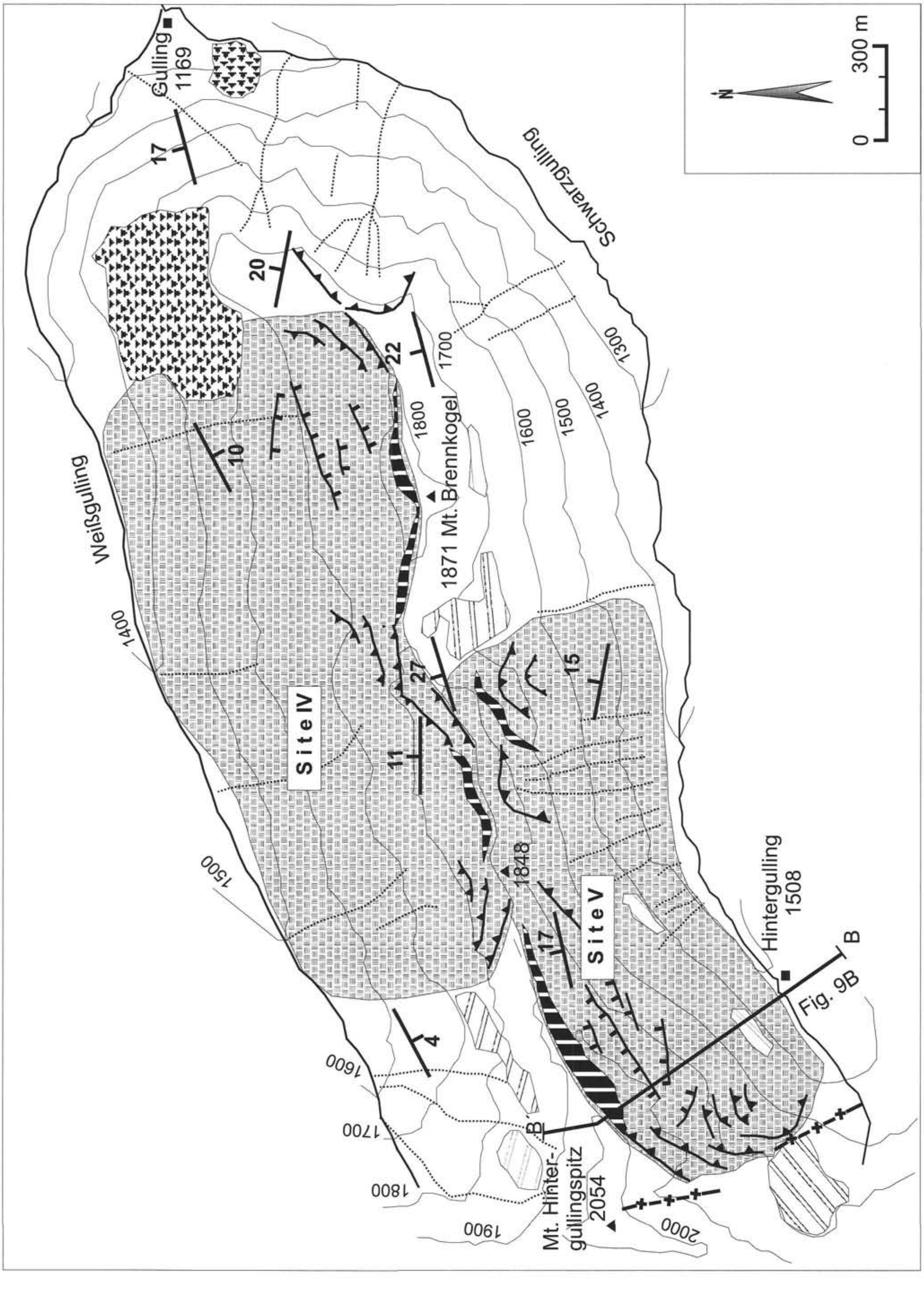
4. Scarp geometry and associated structures

In this section the offset structures that develop into single scarps within mode 2 spreading ridges are discussed. Representative mode 2 scarps are developed at (i) site II, Kleinsölk, (ii) site V, Schwarzgulling and (iii) the northern segment of site I, Schladminger Alm.

