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Plan-curvature effect on the formation of tumuli on shield volcanoes: an example from Leitin lava flow field in Iceland

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with 10 figures and 1 table

Summary. Plan curvature is a slope parameter which governs the divergence or convergence of flow lines of any gravity-driven flowing material such as lava. The slopes of monogenetic shield volcanoes are convex in plan form. Tumuli, which are small dome-like lava structures, are common features on the lava flows of the Icelandic shield volcanoes. On the Leitin shield volcano in SW Iceland the area distribution of tumuli is mainly controlled by the plan curvature. A density increase in tumuli is associated with peaks in the plan convexity. This follows because high plan convexity forces the distributary tube system which supplies magma to the tumuli to branch vigorously. Large lava-inflation structures such as lava rises occur in areas where there were restrictions to branching.

1 *Introduction*

Plan curvature of a slope refers to the shape of the ground along a horizontal plane (YOUNG 1972). Plan curvature affects any gravity-driven material such as surface waters and creeping soil. Plan curvature also influences the stress field of the near-surface rocks. On a plan-convex slope the flow lines diverge, whereas on a plan concave slope the flow lines converge (Fig. 1). A typical shield volcano (Fig. 2) has the form of a cone and, therefore, its slopes are plan-convex. The convexity is highest in the upper flanks of the cones and gradually decreases toward the lava apron, where the slope is practically straight

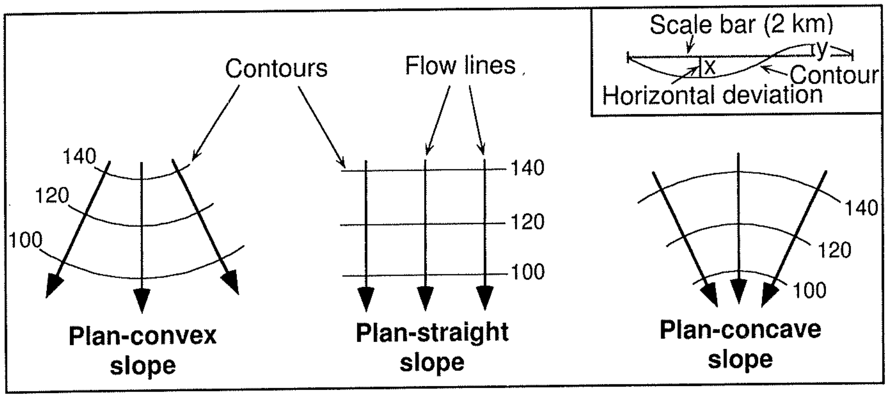

Fig. 1. Flow lines on slopes of different plan forms. Inner caption explains the method of measurement used in this study. The net curvature along the scale bar is derived by subtracting y (concavity) from x (convexity).

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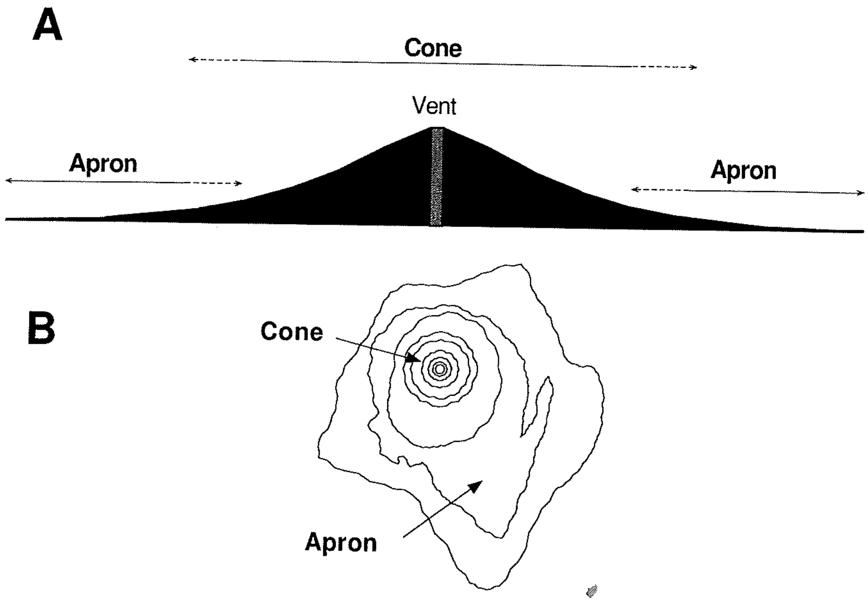

Fig. 2. The constructional elements of a shield volcano (A) in cross section, and (B) in contour map view. Accumulation of many lava flows leads to the formation of a cone around the volcanic vent. The apron around the cone is commonly much thinner than the cone but may be much more extensive areally. The cone is highly plan-convex while the apron is practically straight in plan.

in plan. Plan concavities are normally absent on monogenetic shield volcanoes but exist on erosional slopes of large polygenetic shield volcanoes such as those of Hawaii.

