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RESEARCH ARTICLE

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Rift zone reorganization through flank instability in ocean island volcanoes: an example from Tenerife, Canary Islands

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Abstract The relationship between rift zones and flank instability in ocean island volcanoes is often inferred but rarely documented. Our field data, aerial image analysis, and $^{40}Ar/^{39}Ar$ chronology from Anaga basaltic shield volcano on Tenerife, Canary Islands, support a rift zone—flank instability relationship. A single rift zone dominated the early stage of the Anaga edifice (~6–4.5 Ma). Destabilization of the northern sector led to partial seaward collapse at about ~4.5 Ma, resulting in a giant landslide. The remnant highly fractured northern flank is part of the destabilized sector. A curved rift zone developed within and around this unstable sector between 4.5 and 3.5 Ma. Induced by the dilatation of the curved rift, a further rift-arm developed to the south, generating a three-armed rift system. This evolutionary sequence is supported by elastic dislocation models that illustrate how a curved rift zone accelerates flank instability on one side of a rift, and facilitates dike intrusions on the opposite side. Our study demonstrates a feedback relationship between flank instability and intrusive development, a scenario probably common in ocean island volcanoes. We therefore propose that ocean island rift zones represent geologically unsteady structures that migrate and reorganize in response to volcano flank instability.

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Introduction

Rift zones and volcano flank instability

Dikes in ocean island volcanoes are commonly concentrated in rift zones forming axes of major intrusive volcano growth. The orientation of such dike swarms is commonly subparallel to the direction of the maximum compressive stress, only a small fraction of dikes ever reaching the surface (Gudmundsson et al. 1999). Lasting intrusive and extrusive activity along rift zones typically results in a morphological ridge that may become unstable and be destroyed by giant landslides (Dieterich 1988; Carracedo 1994; Walter and Schmincke 2002).

It is, therefore, of major interest to better understand formation and dynamic interplay of rift zones and flank instability. It is not clear whether rift zones on ocean islands are stable and long-lasting features that ultimately destabilize volcano flanks by outward push, or whether rift zones are transient arrangements that build-up, cease, or change their direction. If the rift architecture is a temporary arrangement that may adjust to near-surface changes in the stress pattern of a volcano, our assessment and long-term prognosis of volcano development will be significantly affected.

Rift zones are arguably the most prominent structural features on the Hawaiian and the Canary Island volcanoes and frequently display a curved axis (Fig. 1). For the Hawaiian Islands, Fiske and Jackson (1972) suggested that the ridge-like topography of rift zones is a principal factor in geometrically focusing dike intrusions. A rift-ridge system causes horizontal expansion normal to its elongation and vertical sagging because of its weight. The topography of rift zones, once established, focuses dike intrusion parallel to the axis of the ridge. Continued deep-reaching faulting that predominates in rift zones allows

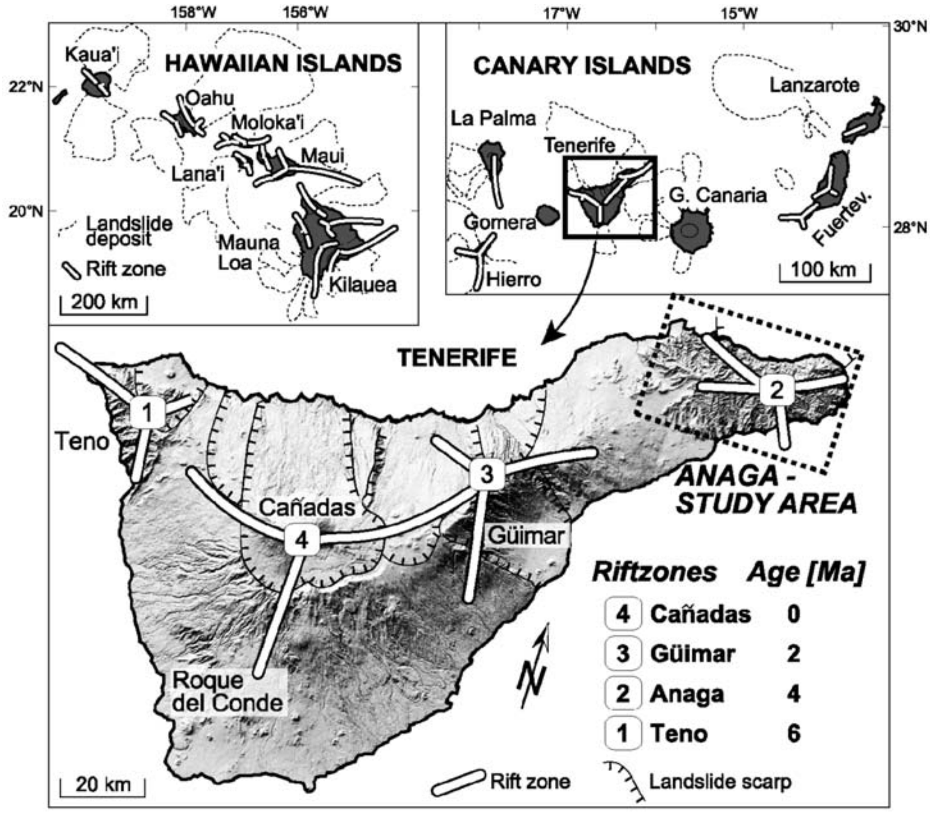

Fig. 1 Relation between flank instability and rift zone position illustrated for the Hawaiian and Canary Islands. Submarine avalanche deposits (*dashed black lines*) frequently originate in between two rift arms of a three-axis system. Each island formed several rift systems, shown in detail for Tenerife Island (*large insert*). On a *shaded relief map*, morphological scarps from flank collapses are visible, commonly enclosed by two rift zones (e.g. Güimar). Study area Anaga is in the northeast. Hawaiian Island map includes data by Fiske and Jackson (1972) and Moore et al. (1989); Canary Island maps include data from Carracedo (1994) and Walter and Schmincke (2002)

expansion and thus permits dike intrusion and rift persistence (Dieterich 1988). An existing rift zone tends to stabilize itself. But the initial mechanisms of rift formation, often accompanied by flank destabilization, remained controversial. One hypothesis suggests that dike swarms may push a volcano flank seaward and thus facilitate fault slip of huge edifice segments (Clague and Denlinger 1994; Iverson 1995; Elsworth and Voight 1996; Cayol et al. 2000). An alternative hypothesis favors the passive control of intrusive rift zones when a flank deforms gravitationally (Delaney et al. 1998; Owen et al. 2000; Walter and Troll 2003). There is growing evidence that the number and orientations of dike swarms in volcanic edifices are largely controlled by the near-surface imbalance that arises from the instability of volcano flanks. A bi-directional interaction may be given, say, when the volcano sector instability changes the structure of a rift volcano, which in turn influences the development of the unstable sector. This might control the structural evolution of individual volcanic edifices. In this paper, we describe the structural evolution of Anaga, the shield volcano that dominates the northeastern sector of Tenerife (Canary Islands). We demonstrate how the arrangement of volcanic rift zones is altered through interaction with an unstable island flank.