(i): The offset of the spreading slope of site II (Kleinsölk) displays one straight aligned single scarp. In central portions this scarp is interrupted by the overlap of several semicircular scarps of the mode 1 spreading scarp structure of site III (Großsölk, see Fig. 4). The northern segment of the scarp scopes strong asymmetry, as outlined by the surface contour lines shown in Fig. 6. There, the scarp appears approximately 100 m aback the original ridge, thus the ridge north of Mt. Ochsenkopf has developed an impressive ridge top graben structure. The geometry of a halfgraben is indicated by a cliffy, west facing scarp and the moderate east dipping surface of the displaced alpine pasture of the hangingwall mass (Fig. 6). Here, some portion of rotation was documented by statistical analyses of the dominant set of master joints (SCHELLHORN, 2001). That argues for a rollover mechanics of the hangingwall mass.

Along the northernmost scarp segment, maximum offset (acquired by laser method surveying) was measured up to 38 m (see insert of Fig. 4). The line measured is show in

Fig. 5 →
Map of the uppermost Gulling valley including site IV (Weißgulling) and site V (Schwarzgulling). For legend see Fig. 3.


Gulling 1169
17
20
22
10
Weißgulling
1871 Mt. Brennkogel
1700
1800
1600
1500
1400
1300
Schwarzgulling
N
0
300 m
Site IV
27
11
15
1848
Site V
17
Hintergulling 1508
B
Fig. 9B
4
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Mt. Hinter-gullingspitz 2054