Leitin is a postglacial monogenetic shield volcano on the Reykjanes Peninsula in SW Iceland (Fig. 3). It is situated in a narrow valley among hyaloclastite mountains and has an estimated volume of 3 km^3 and an age of 4500 years (JÓNSSON 1978). Its lavas were erupted from a central vent and flowed to the northeast and to the south. This study was performed in the southern branch of the flow. The Leitin flow field is almost entirely plan convex, but the magnitude of the slope curvature varies, the highest values being in the areas of unconfined flow. Where the spreading of the lava flow is restricted by the surrounding topography, the values of curvature are low. This follows because lava flows tend to pool against the surrounding hills.

Tumuli are common features on pahoehoe lava flows (OLLIER 1964, WILLIAMS & MCBIRNEY 1979, ROSSI 1996). Recent studies on tumulus formation focus on the physical modelling of them (WALKER 1991, HON et al. 1994, ROSSI & GUDMUNDSSON 1996). Detailed studies on the areal distribution of tumuli on lava flow fields have not been carried out. Furthermore, little attempt has been made to evaluate the topographic effects on the formation of these features. Because lava flows are driven by gravity, the topography on which the lava flows must have a significant effect on the emplacement of lava. The variation in plan curvature on Leitin provides an opportunity to study the effect of plan curvature on the formation of tumuli. In this paper the areal density distributions of the tumuli are considered and viewed against the regional lava topography, in particular against the variation in the plan curvature of the slope.

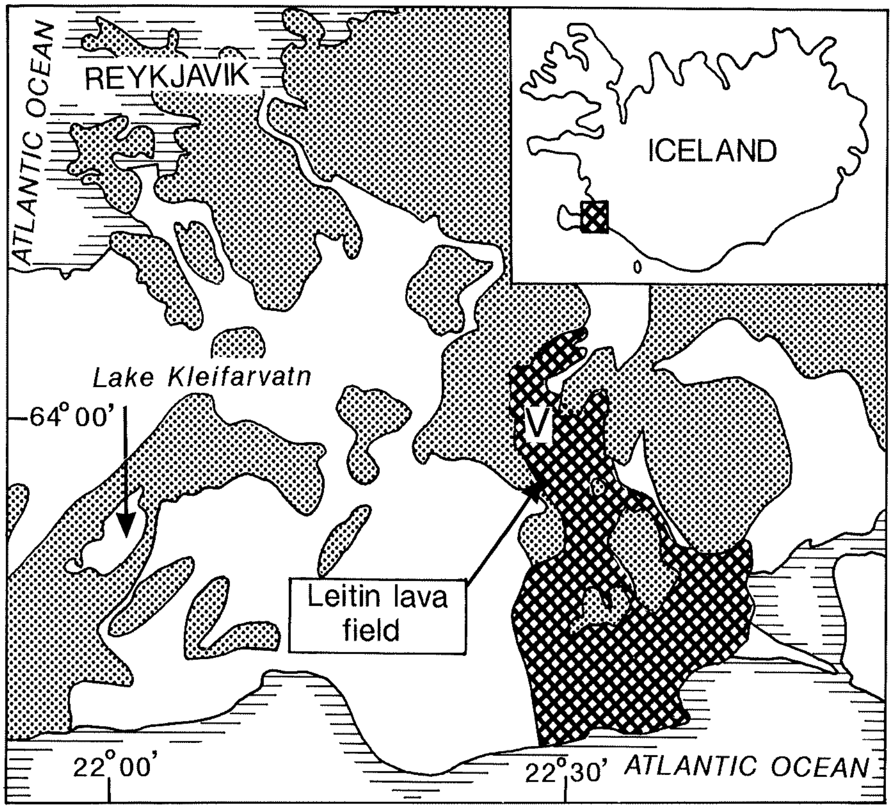

Fig. 3. Regional setting of Leitin lava field. The study area is to the south of the vent (V). Light shade marks Pleistocene hyaloclastite and lavas, and white colour (not shaded) Holocene lavas and sediments. The kipukas (islands) within the Leitin lava field consist mainly of Pleistocene hyaloclastite and, to a lesser extent, of Holocene shield volcanoes older than the leiting lava field.