Geologic background

Tenerife is located ca. 300 km off the coast of NW Africa. Three basaltic shield volcanoes occupy three corners of the island, each representing an independent edifice with its own volcanic history (Fúster et al. 1968). These are Anaga in the northeast, Teno in the west, and Roque del Conde in the south of the triangular island (Fig. 1). These Miocene-Pliocene shields were amalgamated by a Pleistocene fourth edifice (Cañadas) in the center, successively overlapping the three old shields (Ancochea et al. 1990).

Fractures and rift zones on Tenerife repeatedly developed in triaxial patterns. These triple-armed rifts are thought to result from either magmatic doming, and thus slight upward bending of the crust (Carracedo 1994), or gravitational spreading effects (Walter 2003). Several such “triaxial rift zones” exist on the island, some of which were active simultaneously (Fig. 1). The Miocene rift zones developed in the northwest of the island (Teno) and later in the northeast (Anaga). The Teno and Anaga centers represented separate volcanic islands at that time (Carracedo 1994). The youngest triaxial system formed on the Pleistocene central Cañadas volcano and erupted historically several times.

To understand the evolution of rift zones we focused on the deeply eroded Anaga massif (Fig. 2A). Anaga began to grow in the late Miocene and practically terminated in the Pliocene at around 3.3 Ma (Ancochea et al. 1990). The polygenetic evolution of the Anaga massif began with basanitic activity around 8 Ma, alkali basalt

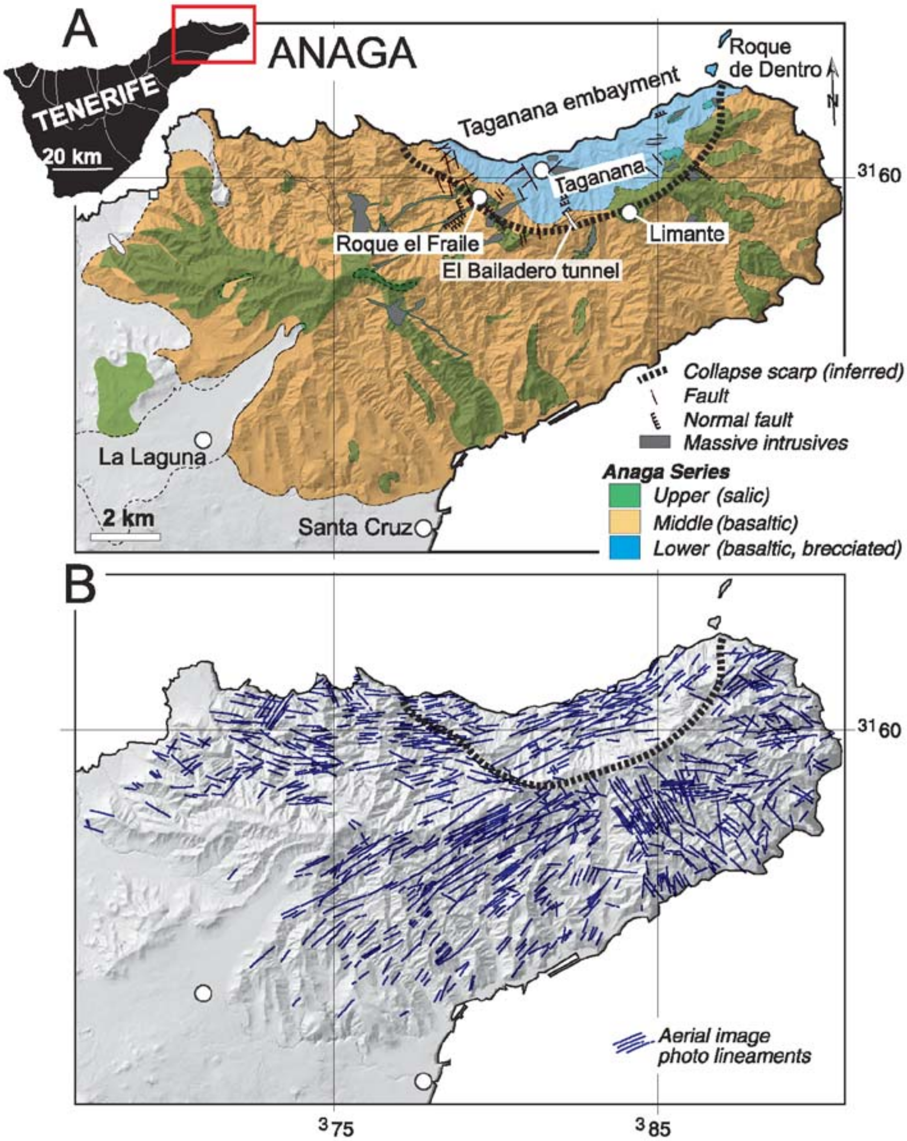

Fig. 2 Maps of Anaga area showing (**A**) a simplified geological map with the three major geological series, and (**B**) lineament distribution from aerial images on Anaga. *Dashed black line* marks the morphologically prominent horseshoe-shaped amphitheater and debrite outcrops. Note the numerous lineament paths that outline this amphitheater. In central Anaga, a NE–SW swarm of lineaments is pronounced. This trend becomes more diffuse towards the northeastern coast of Anaga. To the southeast, lineament traces are oriented NNW-SSE (160°) and thus perpendicularly to the topographic ridge WSW-ENE. This trend is not favored by topography and is not found within the northern sector, i.e. it appears to be confined to the south of the amphitheater

around 5.8 Ma and, again, basanitic activity at ca. 4.2 Ma ago (Thirlwall et al., 2000). The Anaga volcanic series are characterized by two unconformities (Carracedo 1975) about 7 and 4 Ma old (Ancochea et al., 1990). This subdivision is oversimplified for the composite Anaga edifice, but it allows to distinguish three major subseries. We use herein the terms Lower, Middle and Upper Series (from old to young).