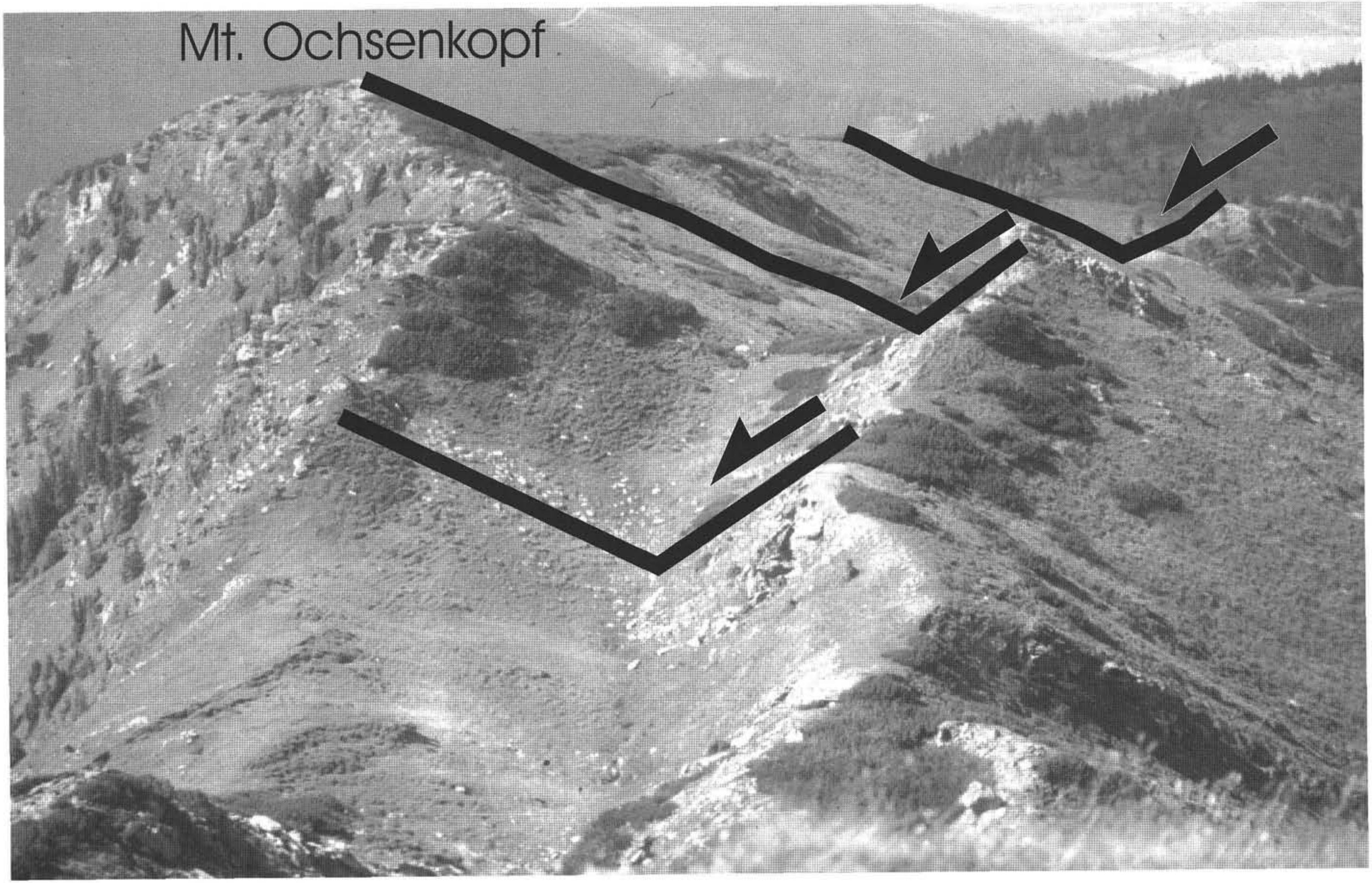

Fig. 6
Oblique view into the ridge top trench of site II (Kleinsölk). This scarp structure defines a mode II spreading. View is to the north, standing on the summit of Mt. Zinken (see Fig. 4). Black lines delineate the surface profile in a direction parallel to the slip direction. The surface profile at Mt. Ochsenkopf and the profile in the background reveal strong asymmetry that may result from a rollover at the main normal fault scarp. Offset direction is indicated by black arrows.