2 *Methods*

The dimensions of two common tumulus types, namely the upper-slope tumuli and flow-lobe tumuli, were measured at two locations to characterise their morphology. The morphological differences between the sample sets were tested statistically.

The areal distributions were studied by a point-count method. The study area was divided into 574 quadrats, each 0.13 km², and the number of tumuli were counted in each quadrat from aerial photographs. The data were analysed on the computer using kriging and trend-surface methods. The significance of the areal distributions and point patterns of the tumuli were evaluated. The regional slope angles were measured from digitised contour maps. Plan curvature of each 20-meter contour was measured by using a scale bar representing 2 km length (Fig. 1). The scale bar was placed at both ends on the contour and the curvature obtained by subtracting the maximum negative deviation of the contour (concavity) from the maximum positive deviation of the contour (convexity). The scale bar was then moved 500 meters onward from the previous location on

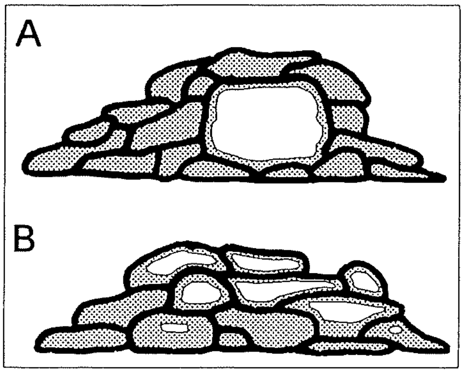

Fig. 4. Schematic cross-section of two types of lava tubes (not shaded) within a pile of flow lobes (see ROWLAND & WALKER 1990). (A) Major lava tube, which forms during persistent through-flow; (B) Distributary lava tubes which are commonly short-lived.

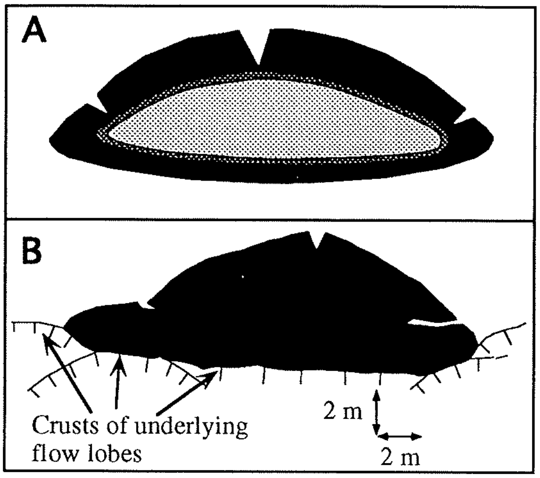

Fig. 5. (A) The layered structure of a tumulus during its formation. Black colour is the brittle crust with the inflation-cracks. Dark shade is the visco-elastic crust which bends in response to the magmastatic overpressure in the molten lava core (light shade). (B) A cross-section measured in a fault scarp in the Thrainsskjoldur lava field in south western Iceland.

the contour. The mean curvature of the contour was obtained by calculating the average of the measurements on the contour.

3 *Geology of tumuli and related structures*

While forming, pahoehoe lava lobs are covered with thin cooling crusts which commonly fail and new lobes form from the pre-existing ones. Chains of budded and interconnected lava lobes form distributary lava tubes (Fig. 4). The distributary networks are commonly short-lived (HALLWORTH et al. 1987, ROWLAND & WALKER 1990, MATTOX et al. 1993, PETERSON et al. 1994). Large lava tubes may form within the piles of flow lobe with persistent through-flow (several days to weeks). Major lava tubes also form by crusting-over of open lava channels (see MACDONALD 1972, ROWLAND & WALKER 1990). However, on the monogenetic shield volcanoes of Iceland crusting-over is of minor importance in the medial and distal parts of the lava fields but more common on the proximal (near-vent) areas (ROSSI 1996).