The northern area is formed by the Lower Series and outcrops in a structural window, concave to the north, with a radius of 10–14 km (Araña et al. 1979; Ancochea et al. 1990; Rodriguez-Losada et al. 2000). The Middle Series are made of strongly eroded basaltic and phonolitic rocks that blanket the Lower Series and are inclined seaward. The Upper Series are made up of capping sub-horizontal basalt flows, differ morphologically and are more resistant than the older units. All three series are traversed by numerous dikes that form well-defined dike swarms, striking NNW–SSE, WSW–ENE, and W–E. The high density of the Anaga dikes resembles that of dike complexes on Oahu, Hawaii (Walker 1992). The stepwise evolution of such rift zones is unclear, particularly the degree to which its development was influenced by flank instability. The occurrence of a giant northward-directed landslide from Anaga was suggested previously based on a distinct embayment at the northern flank and an associated submarine debrite (Hernández-Pacheco and Rodríguez-Losada 1996; Masson et al. 2002; Mitchell et al. 2003). Here, we attempt to unravel the relationship between initiation and development of the unstable northern flank and the triaxial rift system on Anaga and employed several different methodologies.

Methods

Our methods comprise (1) lineament analysis from aerial images, (2) local validation of dike distribution in the field, (3) determination of crosscutting relationships and sampling, (4) $^{40}Ar/^{39}Ar$ age dating, and (5) elastic dislocation modeling.

The combination of these methods allows identification of sector instability and related episodes of rifting.

Lineament analysis

We used remote data to map the structural characteristics of Anaga. Our analysis is based on high resolution 1:8000 colored stereo-paired images (GRAFCAN, Spain). We traced all major obvious lineaments (Fig. 2B). A lineament can be a continuous linear or curvilinear feature or an alignment of shorter features observed on an image. In combination with topographic maps and digital elevation models, we studied lineament orientation and lineament distribution. Our fieldwork confirms that most of the lineaments are dikes.

Fieldwork and relative age analysis

Large parts of Anaga are accessible by hiking trails and outcrops are good, except at altitudes above 500 m a.s.l. where the ground is densely vegetated. Dike trace orientations were measured in the field and data were corrected according to the actual International Geomagnetic Reference Field (IGRF). We took account of the relative ages of intrusive phases such as the stratigraphic position of a unit, the groups of dikes that cut this particular unit, and the crosscutting relationships between these groups of dikes. We used samples from key localities for age determination.

Isotopic age analysis

Plagioclase crystals, whole rock fragments or glass fragments (80–480 μg) were separated and cleaned for $^{40}Ar/^{39}Ar$ laser probe dating. Irradiations were carried out at the GKSS reactor (Gesellschaft für Kerntechnik und Strahlenschutz, Geesthacht, Germany). For the laser probe $^{40}Ar/^{39}Ar$ analyses, we fused individual rock, mineral or glass fragments in single heating steps by a SpectraPhysics 25-W argon ion laser (514 and 488 nm). The argon isotope ratios were determined in a MAP 216 Series mass spectrometer. Argon isotope ratios were corrected for mass discrimination, neutron flux gradients, and interfering neutron reactions. Ages are quoted with 2 sigma errors, including the uncertainties of the monitor's $^{40}Ar/^{39}ArK$ relation and procedural blank measurements.

Numerical modeling

We carried out elastic dislocation models based on the data set of dike intrusions and the rift zone geometry in Anaga. We simulated the displacement and dilatations caused by rift zones of dimensions similar to the ones found in Anaga, and calculate displacement vectors and a dislocation map. Further details are given below.

The combination of these methods allows identification of sector instability and related episodes of rifting.

Structural development of Anaga

Our aerial image analyses reveal a high density of subparallel lineaments in Anaga (Fig. 2B). At the northern flanks of Anaga, the lineaments seem less parallel oriented than in the southern half of Anaga. We distinguish three zones (1) complexly crosscutting orientations in the north of the edifice, (2) parallel SW-NE trending lineaments in the center and southwest of Anaga, and (3) a NNW–SSE oriented trend in the southeast. Below we describe these structural trends, together with field observations, in a geological context starting with the oldest units.

Early linear rifting

The northern flank of Anaga is intruded by an exceptionally dense, largely basaltic dike swarm plus several alkali gabbro and syenite plugs. The oldest and deepest Anaga rocks are exposed within this eroded sector (encircled by dashed line in Fig. 2; Araña et al. 1979). Abundant dikes in the eroded northern sector allow to estimate the earliest stage of rifting on the edifice. The subparallel direction of dike traces implies a SW–NE-oriented rift zone. The northern flank is dominated by subparallel dikes (Fig. 3), striking broadly 060° ±20°. The amount of dike intrusions along several profiles differs significantly from photolineament analysis (Fig. 2B). A significant part of the rock mass is formed by dikes along the northern and northwestern coast, making it hard to find any host rock. The maximum amount of dikes just south of Taganana constitutes more than 80% of the entire rock mass (measured along 100-m-profiles). By considering the rift zone width, one can thus infer the amount of extension normal to the rift. Although only part of the entire rift zone is accessible, a horizontal extension of at least 0.5 km is derived. This value has to be treated with caution, however, because the Taganana Rift Zone Complex is tectonically deformed, sheared and altered (see below).

Flank deformation and flank instability in the north

Individual traces of the beds, layers and dikes at the northern edifice sector are difficult to correlate due to shearing and secondary mineralization. Faults and fragmentation patterns show small scale rotational offsets, but also define km-sized megablocks, resulting in a range of dike inclinations. The old dikes at the Taganana embayment dip towards the southeast at about 50°–70°, a feature

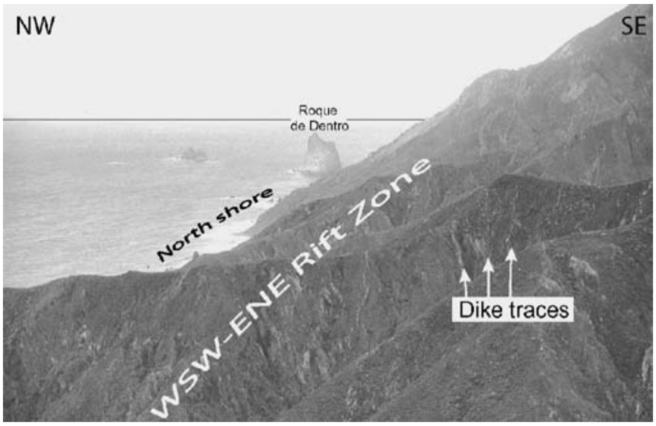

Fig. 3 Taganana embayment looking eastward (photograph taken north of the El Bailadero tunnel, see Fig. 2a). Most rocks here are dikes, inclined to the south (to the *right of the picture*). Later dikes (*arrows*) have wavy contacts and intruded subvertically

that is untypical for generally subvertical dike swarms on Tenerife (Carracedo 1994). Only the few unbroken dikes that were emplaced into this rift zone later, are subvertical. These later dikes are characteristically segmented and have wavy contacts, typical for dikes that intrude into a mechanically weak material.

