Volcanic evolution of Southern Tenerife (Canary Islands) during the Pleistocene and Holocene

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Abstract

The Canary Islands are a group of volcanic ocean islands in the Central Atlantic near the continental margin of northwest Africa. Tenerife, with a volcanic history of more than 12 Ma of subaerial eruptions, is the largest island of the Canaries and is situated in the centre of the Archipelago. The Quaternary Bandas del Sur Formation in the South of Tenerife comprises a complex sequence of pyroclastic rocks and lavas and is part of the southern rift zone. In contrast to the northwest and northeast rift zones on Tenerife, the southern rift zone comprises a number of characteristics with respect to the morphological features, eruption cyclicity, and the geochemistry of the volcanic deposits. Various flank eruptions of the Las Cañadas volcano associated with basaltic lavas and the formation of cinder cones within the Bandas del Sur are important volcanic units for understanding the explosive volcanic cycles during the Pleistocene on Tenerife. Paleomagnetic studies, geochemical analysis of major and trace elements, and two radioisotopic dating (K-Ar) have been carried out on prominent cinder cones, to determine their stratigraphic position. By combining the results with previous K-Ar data in the Literature, the cones and lavas can be subdivided into three stratigraphic units. Cinder cones that belong to the first unit show reverse magnetization and Y/Nb ratios between 0.37-0.41; cinder cones of the second unit show normal magnetization and Y/Nb ratios of <0.35. The third unit comprises cinder cones with normal magnetization and Y/Nb ratios of about 0.47. The first two units were constructed between ~0.948-0.779 Ma and 0.323-0.300 Ma. These units define volcanic cycles that culminated in violent Plinian eruptions. The third and youngest unit possibly marks the beginning of a further volcanic cycle that started ~0.095 Ma ago.

In order to reconstruct the uplift history of Tenerife, numerous uplifted fossil beaches and tuff cones were investigated. In the North and Northeast of Tenerife, the positions of fossil beaches indicate stable conditions since 130 ka. The uplift rates in southern Tenerife (within the Bandas del Sur) amount to a minimum of 15 m since 778 ka at Montaña Pelada and to a maximum of up to 45 m since 10 ka in the area of El Médano, suggesting an asymmetrical uplift of the island complex. The uplift in the South could be caused by seismic activity or mass loss due to flank collapse events. However, uplift due to ascending magma is more plausible. The fossil beach deposits of the El Médano area exhibit tubular-shaped concretions and concretionary dykes. These sediment structures have been interpreted as the result of a) the interaction between hot ignimbrites that overflowed wet beaches, b) fast accumulation of beach sands on hot and degassing ignimbrites, c) paleoliquefaction caused by an earthquake (seismites). Based on the interpretation as seismites, an intense paleoearthquake was proposed to be responsible for the generation of the paleoliquefaction structures. However, the sedimentary structures in question show the general criteria diagnostic for rhizocretions and root tubules with respect to their orientation, size, branching system, and style of cementation.

Faults of a well-defined strike direction that precisely coincides with the southern rift fault system occur in the El Médano site. This fault system was generated contemporaneously with a chain of cinder cones ~948 ka ago. Open fractures in ignimbrites (~668 ka) and the fossil beach deposits (~10 ka) of the El Médano area suggest that the rift-associated fault system has been seismically active in the aftermath and probably is still active. A further fault system striking perpendicular to the rift-associated faults probably originates from a Holocene paleoearthquake of moderate intensity. Earthquake-induced ground effects in the fossil beach deposits of the study area are consistent with seismically induced ground effects of several recent and well-documented earthquakes and gravitational sliding triggered by an intense earthquake in Nicoya/Costa Rica in 1990. Both, the rift-associated and the earthquake-induced fault system, initially produced open cracks in the fossil beach deposits that were occupied by plants and subsequently stabilized by cementation.

These results accentuate that the densely settled southern part of Tenerife is latently endangered by volcanic and seismic activity, though, currently, there are no indications of increasing volcanic activity in this region. Uplift due to recent magma loading is not observable and the intensity of a paleoearthquake in the El Médano area was probably considerably lower than mentioned in the literature. In addition, the rift-associated faults that are very common in the ignimbrite (~668 ka) of the El Médano site are rare in the Holocene fossil beach deposits, indicating that rift-associated extensional movements decreased in the area of El Médano since the formation of the chain of cinder cones ~948 ka ago.