Often the originally small lava lobes expand to large features such as tumuli. A tumulus forms as the lava crust is bent up by the magmastatic overpressure in the associated molten lava core (ROSSI & GUDMUNDSSON 1996; Fig. 5). The expansion of a flow lobe is related to the flow rate – cooling rate relationship (e.g. FINK & GRIFFITHS 1992). At a high flow rate (or a low cooling rate) the lava crust will fail. At a low flow rate (or a high cooling rate) the crust that forms may be strong enough to keep the incoming lava within the lobe. The formation of tumuli and other inflation features requires a lava crust

Fig. 6. Flow-lobe tumulus in the flow field of Skjaldbreidur shield volcano in southwestern Iceland. Note the smooth convex shape and a wide axial crack.

adequately strong to accomodate the inflowing lava. If the magmastatic overpressure exceeds a certain limit the crust inflates without failure. Thus, the formation of a tumulus is favoured by a low supply rate and sufficiently high magmatic overpressure. Many tumuli in Iceland occur at the distal ends of distributary flow paths where there is normally high magmastatic pressure and low magma supply rate (ROSSI & GUDMUNDSSON 1996).

Three types of tumuli occur on Icelandic shield volcanoes: outflow-tumuli, upper-slope tumuli and flow-lobe tumuli (ROSSI & GUDMUNDSSON 1996). Flow-lobe tumuli (Fig. 6) are the most common tumulus type on the medial and distal parts of flow fields. They are dome-like mounds of inflated lava crust with tension cracks. The cracks form as the upper brittle lava crust (Fig. 5) is subject to tensile stress during the inflation of the lava crust. The axial crack is wider than the radial and circumferential cracks. The lower viscoelastic crust bends; it is also subject to compressive stress and, therefore, capable of keeping the molten lava within the structure. Occasionally, the viscoelastic crust cracks (HON et al. 1994, ROSSI & GUDMUNDSSON 1996), giving rise to outflows. Outflow tumuli have steeper flanks than the flow-lobe tumuli and the flanks are often completely covered with outflows. Upper-slope tumuli (Fig. 7) are also steep-sided but have a lesser amount of outflows than the outflow tumuli.

Lava rises (WALKER 1991) are similar features to flow-lobe tumuli, have a similar mode of emplacement, but are larger in size (ROSSI & GUDMUNDSSON 1996). Unlike tumuli, lava rises are flat-topped and their inflation-cracks are in the margins of the structures only.

Fig. 7. Upper-slope tumulus in the Skjaldbreidur lava flow field. Note lava that has been squeezed out from the cracks.

On the Leitin lava field outflow tumuli are rare. Two common tumulus types are flow-lobe tumuli and upper-slope tumuli. A t-test performed on log-transformed data indicate that flow-lobe tumuli have significantly larger areas (99.9% confidence) and significantly lower height/width ratios (99 % confidence) than the upper-slope tumuli (Fig. 8). Flow-lobe tumuli also differ from the upper-slope tumuli by having much smaller outflows from their cracks. It is estimated that around 15% of all tumuli counted from aerial photographs area are upper-slope tumuli, and the rest are flow-lobe tumuli. Upper-slope tumuli dominate the upper flow field to a distance of 2.5–3 km from the vent. At greater distances from the vent flow-lobe tumuli dominate overwhelmingly. In the following analysis both tumulus types are considered together.

4 *Areal distribution of tumuli*

2526 tumuli and 191 lava rises were counted in this study. The highest density of tumuli (18 per quadrat) is reached in the southeastern part of the flow field. The average number of tumuli is 4.4 per quadrat. The Kolmogorov-Smirnov test, where an expected random (Poisson) distribution is compared with the observed distribution, suggests that the areal distribution of tumuli is non-random at the 99.9% confidence level (Table 1). A point-pattern analysis (SHAW & WHEELER 1985) also suggests that the distribution is non-random and a large negative z-value indicates that tumuli tend to be regularly spaced (Table 1). A cubic regression analysis carried out in the area (Fig. 9) shows a significant

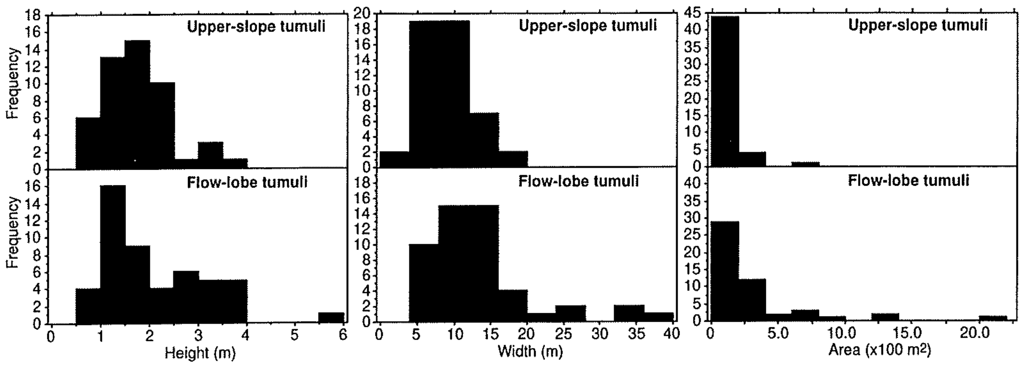

Fig. 8. Frequency distribution of height, width and area of upper-slope tumuli and flow-lobe tumuli measured at distances of 2.5 and 6 km, respectively, from the vent.