Deformation was mostly brittle, causing secondary fractures in the dikes and shearing near their (chilled) margins. Figure 4 shows typical outcrops of highly fractured and altered dikes that dip to the southeast (dip to the left in the photograph). The fracture sets as shown in Fig. 4B show that extension was accomplished by a conjugate fracture system. Brittle deformation occurred along abundant small-scale fractures, often with fracture spacing of a few millimeters only. Fracture length is on a centimeter scale, giving the rocks a breccia appearance, i.e. defining small jigsaw pieces. The intensely sheared character of the Taganana sector suggests that this volcano sector was creeping towards the sea fracturing the rocks involved. The majority of the dikes are brecciated implying that an episode of profound extensional tectonics followed the main rifting period.

Age of flank creep

Dating of individual volcano-tectonic episodes, especially flank deformation processes, is generally difficult. Our strategy on how to obtain the age of the flank instability was to date two critical samples: a representative sheared dike intrusion within the northern sector, and a largely undeformed dike intrusion that crosscuts marginal debrites of this sector. Sample locations are given in Fig. 5. The oldest ages were found for Plg-crystals of a dike in a deeply eroded valley in the southeastern Anaga (5.1±0.2 Ma), and of a highly fractured dike west of Taganana (5.0±0.7 Ma). A date, resulting from a groundmass separate of one of the sheared dikes in the eastern Taganana embayment yielded an age of 4.7±0.1 Ma, and for one sheared sample E of that we obtained 4.3±0.1 Ma. Plg-crystals of a nearby young and undeformed phonolitic dike gave a lower age limit of 4.1±0.3 Ma. The samples therefore span the likely time period of flank creep and fracturing between ca. 4.7 to

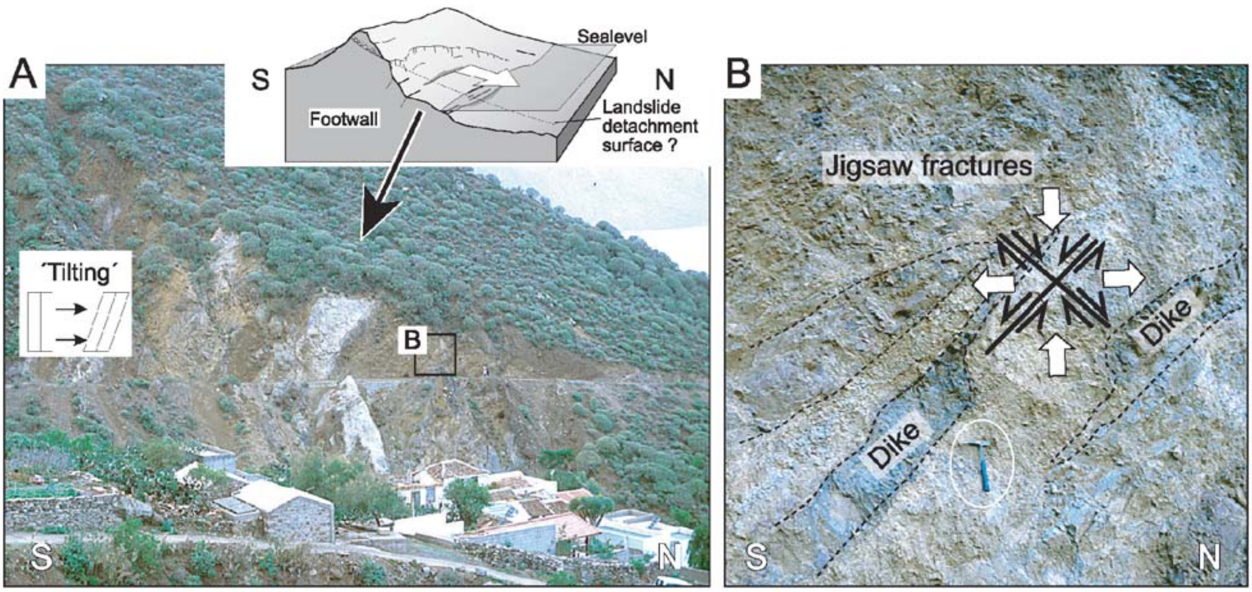

Fig. 4 Photographs of sheared northern sector of Anaga. Landslide detachment surface is eroded and thus not found near sea level (see *inset*). (**A**) The footwall is intensely sheared, movement "top to the north". Dikes of the oldest WSW-ENE rift zone show intrusive volumes reaching up to ~90% of the rock mass. (**B**) Close-up photo illustrates mixed-mode shearing and jigsaw fractures. Dike intrusions here occurred prior to fracturing. The material is extremely altered and unstable. Strong shearing and fragmentation has lead to structures resembling those of proximal debris avalanche deposits. Dike traces are unclear and have diffuse margins, a feature that earned them the name "ghost dikes" by local geologists (Spanish "diques fantasma")