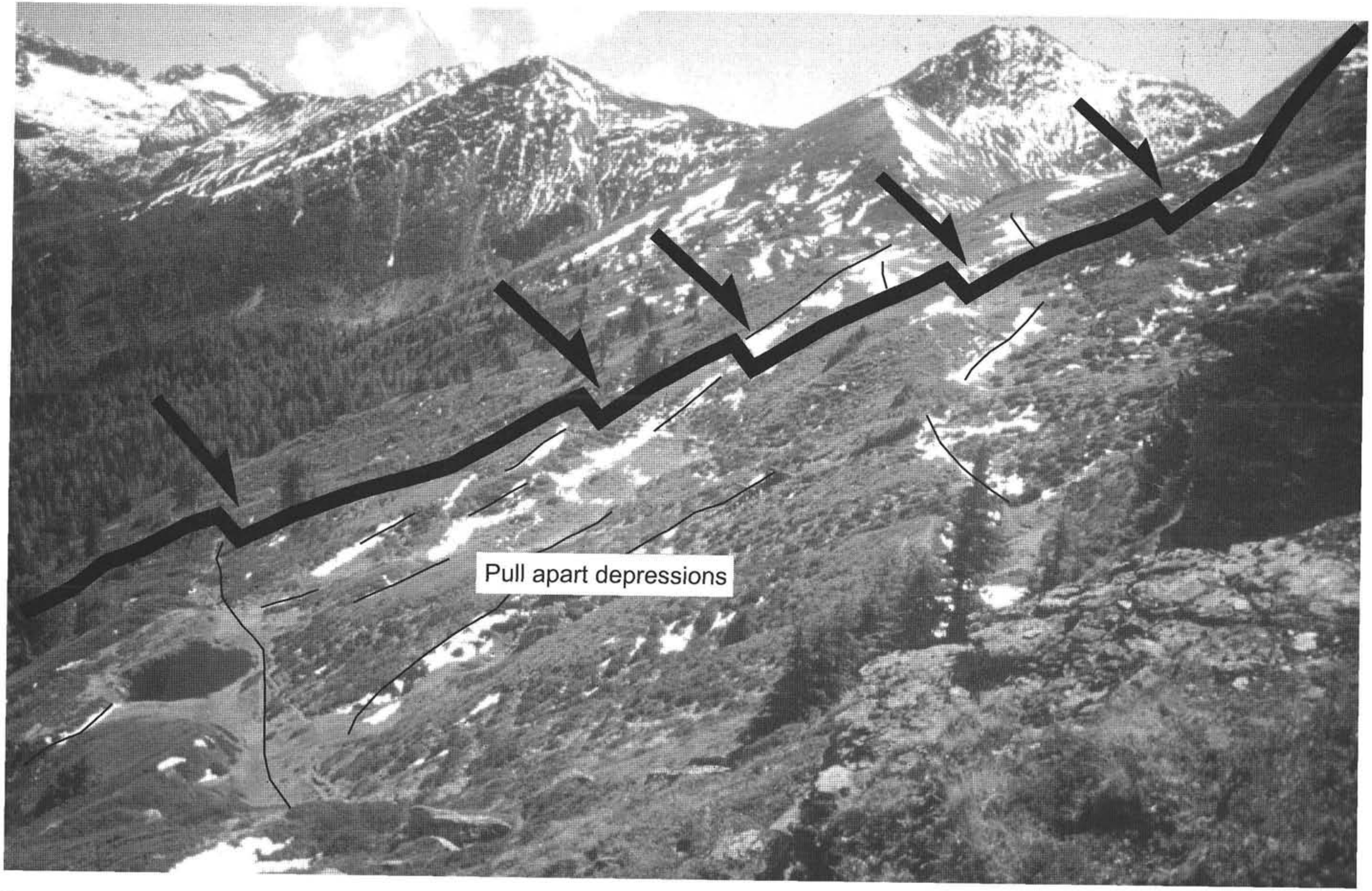

Fig. 7
The middle foreground of the photograph shows the landscape of the collapsing upper slope portion of site I, Schladminger Alm. Location of the black line can be seen in Fig. 3. Snow filled trenches mark uphill facing scarps. Pull apart like depressions are developed where sets of uphills intersect (stippled squares). At the lower left a larger depression carries an ephemeral pond.

Table 1
Data set for the scarp detachment of the spreading slope site II (Kleinsölk).

Measuring points (see Fig. 4)	Total surface displacement (m)	Vertical offset (m)	Horizontal offset (m)	Inclination of detachment (m)
1	1,24	1,12	0,53	64,50
2	1,82	1,54	0,96	58,00
3	2,92	2,53	1,46	60,00
4	4,17	3,63	2,05	60,50
5	6,33	5,22	3,58	55,50
6	5,14	4,56	2,37	62,50
7	6,81	5,06	4,56	48,00
8	9,25	5,88	7,13	39,50
9	11,93	7,74	9,07	40,50
10	24,60	15,65	18,98	39,50
11	35,36	21,28	28,24	37,00
12	35,40	27,31	22,51	50,50
13	38,04	28,49	25,21	48,50
14	36,74	26,67	25,06	47,00
15	37,22	24,17	28,30	40,50
16	34,90	26,14	23,13	48,50
17	31,88	20,92	24,06	41,00
18	33,40	21,47	25,58	40,00
19	29,44	21,71	19,89	47,50
20	30,97	23,72	19,90	50,00
21	28,64	23,46	16,43	55,00
22	20,55	15,03	14,02	47,00
23	14,80	11,17	9,71	49,00
24	6,65	5,70	3,42	59,00
25	2,27	2,05	0,98	64,50

Fig. 4, the results of laser method surveying are shown in Tab. 1. Displacement pattern display that offset continuously increases from breakpoint 1 to breakpoint 9, but abruptly increases to the maximum from breakpoint 10 to 13. We emphasize that at this position trenches oriented perpendicular to the main scarp occur. These trenches run into the avalanche track Ahornrinne. Central portions (measuring points 14 to 21) indicate constant displacement. West of Mt. Ochsenkopf the scarp is cut by the overlapping scarps that belong to site III (Großsölk). The southern portion of the offset of site II, Kleinsölk delineates a more or less symmetric ridge top graben structure (see the foremost surface contour in Fig. 6) that smoothly changes into a single scarp at the summit of Mt. Zinken.

(ii): At the site V (Schwarzgulling) a single scarp can be traced over a distance of more than 1200 meter south of Mt. Hintergullingspitz. That scarp has formed a ridge top valley of pronounced asymmetry (see Fig. 9 B). Offset continuously increases from the eastern segment to the western. The Displacement surface is well defined by a scarce covered slope where alpine vegetation has been denuded through numerous soil slips. Below the main scarp upward facing scarps may be documented but no remarkable bulging of lower slope portions could be evaluated. However, a glacial formed plateau, that outside deformed slopes continuously can be tracked at 1700 m altitude (RAUTH, 1996) below the scarp of site V has been down- shifted appreciably in the vicinity of the pasture of Hintergulling (Fig. 5).