spatial trend at the 99.9% confidence level for the distribution of tumuli according to the analysis of variance (Table 1). The expected density values of tumuli are rising slightly away from the vent (and from the south) toward the northeastern and southeastern parts of the flow field. Thus, the expected values are not related to distance from the vent. By smoothing a matrix which was produced by the kriging method (Fig. 9), three main areas of high tumulus density can be identified at distances of roughly 0.3, 0.6 and 0.9 times the flow length (Fig. 9). The same pattern occurs in a plot of tumulus density against the distance from the vent (Fig. 10).

Matrix smoothing and trend surface maps indicate that the main concentration of lava rises is in the mid-flow field just above the narrow passages between the hyaloclastite mountains (Fig. 9). Analysis of variance indicates a significant spatial trend at the 99.9% confidence level for lava rises.

Table 1. Results of areal statistical analysis.

Kolmogorov-Smirnov test

Degrees of freedom	D
574	0.142

D_{crit} at 0.01 level 0.068

Point-pattern analysis

Degrees of freedom	Variance/mean ratio	Standard error	z-value
573	0.576	0.059	-7.186

ANOVA-table for cubic regression

	Sum of squares	Degrees of freedom	Variance	F-ratio
Cubic surface	378.686	9	42.076	
Residual	6119.698	564	10.851	3.88

F_{crit} at 0.01 level 2.71

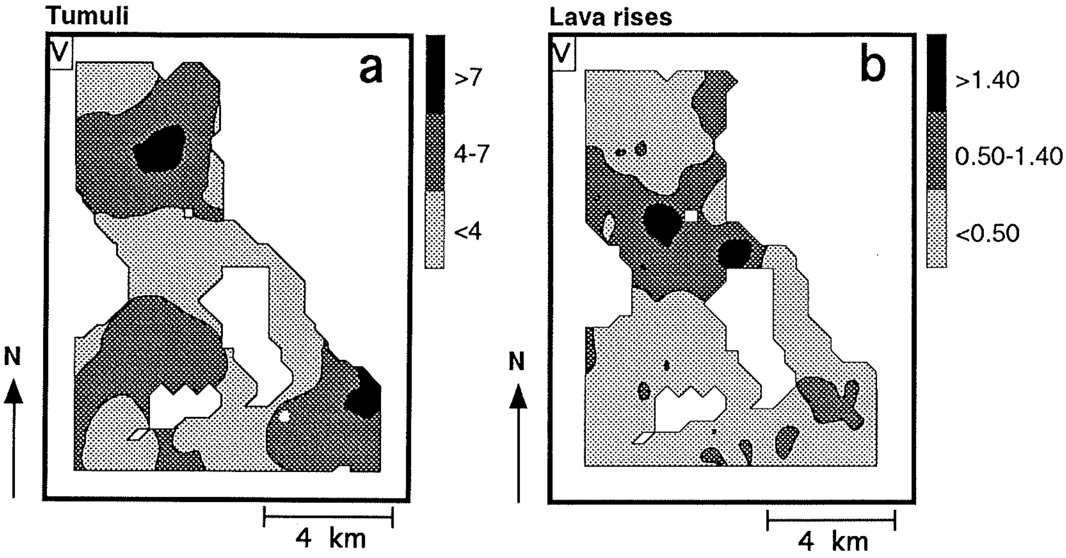

Fig. 9. Kriging contour maps smoothed by an inverse-distance method for tumuli and lava rises. The kriging matrix shows the concentration of the structures in the flow field. The values for smoothed kriging matrix are derived from power equations; therefore, they are not true density values. A distance weighing power of 3.2 is used for the matrix smoothing. Note that the flow margins decrease as a result of the smoothing procedure.

5 *Discussion*

Both major lava tubes and distributary lava tubes are found on pahoehoe lava flow fields. Lava tubes form a branching network that supplies lava to the flow lobes. A new branch has a lower supply rate than its upslope source. With increasing number of branches the supply rate in individual branches decreases. The magmastatic pressure in each new branch increases downslope because the height to the source above the branch increases.