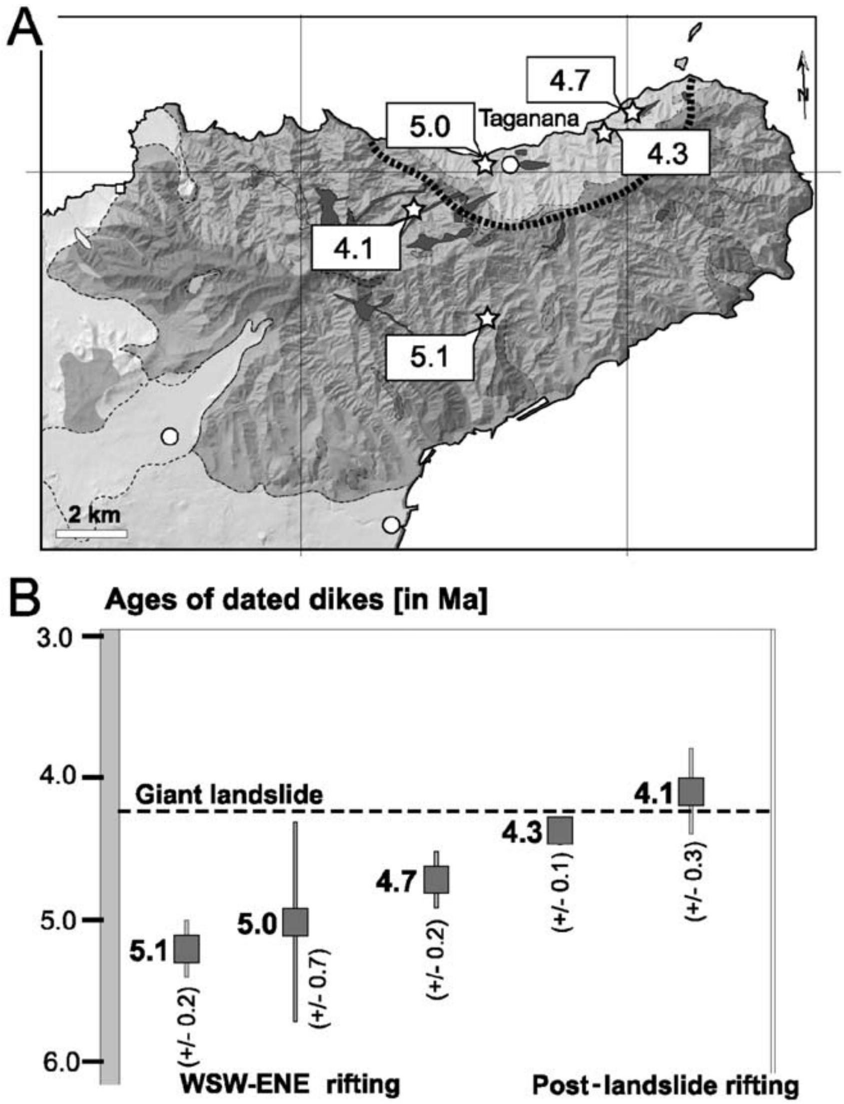

Fig. 5 Geologic map and sample localities for $^{40}Ar/^{39}Ar$ samples (*stars*). Ages are given in Ma. The 4.1 Ma age is derived for a phonolitic dike that crosscuts the landslide unconformity. Within the fractured northern sector, fractured dikes pre-date flank failure. Dike ages hence define the timing during which the sector collapse occurred at around 4.2 Ma. See text for details

4.1 Ma, probably between 4.3 and 4.1 Ma. Repeated landslides possibly occurred on a smaller scale towards the north, which, in combination with erosion of the weak and fractured material, carved the present north embayment into the shield volcano.

Faulting and intrusion around the unstable sector

The northern sector is structurally and lithologically separated from the younger series by a unit of brecciated polylithological material inclined towards the north. This unit locally contains debris avalanche deposits and commonly redeposited breccias. The latter beds characterize cyclic slumps into a scarp and are generally inclined 20–35° to the north. Outcrops are common particularly at higher levels in cliffs as e.g. at Limante and around Roque el Fraile, outlining a horseshoe-shaped sector that opens to the north. This belt is covered and surrounded by younger rocks of the Middle Series. Faults and fractures within the Middle Series indicate extension at the crest of the morphological ridge, but also around the intrusive complex of Taganana. The density of faults and fractures, however, increases significantly towards the unstable northern sector. Many faults also cut the intrusions of the old WSW-ENE rift zone; fractured rocks are altered and show secondary mineralization. The faulting event thus postdates the old Taganana rift zone activity. Fault trends commonly outline a curved sector in a concentric and radial pattern, defining a sector that is somewhat larger (1–3 km) in the west than the landslide scarp (Figs. 2A, 5). The horseshoe-shaped sector encircled by faults, fractures and breccias thus shows characteristics typical for collapsed sectors of ocean island volcanoes (see Walter and Schmincke 2002).

Younger dike intrusions and differentiated domes were emplaced during a stage that followed the period of tectonic deformation and erosion in the north (see also Ancochea et al., 1990). The younger dikes are oriented slightly differently when compared to the old Taganana rift zone. The intrusions contain generally more differentiated dikes and domes of trachytic and phonolitic composition (see also Carracedo, 1975). The orientation we measured for this younger dike swarm is curved from WNW-ESE (105°) to E-W to SW-NE (050°) around the northern embayment, consistent with our aerial photolineament analysis described earlier. In the western part of the horseshoe-shaped scarp, an up to 15-m-thick phonolitic intrusion that crosscuts the landslide unconformity and the northward inclined debrites was dated by us at 4.1±0.3 Ma from K-feldspar single crystals. This post-dates the tectonic episode of the north flank of Anaga (Fig. 5).

Atypical rifting in the south?

Most of southern Anaga is made of the Upper Series (Fúster et al., 1968; Carracedo, 1975). Intrusions herein represent therefore a more recent activity. Our aerial photolineament map shows a restricted zone on the southern flank of Anaga where the direction of dikes differs fundamentally (atypical) from the ones in the north by being orientated NNW-SSE (160°). Similar dike orientations were not found either on the northern edifice flank, nor in the eastern or western areas of Anaga. This NNW–SSE direction is a locally developed rift arm, oriented away from the unstable northern sector.

Vesicle elongations in these dikes indicate a subhorizontal flow direction. This may imply horizontal magma transport along the rift zone. The atypical NNW-SSE rift zone has nucleated at the curved rift zone in the north, to form a triaxial rift zone with a likely focal point at the headwall of the destabilized horseshoe-shaped Taganana sector in the north (Fig. 6). This focal point probably marks the position of the volcanic center of the younger Anaga edifice.

Extensional faults are the dominant faults in southern Anaga, where about 80% of the faults are normal faults, most striking NNW–SSE. The direction of extension in southern Anaga is hence WSW–ENE. Based on two road profiles, Marinoni and Gudmundsson (2000) calculated a horizontal extension of ca. 160 m for southern Anaga in direction 60°, and a horizontal extension in direction 145° of ca. 190 m. The dikes strike approximately perpendicular to these extensional directions 160° and 055°, respectively (Fig. 6). For the NNW–SSE rift, horizontal extension by dike intrusions was about one order of magnitude larger than that due to faulting.