(iii): The offset of site I, Schladmingeralm specifies three types of scarp development. (a) In central portions, between Mt. Dromeispitz and the peak at altitude 2042 m, the slope failure involves one main single scarp that approximately follows the north-south trending ridge. The scarp has develop into a cliff of maximum 50 meter height and has displaced gently north dipping garnet bearing micaschists, quartzites and hornblende bearing schists (WEISS, 1958, see Fig. 3). The slope failed perpendicular to the strike of schists. Beyond the cliff two sets of uphill facing scarps developed (Fig. 7). (b) At the southern branch, south of Mt. Dromeispitz the single scarp structure has converted into numerous minor scarps and the scarps thereby formed a multiple crested ridge within an area of mountain splitting. (c) The northern branch of the scarp splits into two subparallel running offsets that consequently perform a horst and graben structure, enclosing an asymmetric ridge top basin (Fig. 8).

5. Discussion

Slope height and slope stability are limited by the materials involved as well as the orientation of the dominant planar discontinuities with respect to the slope faces (HOEK and BRAY, 1981). It is widely accepted that the occurrence of spreading slopes is connected to high and steep slopes of strongly foliated host rock lithologies (e. g. MOSER, 1993). Evaluation of crystalline bedrock fabric of many slopes in the Niedere Tauern mountains indicate that orientation of planar discontinuities control the manner of gravitational spreading. (HERMANN et al., 2001). Two opposite modes of occurrence may be distinguished: Mode 1 spreading particularly occurs, when planar discontinuities are running out of the slope. On the contrary, when planar discontinuities run into the slope mode 2 spreading occurs. Fundamental morphological differences for mode 1 and mode 2 spreading suggests for different mechanics. Mode 1 spreading displays more or less chaotic re-assemblage of failed slope portions, that can be interpreted by multiple sliding (HUTCHINSON, 1988) of probably limited depth. Mode 2 spreading displays systematic re-assemblage of gravitational faults and indicate similar features produced by the formation of normal fault tectonics.

The geometry of normal faults at any scale is well-known (ROBERTS et al., 1991). Gravitational spreading, as far as we know, never has been described as normal faults. Here, we compare significant surface features of mode 2 gravitational spreading slopes with features that occur at normal faults. Using the approach of normal faults, we try to predict subsurface geometries of spreading slopes. Among the sites presented, three mode 2 spreading offset structures are used for interpretation: The northern portion of the offset of site I (Schladminger Alm), the offset of site II (Kleinsölk) and the offset of site V (Schwarzgulling). Furthermore we outline the importance of site Kaponig – Sickerkopf that was passed through railway tunnelling and where subsurface information is known (KNOLL et al., 1994, RAMSPACHER et al., 2000). The site Kaponig is situated in the southern wedge of the Tauern window (see Fig. 1).

As documented in chapter 3 total displacement is generally accumulated in one offset during mode 2 spreading. Such gravitational faults formed double crested scarps at site I (northern branch) site II, site V and single sided scarps at site I (southern branch) and site II (southern branch). Evaluation of displacement data determine maximum displacement in central portions of the fault scarp, decreasing

Fig. 8
The asymmetric depression in the centre of the photograph features the ridge top structure at the northern offset of site I (Schladminger Alm). For location see Fig. 3. The basin is equal to a graben structure bordered by the footwall cutoff to the right and a counter scarp (antithetic branch fault) to the left. The offset scarp to the right shows increasing displacement from background to the foreground. Snow filled trenches which are oriented perpendicular to the scarp form release faults. Main offset is marked by the cliff line in upper left of the photograph. The plateau like landscape in the middle left forms a horst.

more or less continuously towards the externally branches. Suchlike displacement gradients at single offsets are characteristically for normal faults (e. g. Walsh and Watterson, 1987, Wilkins and Gross, 2002).