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Kurzfassung

Die Kanarischen Inseln sind eine Gruppe von vulkanischen Ozeaninseln im Zentralatlantik nahe der Küste von Nordwest-Afrika. Teneriffa ist die größte Insel des Archipels und liegt im Zentrum der Inselgruppe. Die Quartäre Bandas del Sur Formation im Süden Teneriffas ist Teil der südlichen Riftzone und umfasst eine Sequenz von pyroklastischen Ablagerungen und Laven. Die Ablagerungen zahlreicher Flankeneruptionen des Las Cañadas Vulkans (primär basaltische Laven und Schlackenkegel) stellen wichtige stratigraphische Marker innerhalb der Bandas del Sur Formation dar, die zum Verständnis der explosiven vulkanischen Zyklen während des Pleistozäns auf Teneriffa beitragen. Um die stratigraphische Position der Schlackenkegel innerhalb der Bandas del Sur bestimmen zu können, wurden paläomagnetische Messungen, geochemische Analysen der Hauptund Spurenelemente, sowie zwei radiometrische Altersdatierungen (K-Ar) durchgeführt.

Durch die Kombination der Ergebnisse konnten die Schlackenkegel in drei stratigraphische Einheiten untergliedert werden. Die erste Einheit umfasst Schlackenkegeln mit inverser Magnetisierung und Y/Nb-Verhältnissen zwischen 0,37 und 0,41. Schlackenkegel der zweiten Einheit zeigen normale Magnetisierung und Y/Nb-Verhältnisse von <0,35. Die dritte Einheit umfasst Schlackenkegel, die normal magnetisiert sind und Y/Nb-Verhältnisse von etwa 0,47 aufweisen. Die ersten beiden Einheiten wurden im Zeitraum von ~0,948-0,779 Ma und 0,323-0,300 Ma gebildet. Diese Einheiten stellen jeweils den Beginn von vulkanischen Großzyklen dar, die mit strombolianischen Flankeneruptionen begannen und in zerstörerischen plinianischen Eruptionen endeten. Die Ablagerungen der dritten und jüngsten Einheit markiert möglicherweise den Anfang eines weiteren vulkanischen Zyklus, der bereits vor ~0,095 Ma startete.

Um die Hebungsgeschichte Teneriffas zu rekonstruieren, wurden zahlreiche fossile Strandablagerungen und Tuffkegel untersucht. Im Norden und Nordosten von Teneriffa zeigen die Positionen der fossilen Strandablagerungen stabile Verhältnisse seit ihrer Ablagerung vor 130 ka an. Im Süden Teneriffas konnten am Montaña Pelada Hebungsraten von 15 m seit 778 ka und von bis zu 45 m seit 10 ka im Gebiet um El Médano ermittelt werden. Das bedeutet, dass der Inselkomplex eine asymmetrische Hebung erfahren hat. Die Hebung im Süden Teneriffas wurde wahrscheinlich durch aufsteigendes Magma verursacht.

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Die fossilen Strandablagerungen bei El Médano weisen eine weitere Besonderheit auf. Sie enthalten röhrenförmige Konkretionen und konkretionär verfestigte Gänge. Erklärt wurden diese Sedimentstrukturen bisher als Entwässerungsstrukturen (Interaktion zwischen Ignimbriten und nassen Strandsanden), oder als Seismite (durch Erdbeben erzeugt). Basierend auf der Interpretation als Seismite, wurde ein starkes Erdbeben als Ursache für die Bildung der Sedimentstrukturen mit einer Magnitude von M=6,8 angenommen. Die röhrenförmigen Konkretionen erfüllen jedoch alle Kriterien, die für Wurzelkonkretionen und Wurzelröhren diagnostisch sind (Orientierung im Sediment, Größe, Art der Verzweigung und Zementation). Dies spricht für die biogene Herkunft der Konkretionen.