Development of a triaxial rift zone

Rift zones that curve around unstable volcano sectors have been reported from several other locations (e.g. Lipman 1980; McGuire and Pullen 1989; Walter and Schmincke 2002; Walter and Troll 2003). Rift curvature takes place due to the stress field reorientation near an unstable volcano flank. Younger dikes follow normal to the new least compressive stress direction (Anderson 1951) and thus intrude preferentially around unstable

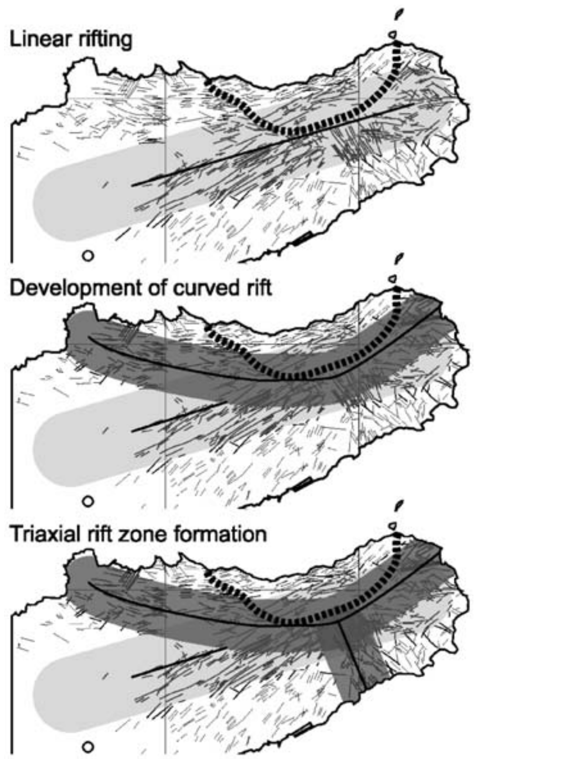

Fig. 6 Reconstructed rift development on the basis of crosscutting relationships of dikes. The straight SW–NE dike trend crops out mainly within the unstable sector and in the younger southwestern part of Anaga. A curved rift developed later where many dikes transect the Middle Series. The rift with a NNW–SSE (160°) direction formed during the late evolutionary stage of the curved rift

sectors. The rift zone that trends towards the south of Anaga, however, seems to be atypical in the context of gravity-driven volcano deformation in the north of Anaga edifice. Below, we study how the swarm of southward intruding dikes is coupled to the development in the north of Anaga.

Elastic dislocation models

We developed elastic dislocation models to explain the formation of the third rift arm in Anaga, which we suppose is coupled to sector destabilization in the north. We numerically simulate a dilating rift zone with curved tipline that has a similar outline and dimension as the curved rifting episode of the destabilized Anaga sector (Figs. 6, 7). We assume that rift zone-widening imposes a tensile component of displacement. The underlying theory of dislocation and opening of a crack-like body was described in detail by Okada (1985, 1992). Following the equations of Okada (1992), we define uniform dislocation planes that simulate opening of a rift zone in a homogeneous, isotropic elastic half-space.

A number of planar dislocation bodies describe the segmented rift zone. We assume a height of this rift zone from the free surface to 7 km depth, the lower limit thus

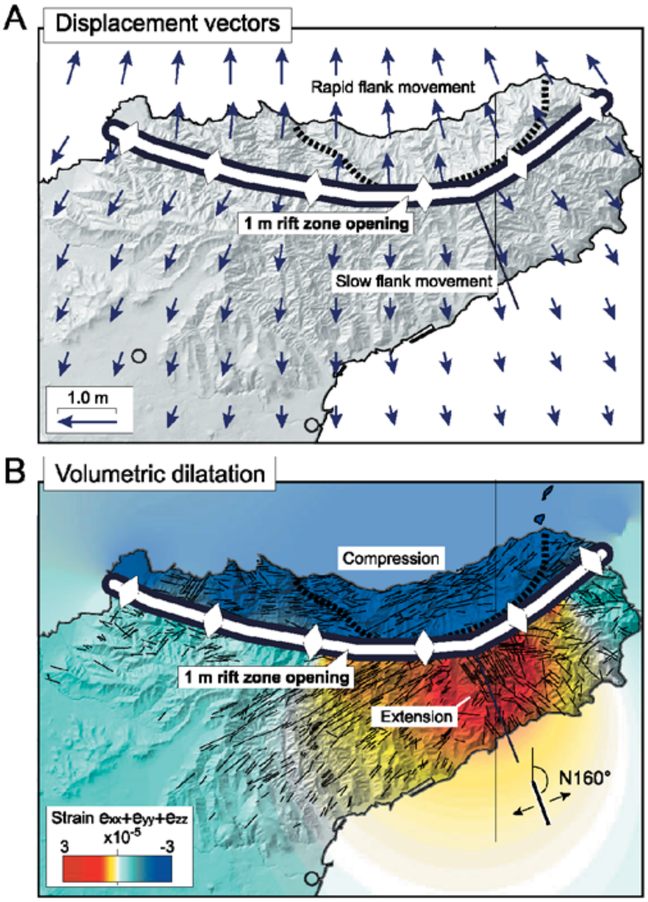

Fig. 7 Dislocation models calculated at a horizontal plane. A segmented rift zone was defined with an outline similar to the middle rift episode on Anaga. A curved tensile fault simulates the curved rift zone, uniform dislocation is 1 m. (**A**) Surface displacement vectors show that movement focused on the northern flank that is encircled by the rift zone. Dike intrusion along such a curved rift zone will thus promote flank creep. (**B**) Volumetric dilatation caused by 1-m horizontal widening of a curved rift zone. Dislocation models were calculated for a horizontal plane at 2 km depth, i.e. approximately at sea level. Positive strain (*red color*) matches the region where the third rift arm oriented NNW–SSE (160°) developed on Anaga. Negative volumetric dilatation is found elsewhere, strongest in the northern sector. Virtually complete absence of the NNW–SSE dike trend in the northern sector is due to the compressive field to the north of the curved rift

translating approximately to the base of the edifice. The sole applied load was rift zone-opening by 1 m. We assume a Young's Modulus E=50 GPa, coefficient of friction μ=0.6, and a Poisson's Ratio v=0.25. We calculate displacement vectors and volumetric distortion at 2 km depth, which translates approximately to sea level in Anaga.

The displacement vectors caused by intrusive widening normal to the curved rift are shown in Fig. 7A. The length of displacement vectors is scaled to the displacement magnitudes in the horizontal plane. Close to the rift, displacement is 0.5 m in each direction (half the total widening) normal to the rift. With slight distance, however, horizontal displacement in the northern sector is up to more than twice as much as south of the rift zone. In the northern sector, the northward displacement is accordingly a sum of the dilatation at the enclosing curved rift. This suggests that once a curved rift zone formed, forceful intrusions amplify deformation and increase instability and lateral spreading of the sector enclosed by the concave rift.