Flow-lobe tumuli form along distributary pathways of lava and should therefore be most common where the separation of flow lines (branching) is greatest. A plot of number of tumuli versus distance from the vent (Fig. 10) demonstrates that the formation of tumuli is favoured after peaks in plan convexities. The length of distributary tube segments along which tumuli form are probably in the order of several hundred metres to a few kilometres. Because tumuli are the end products of flow lines which have separated upslope, the peak in plan convexity and the maximum density of tumuli do not coincide.

The angle of slope also has an effect on the formation of tumuli. Generally, the slope must be gentle for tumuli to form (WALKER 1991, HON et al. 1994). In Iceland, most upper-slope tumuli occur on slopes less than 8° and most flow lobe tumuli on slopes less than 4° (ROSSI & GUDMUNDSSON 1996). The slope angle on the Leitin lava field varies from 0.6° to 4.8° which is well within the favourable range for tumulus formation. However, the areal density variation of tumuli does not correlate well with changes of the slope angle (Fig. 10).

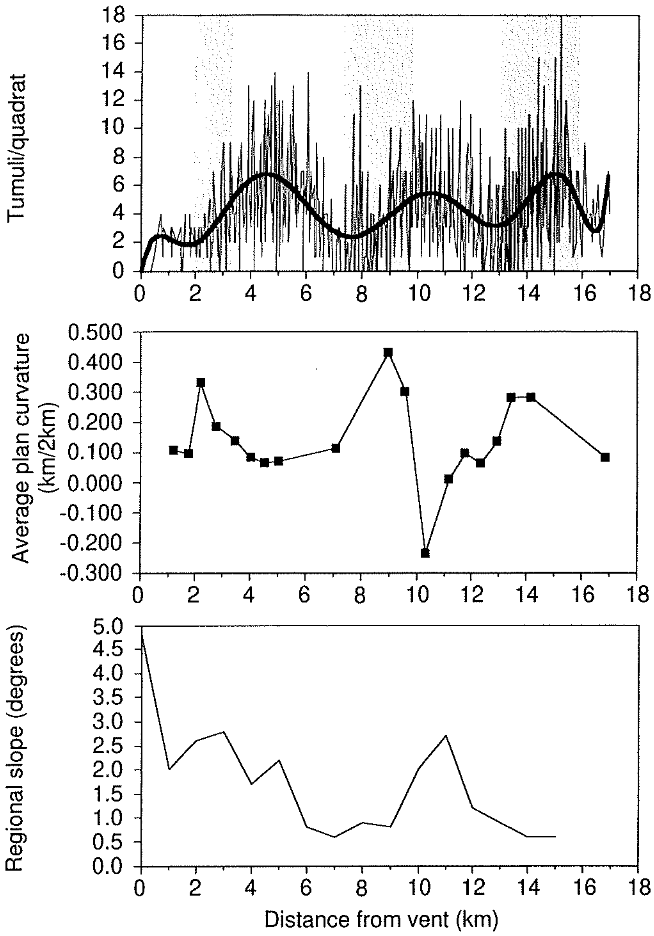

Fig. 10. Change in tumulus density, average plan curvature and regional slope as a function of distance from vent. The best fit of the tumulus density data is given as a polynomial curve. Shading in the upper figure represents high values (over 0.15) of plan convexity.

Lava rises and other large inflation-structures, such as Hawaiian sheet flows, form at higher supply rates than tumuli (HON et al. 1994), ROSSI & GUDMUNDSSON 1996). Most lava rises on the Leitin lava field occur just above narrow passages where the surrounding topography forces the flow lines to converge. In areas with little branching the flow rates in lava tubes are generally higher than in areas where branching is greater. These areas are thus favourable for the formation of lava rises.

6 *Conclusions*

Most tumuli on the Leitin lava field are flow-lobe tumuli which form along distributary lava tubes. The distribution of tumuli on the Leitin lava field is rather regular with slight variations in the areal density. The amount of distributary lava tubes increases positively with the plan convexity of the slope because then the branching of the tubes becomes more intense. As a consequence, flow-lobe tumuli, which form at the ends of distributary lava paths, increase in number. Monogenetic shield volcanoes are plan-convex structures and the large number of tumuli on their flanks is a surficial expression of the extensive lava tube branching. By contrast, lava rises are likely to form where flow rates in tubes are high. Therefore, they occur on slopes on which branching of the tubes is less extensive.

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