All the ridge top structures generated by the single offsets reveal asymmetry. For example central and northern portions of the ridge top trench at site II pictures strong asymmetry as outlined by the two backward surface contour lines shown in Fig. 6. That trench is very similar to a halfgraben resulting from a rollover structure. The strong asymmetry of the ridge top trench is also shown in Fig. 9 A. We emphasize, that the halfgraben structure at site II is not guarded by any pre-existing fabric, consequently the trench exposed strikes 80° away from the main foliation and 20° away from the dominant joint set (Fig. 4). A similar asymmetric ridge top structure with comparable fabric of the host rock is detected at the offset at site V.

In the hangingwall masses, two main types of trenches may be observed: (i) Trenches that are oriented perpendicular to the main scarp and (ii) trenches that are oriented parallel to the main scarp. The trenches perpendicular to the scarp represent transfer faults and may be interpreted as release faults. At site II, on both sides of such release structures, unequal displacement of the hangingwall mass was observed (Fig. 4, insert). Within the ridge top graben of the scarp of site I, release faults are indicated by transversal fissures (Fig. 8). The trenches parallel to the scarp represent antithetic branch faults and have been termed as uphill facing scarp. Such uphills always indicate small displacement in relation to the main normal fault, the main scarp, respectively. Uphills often occur as a group of closely spaced trenches indicating antithetic faults. For example the ridge below the Mount Ochsenkopf is spangled with uphills of limited length, intercalated by some longish uphills. These generate a horst and graben like profile of the upper slope. The surface profile indicates some collapse of the upper slope at Mt. Ochsenkopf (Fig. 9 A). Similar upper slope morphology, but undeveloped, is indicated by the spreading slope at site V, Schwarzgulling (Fig. 9 B).

Several sets of uphills occur at site I, Schladminger Alm (see Figs. 3, 7, 9 C). There, short uphills as well as longish uphills are oriented oblique to the main offset. (Fig. 3). At the points where the two sets intersect they perform smooth depression on the hillslope indicating intensified collapsing slope portions. Areas of intersecting uphills are connected with run over springs. The oblique orientation of the two sets of uphills compound the picture of a collapsing upper slope also in horizontal direction. Collapse of upper slope portions as indicated by uphills directly point towards lateral extension in lower slope portions.