Störungen mit gut definierter Streichrichtung, die exakt mit dem Störungsmuster der südlichen Riftzone übereinstimmen, kommen ebenfalls im Gebiet um El Médano vor. Dieses Störungssystem wurde zeitgleich mit einer Reihe von Schlackenkegeln vor ~948 ka angelegt. Offene Brüche in Ignimbriten (~668 ka) und fossilen Strandablagerungen (~10 ka) von El Médano verdeutlichen, dass das Rift-assoziierte Störungssystem bis in das Holozän aktiv gewesen ist. Ein Großteil der offenen Brüche in den Holozänen Strandablagerungen weisen jedoch eine Streichrichtung auf, die Senkrecht zum Störungsmuster des Südrifts verläuft und zudem zeigen die Brüche ein typisches Riedelbruchmuster. Ein Holozänes Erdbeben geringer bis moderater Intensität im Gebiet von El Médano kann als Ursache des seismisch induzierten Bruchmusters angenommen werden. Sowohl die seismisch induzierten, als auch die Rift-assoziierten Brüche, wurden von Pflanzen besiedelt und durch Zementation stabilisiert.

Meine Untersuchungen zeigen, dass der dicht besiedelte und von Tourismus geprägte südliche Teil Teneriffas latent durch vulkanische und seismische Aktivität gefährdet ist. Aktuelle Hinweise auf eine gesteigerte vulkanische Tätigkeit gibt es jedoch nicht. Heutige Hebungen durch aufsteigendes Magma sind nicht zu beobachten; die Intensität früherer Paleoerdbeben wurde wahrscheinlich überschätzt. Es ist daher bei erneut auftretender seismischer Aktivität eher mit moderaten Beben zu rechnen. Zusätzlich sind die Rift-assoziierten Störungen in dem ~668 ka alten Ignimbrit noch sehr häufig, in den Holozänen Strandablagerungen jedoch eher selten, was auf eine nachlassende Riftaktivität seit der Entstehung der Schlackenkegel vor ~948 ka im Gebiet um El Médano hinweist.

1. Introduction

1.1 Aim of the study

The Canary Islands are a group of volcanic islands situated in the Central Atlantic near Morocco's west coast. They show a remarkable history of more than 20 Ma of subaerial volcanic activity. Tenerife, the largest island in the centre of the archipelago, started to grow 12 Ma ago and volcanic activity continued till historic times with the last eruption of the cinder cone Montaña Chinyero in the year 1909. During the Pleistocene, Tenerife has undergone cyclic volcanic activity with three major volcanic cycles. Each cycle started with basaltic flank eruptions at the rift zones and ended with violent Plinian eruptions. Today, the volcanic residues of these cycles define the landscape of the southern rift zone on Tenerife, with aligned and nested cinder cones, lavas, and widespread ignimbrite sheets.

The intention of this study is to reconstruct the volcanic activity during the Pleistocene and Holocene, with a special focus on the southern part of Tenerife. The first approach was to define the onset, duration and recurrence time of the volcanic cycles and to specify the genesis of the southern rift zone, as well as its plumbing system, using paleomagnetic methods, geochemistry, and radiometric age determinations. The second part of the study describes the occurrence of raised Pleistocene and Holocene fossil beaches and tuff cones as indicators for uplift of the island complex due to magma loading. The third approach was to provide proof for the occurrence of paleoearthquakes that have been recorded in sedimentary deposits in southern Tenerife. Finally, a possible hazard assessment for the touristic and densely settled southern coast of Tenerife island was carried out.

1.2 Geological background

The origin of the Canary Islands has been discussed controversially. Currently, a hotspot model is favoured (e.g., Carracedo, 1999, Guillou et al., 2004a; Paris et al., 2005). With a base area of >2.000 km², Tenerife is the largest and topographically highest (Pico de Teide 3718 m) island of the Canaries. The island of Tenerife is an example for a "rejuvenated stage island" (Paris et al., 2005), associated with remarkable historic volcanic activity.

Initial subaerial volcanism started on Tenerife with the construction of the basaltic shield massifs of Roque del Conde (South Tenerife), Anaga (Northeast Tenerife),

and Teno (Northwest Tenerife; Fig. 1A), with a constructional age between 11.9 Ma and 3.9 Ma (Guillou et al., 2004a). Fuster et al. (1968) combined the volcanic rocks of these massifs to the Old Basaltic Series (Fig. 1B).