Fig. 7B shows the elastic strain (volumetric dilatation) due to rift opening. The dilatation is defined by the dimensionless number $e_{xx}+e_{yy}+e_{zz}$. We assume that the intrusion of dikes is facilitated in areas subjected to positive dilatation, whereas dike intrusions are hindered in areas where the volumetric dilatation is negative. The sole load we apply is again opening of the rift zone by 1 m. The resultant area of calculated positive dilatation is to the southeast of the curved rift (Fig. 7B; red area). This area matches the position of the 160° rift zone as described earlier. The compressive field north of the rift, in turn, explains the virtual absence of dikes in this direction within the unstable sector.

Discussion

Flank creep on ocean island volcanoes is facilitated or even triggered by dike intrusion into rift zones, and giant landslides are often located between two axes of a three-armed (triaxial) rift system (Siebert 1984). We studied the Anaga shield volcano on Tenerife island and found that the northern embayment of Anaga represents the deep root of a creeping flank. Hernández-Pacheco and Rodríguez-Losada (1996) and Rodríguez-Losada et al. (2000) suggested that the tensional stress on Anaga was produced by major normal faults located offshore to the north. Also our data suggest that a giant landslide deeply carved out the northern flank, where the remainder, i.e. the intensely disturbed rock mass, belongs actually to the footwall of the proposed major normal faults. The older dikes in the northern sector of Anaga are brecciated throughout and tilted (dip towards the south). Conjugate slip-lines (optimum fault traces), which may be listric, could cause such rotation and thus variability of the dike dip (Fig. 8). The structure of the northern flank of Anaga thus resembles areas subjected to rock flow. Rock flows can occur in bedrock where movement roughly resembles the velocity distribution of fluids and common flows (Varnes, 1978). In northern Anaga, the deformation is spread throughout the displaced material, which is typical for rock flow, suggesting that volcano flank deformation and flank creeping can potentially occur as a flow. In the marginal region of the destabilized flank, discrete faults caused block rotation and influenced also the dike strike. In comparison, the creeping flanks of Piton de la Fournaise (Reunion) or at Casita (Nicaragua) may be recent analogues, where local zones of highly altered volcanic rocks encourage flank instability (van Wyk de Vries et al. 2000; Merle and Lénat 2003). The common assumption that such flank deformation is accomplished along few discrete fault planes may be oversimplified. Our study

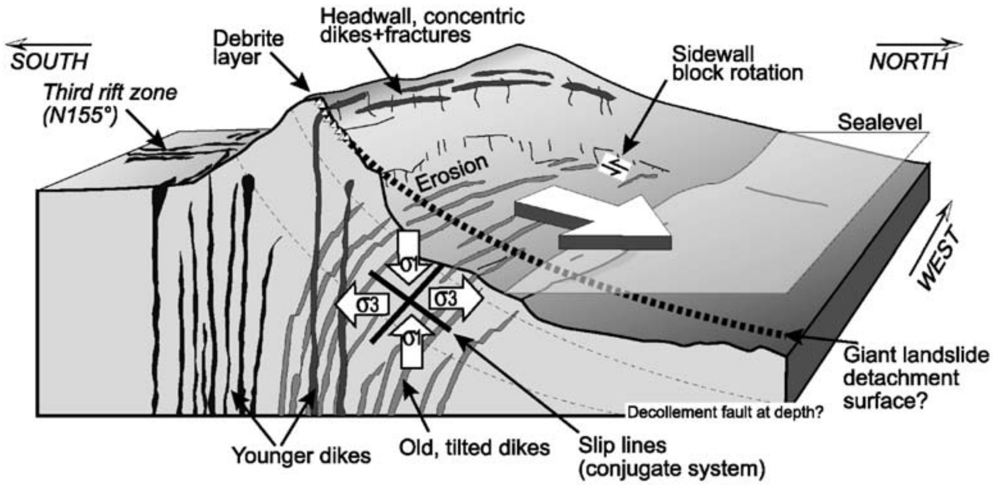

Fig. 8 Block diagram showing main types of faulting and dike orientations. The landslide detachment fault is eroded, and lies probably offshore to the north. A conjugate system indicates two common fracture trends associated with gravitational spreading in Anaga. Fracturing of the unstable sector caused the dikes to tilt towards the south. The strike of dikes remained largely constant. Closer to the sidewall, a greater variability of the strike lines of dikes is observed, possibly caused by block rotation. Younger dikes intruded subvertically and curve around this sector. Even younger dikes intruded to the south of the unstable sector, forming a later third rift arm in direction NNW–SSE (160° trend)

suggests that (brittle) deformation and flank creep could affect the entire volcano structure and that on Anaga this profound flank destabilization was linked to the development of a triaxial rift zone.

Triaxial rift zones may form during various stages of a volcano's life span. On Tenerife Island, at least four triaxial rift zones formed, defining individual volcanic centers. Similarly, such triaxial centers are known from many other ocean islands such as La Palma and El Hierro (Carracedo et al., 2001), Hawaii Big Island and Maui (Fiske and Jackson, 1972), or Reunion (Duffield et al., 1982). The mechanism of initiation of triaxial rift zones may vary. One hypothesis states that repeated updoming of the crust causes major zones of weakness that are arranged according to the least effort principle in a regular three-armed system (Carracedo, 1994). In another hypothesis, the rift development is predominantly controlled by shallow processes within the volcanic construct itself. Based on gelatin analogue experiments, Fiske and Jackson (1972) demonstrated that gravity-induced deformation controls the rift zone development on the Hawaiian Islands. In the concept of volcano spreading (see Borgia et al., 2000 for a review), the gravity field of a volcano directs the paths of individual dike intrusions and entire rift zones (Nakamura 1980; Dieterich 1988). On the eastern flank of Mount Etna, for instance, dikes intrude along the topographic crest around the deep and several km-wide 'Valle del Bove' (McGuire and Pullen 1989; Borgia et al. 2000). There too, strengths and inclination of the subvolcanic strata may significantly influence the development of rift zones and unstable flanks. Tilting of the uplifted interior of the edifice of La Palma Island may cause flank instability and flank creep and thus initiate rifting (Walter and Troll, 2003). This caused the island's dike trends and its volcano architecture to change from a radial to an axial N–S arrangement. Alternatively, rift zones may form by buttressing effects. Fiske and Jackson (1972) showed that Hawaiian rift zones are influenced by older and overlapping edifices that act as buttresses. Walter (2003) illustrated that spreading and partly overlapping volcanoes may form a rift zone in between, thus forcing two volcanoes to grow together. The studies suggest that the configuration of rift zones is essentially driven by the edifice gravity.