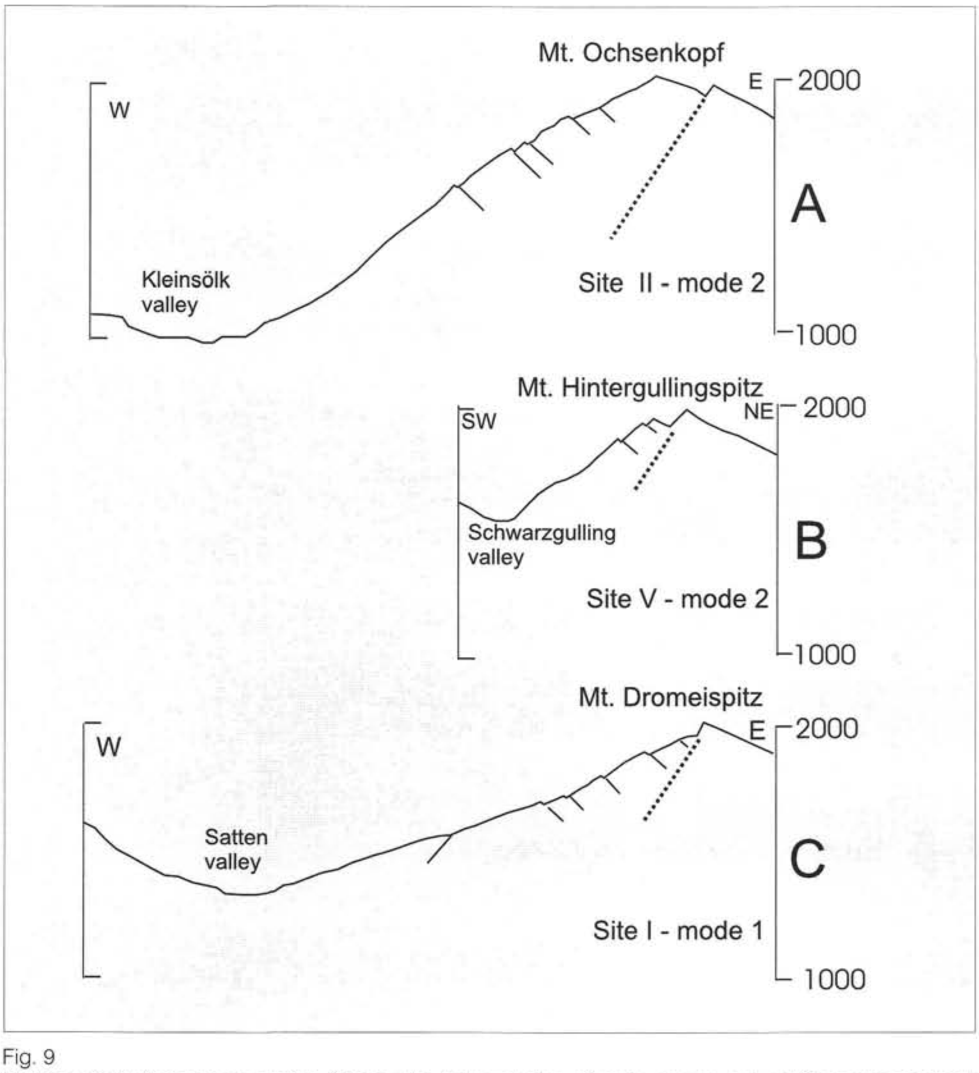

Fig. 9
Profiles of gravitational spreading ridges. The Interpretation of main scarps and uphill scarps as steep normal faults and anithetic normal faults respectively, suggests deep reaching extension for spreading slopes. Stippled lines represent calculated prolongation of footwall cutoff.

At the site Kaponig similar offset structures as described in section 3 are known (Knoll et al., 1994, Ramspacher et al., 2000). One main offset generated a single sided scarp at the southwest facing slope of the Mt. Sickerkopf. Downslope that scarp several sets of uphills have formed. The slope below Mt. Sickerkopf indicate collapse of the upper slope portions and therefore may be a comparable ridge to the spreading ridges shown in Fig. 9 A-C. The slope of site Kaponig was maltreat by the construction of the Kaponig tunnel as part of the double track consolidation of the Tauern railway. During construction of the tunnel the hangingwall mass of the spreading slope was passed and the spreading slope was crossed in oblique direction with respect to the strike of the main scarp. Over a distance of almost 1200 m enhanced water inflow into the tunnel was registered, reaching the maximum at station 1169 m. There a fault zone was crossed, accompanied by 300 litre per second water inflow. It was suggested that the water inflow was related to planar openings as a consequence of rock deformation of the spreading slope above. The fault zone at site Kaponig later was interpreted as the basal detachment of the sliding mass that crops out at scarp of Mt. Sickerkopf (KNOLL et al., 1994). Extension and predominantly lateral rock deformation in depth, as documented in the Kaponig tunnel has been predicted through processes of gravitational spreading by SCHULTZ-ELA (2001).

Calculations for the subsurface prolongation of the main fault scarp predicted approximately 50° of inclination. Because similar surface structures at comparable rock properties (strongly foliated schists) and fabric association, we predict similar subsurface prolongation for mode 2 gravitational fault scarps in the Niedere Tauern mountains (Fig. 9 A-C). Steep inclination of basal detachment argues for a deep reaching rock deformation by processes that are similar to the mechanics of steep normal faults. Such interpretations contrast calculations by numerical modelling. In those models rock deformation does not extend around 300 m below surface (SAVAGE and SWOLFES, 1996; BARLA & CHIRIOTTI, 1995, VENGEON et al., 1999; BONZANIGO et al., 2001). However, the theory may be confirmed by surface observation of single offset scarps. As shown in table 1, the average surface inclination of the offset scarp at site II, Kleinsölk is 50 degree.

6. Conclusions

- Exploration on slope failure occurrence has revealed high susceptibility of exposed crystalline basement for gravitational spreading.
- Mode 2 spreading ridges generate ridge top structures that are comparable to offset structures generated by steep normal faults. This include main normal faults, branch faults in syn- and antithetic manner, horst and graben structures, halfgrabens, hangingwall rollover and release faults. Scarp development of mode 2 spreading ridges therefore can be interpreted by normal fault mechanics.
- Normal fault mechanics argue for a deep structure of gravitational spreading slopes. We suggest that basal detachment dips between 50° to 65°.
- Slopes affected by gravitational spreading indicate individual water management and may give aspiration for undiscovered water reservoirs.

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