The Las Cañadas volcano in the central part of Tenerife started to grow >3 Ma ago (Fuster et al., 1994). The rock formations of the Las Cañadas volcano were divided into a Lower and an Upper Group (Fig. 1B) by Marti et al. (1994). The Lower Group was erupted between >3 Ma (Fuster et al., 1994) and 2 Ma (Marti et al., 1994) and comprises basaltic, phonolitic and trachytic lavas and subordinate pyroclastic rocks (Ancochea et al., 1990). The volcanic rocks of the Upper Group are dominated by pyroclastic deposits that have been erupted during cyclic explosive volcanic activity (Marti et al., 1994). Marti et al. (1994) subdivided the Upper Group into three explosive volcanic cycles: the Ucanca Formation (1.59-1.18 Ma), the Guajara Formation (0.85-0.65 Ma), and the Diego Hernández Formation (0.37-0.17 Ma).

The summit region of the Las Cañadas volcano is characterised by a large depression, known as the Las Cañadas caldera. For the genesis of this caldera, several models have been discussed. Gravitational collapses resulting in giant landslides, vertical collapses caused by emptying of shallow magma chambers or a combination of vertical and lateral collapses are the most plausible processes (a detailed discussion is given by Brown et al. (2003), Carracedo et al. (2007), Edgar et al. (2007)). Inside the Las Cañadas caldera, the stratovolcanoes of Pico de Teide and Pico Viejo postdate the caldera forming Upper Group cycles and have a constructional age of >150 ka (Araña et al., 1989). Volcanic activity of the stratovolcanoes continued until prehistoric and historic time. Basaltic eruptions with the formation of cinder cones and lava flows occurred in historic time on numerous sites on Tenerife, with the last eruption of Montaña Chinyero in the year 1909. The eruptions outside the Las Cañadas caldera were mostly related to the rift zones. The three-armed rift geometry (with angels of 120°, Fig. 1A) on Tenerife is typical for ocean island volcanoes with a central supply of magma. This results in a reduced stability of one sector with the consequence of two active rift zones with intense volcanic activity and one less pronounced rift zone with weak volcanic activity (Walter & Troll, 2003).



Fig. 1: A: Simplified geological map of Tenerife island, showing the main volcanic features; modified after Ablay & Martí (2000), Carracedo (1994), and Carracedo et al. (2007). Frame marks the southern study area. CR: Caldera del Rey, GZ: Montaña Guaza, MB: Montaña Blanca, PT: Pico de Teide, PV: Pico Viejo, SL: San Lorenzo Iava field; B: Volcanic stratigraphy of Tenerife; modified after Bryan et al. (1998).

Only two moderate earthquakes related to volcanic activity in the years 1706 and 1909, with an intensity of I=VII, are known for the historic period of Tenerife since seismic surveillance began (Mezcua et al., 1992). Numerous low magnitude earthquakes have been detected between the islands of Tenerife and Gran Canaria along the seafloor, with a maximum earthquake (M=5.2) on May 9, 1989 (Mezcua et al., 1992). Only one nameable earthquake (M=5.3) occurred in May 1998 on Tenerife island (Carracedo & Valentine, 2006). The sole record of a possible intense earthquake with an estimated magnitude of M=6.8 has been given by González de Vallejo et al. (2003, 2005); sedimentary structures interpreted as seismites near the township of El Médano in the South of Tenerife are mentioned as evidence for this event. However, sedimentary structures in the putative seismites of this site have been alternatively interpreted as the product of hot ignimbrites flowed over wet beaches (Carracedo & Day, 2002).

2. Volcanic evolution of the southern rift zone

2.1 Introduction

As a part of the southern rift zone the Quaternary Bandas del Sur Formation (Fig. 1) comprises more than seven widespread ignimbrite sheets erupted from the Las Cañadas edifice (Brown et al., 2003), during two explosive volcanic cycles (Cycle 2: >0.76-0.57 and Cycle 3: >0.32-0.17 Ma; Bryan et al. (1998; Fig. 1B) correlating with the volcanic cycles of the Upper Group (Fig. 1B). Each cycle is inferred to have started with flank eruptions of alkali basalt lava and the growth of cinder cones. Three widely eroded cinder cones, outcropping in the East of the Bandas del Sur (Fig. 1A) are all the remains of the basaltic eruptions at the initial phase of Cycle 2 (Bryan et al., 1998). The Cycle 3 basalts (Series III basalts of Fuster et al., 1968) are widely distributed within the Bandas del Sur. The youngest episode of flank eruptions within the Bandas del Sur resulted in the lavas and cinder cones of the San Lorenzo lava field (the Recent basalts sensu Bryan et al., 1998). These are equivalent to the Recent Series of Marti et al. (1994) and Series IV (Series Recientes IV e Historica) of Fuster et al., 2002).