The present study of Anaga is consistent with the concepts of gravity-tectonic deformation, detailing that (1) volcano destabilization affected a large sector of the edifice, while only part of it collapsed in a giant landslide, (2) dikes encircle the weakened horseshoe-shaped embayment and thus (3) encouraged formation of a third rift zone on the opposite side. The third rift arm in Anaga, is however not obvious in morphology. According to Johnson (1995) and Fialko and Rubin (1999), the along-strike slope of a rift zone needs to be shallow enough to allow for lateral dike propagation. We speculate that a topographic WSW-ENE-oriented Anaga ridge was well expressed before the rift zone reconfigured into a triaxial complex. Destabilization of the northern sector occured in combination with curved rift formation, which promoted a third rift to the SSW (160°). There, however, slope inclination was probably too steep to allow long lateral dike propagation. Slope conditions in the direction of the initial Anaga ridge, in contrast, favored lateral intrusion and volcanism in distal areas ENE and WSW from the triaxial nucleus, which was still active during formation of the younger Anaga Series. The morphological conditions do thus not support the development of a perfect 120° triaxial system. In addition, a considerable buttressing effect could have prevented the triaxial Anaga system to further develop. The growth of the Cañadas volcano started subaerially after ~3 Ma, building on a substantially older (probably >5 Ma) submarine phase to the southwest of Anaga (cf. Ancochea et al., 1999). The Cañadas shield volcano overlapped the Anaga edifice. This resulted in a buttressing effect that encouraged the most pronounced rift zone on Tenerife Island to form in between the Cañadas and Anaga volcanoes (Walter, 2003).

The third rift zone of three-armed rift systems, which may form as a consequence of dilation at a curved (nonlinear) intrusive axis, is often less pronounced. If our idea of forceful intrusions and dilation normal to rift zones is correct, rules of geometry require extension and dike intrusions on the opposite side of the sector that is enclosed by the curved rift zones. A similar scenario applies to Hawaii, where Mauna Loa erupted historically mostly along the NE rift and the rift zone to the south, and—less frequently—at the radial vents (Lockwood, 1995). These radial vents are all located in the northwestern sector of Mauna Loa and may be regarded as a poorly developed third rift arm. As shown by our dislocation models for Anaga, a forceful intrusion into a curved rift causes passive widening and facilitates intrusions on the convex side. Seismic activity at Mauna Loa's northwest flank corroborates the presence of a third less active rift zone opposite to the enclosed unstable sector (Baher et al., 2003).

Concluding remarks

Volcano deformation starts long before failure and is characterized by thrusting of the lower volcano flank and by normal faulting higher up (van Wyk de Vries and Francis, 1997). Our combined work of remote and field analysis and numerical modeling illustrates the nondurability of rift zones, as exemplified for Anaga (Tenerife). The early structure of Anaga was dominated by a single rift that significantly changed its rift geometry as the northern sector became unstable. $^{40}Ar/^{39}Ar$ chronology allows dating age and direction of flank instability between 4.7 and 4.1 Ma. The overall subaerial activity in Anaga lasted at least 3 million yr (Ancochea et al., 1990), hence the time frame enclosed by rock ages illustrates a relatively short period of flank creep. During this period, intense shearing took place and weakened the normal fault footwall, implying that a much larger region was structurally unstable. Only a part collapsed into the sea, however.

Intrusive widening is forceful, but the direction of these intrusions and thus the widening is controlled by the external state of stress which in this case is gravity-controlled. Based on remote and field data and numerical modeling, we suggest that extension along a creeping flank may lead to dike reorientation or even rift zone formation. Other curved rift zones and triaxial configurations may likewise result from extension around an unstable volcano flank. Migration of a linear rift towards a curved rift geometrically accelerates flank movement of the enclosed sector, hampers intrusive activity in the compressed sector (i.e. in the enclosed northern sector), but promotes passive rifting on the opposite side. Figure 9 sketches a positive feedback mechanism that starts once a volcano flank begins to creep outward, encouraging (1) rift migration and rift curvature, and thus (2) acceleration of flank movement; while the nonlinear rift promotes the development of a third rift axis.

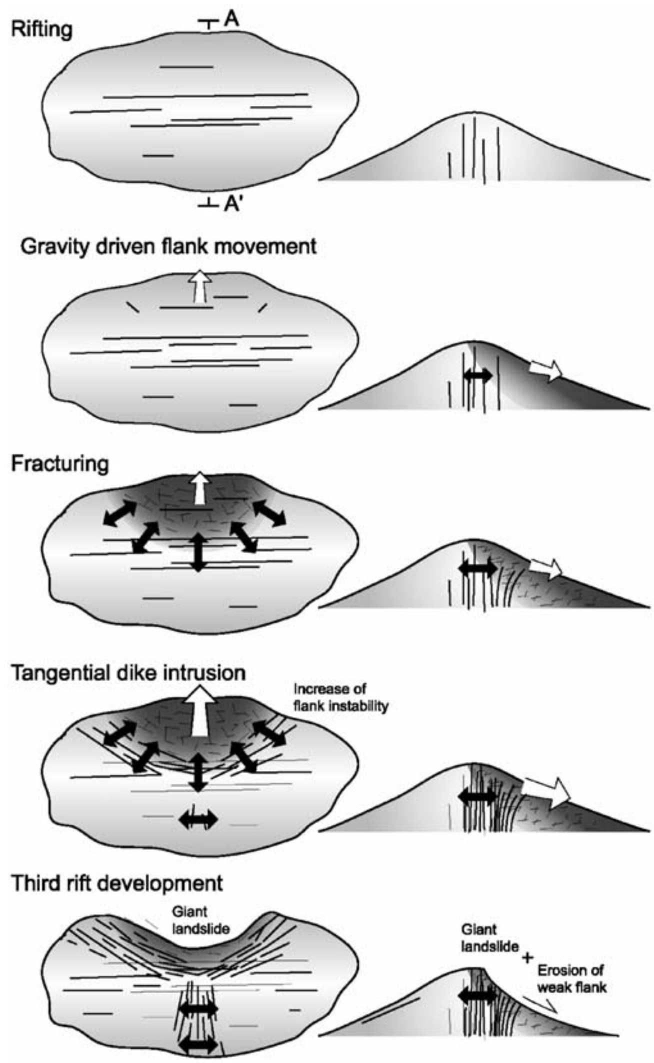

Fig. 9 Evolutionary model for dynamic feedback between flank destabilization and rift organization. The evolution, as reconstructed for Anaga, is subdivided in five stages. These are (1) intrusions along a E–W rift zone, (2) destabilization of the north flank, extension at its limits, (3) migration of the rift axis into two tangential arms, (4) increase of flank destabilization and displacement by dike intrusions, (5) collapse of the northern flank and development of a third rift arm to the south

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