2.2 Methods

Paleomagnetism

Paleomagnetic studies were carried out on 44 cinder cones within the Bandas del Sur, using a modified version of the fluxgate magnetometer "Fluxmaster" (Stefan-Mayer Instruments). Field measurements using a portable magnetometer have been successfully carried out in the Canary Islands (e.g., Carracedo 1979, Guillou et al., 2004a, b; Paris et al., 2006). The magnetisation of 85% of the samples measured during field work has been identical with samples measured in laboratory (Guillou et al., 2004b). In a study by Doell & Cox (1962), the error margin of the samples measured in the field was ~5% for volcanic rocks. Accordingly, a minimum of six measurements were carried out for each cinder cone, using orientated samples of the cores from large *in situ* volcanic bombs and/or samples of lava flows issued from the cones. The samples were collected over the entire extent of each cone, in order to obtain statistically viable results and to avoid local polarity reversals caused by lightning. For readability, the following terms are used: "R-Basalts" for cones and

lavas with reverse remanent magnetization, "N-Basalts" for cones with normal remanent magnetization (except the younger cones of the San Lorenzo lava field), and "N-Basalts-SL" for all cinder cones of the San Lorenzo lava field, owing to the fact that these cones invariably show normal remanent magnetization.

Geochemistry

Major and trace element concentrations have been determined for 16 whole-rock samples at the Institute of Mineralogy, University of Stuttgart, and at the IFM-GEOMAR, Kiel, by XRF methods. After crushing they were pulverised using an automatic tungsten carbide mill. The analyses were carried out using a Rh-tube, calibrated by international geological standards. The CO₂ and H₂O concentrations were dissected by infrared photometry after the pulverised samples were heated up to 1000°C.

K-Ar age dating

For the K-Ar age determination unweathered samples were used. The age determinations were carried out for two samples at the Laboratoire des Sciences du Climat et l'Environment (France). The materials used were whole rock samples, crushed to particle sizes varying between 0.250 and 0.125 mm, and ultrasonically washed in HC₂H₃O₂. The converted ages were calculated using the following constants: ⁴⁰K/K = 1.167 10⁻⁴ g/g; $\lambda_{\epsilon} = 0.572 \ 10^{-10}/a$; $\lambda'_{\epsilon} = 0.0088 \ 10^{-10}/a$; $\lambda_{\beta} = 4.962 \ 10^{-10}/a$. The error margin for the age is 2 σ .

2.3 New data

Paleomagnetic data

The cinder cones in the study area show both normal and reverse remanent magnetization (Fig. 2, Appendix Tables 1, 2). Thirteen cinder cones exhibit reverse polarities, 27 normal polarities, and 4 cinder cones do not show any clear paleomagnetic signal (Fig. 2), due to either the lack of adequate volcanic bombs or to demagnetization induced by lightning (Graham, 1961). The locations (UTM-Coordinates) and sample denominations are listed in Appendix Table 2. According to the geomagnetic polarity time scale (GPTS), the last geomagnetic polarity reversal event (Matuyama/Brunhes) was dated at 778.7 \pm 1.9 ka ago (Singer & Pringle 1996). Accordingly, at least 13 cinder cones in the study area must be considered to be

older than 778.7 ka (Fig. 2 and 3A-D). The other cones, displaying normal polarity, erupted during the Brunhes (>778.7 ka).



Fig. 2: Position and magnetisation of cinder cones in the study area; light face type: known K-Ar ages are given from Carracedo et al. (2007); bold type: new K-Ar ages presented in this study.



Fig. 3: A: General view over the distribution of cinder cones within the Bandas del Sur, southern Tenerife; a chain of cinder cones orientated along the trend of the southern rift zone can be recognised in the centre of the photo; B: Intensively eroded cinder cone of Montaña Ifaro with gently inclined flanks that are partly covered by ignimbrites (constructional age of ~950 ka, Cycle 2); C: Slightly eroded cinder cone of Montaña Gorda with steep flanks (constructional age of ~300 ka, Cycle 3); D: Largely unweathered cinder cone of Buzanada with steep flanks and fresh scoria (constructional age of ~95 ka, Cycle 4).

Geochemical data

The geochemical data, in particular the immobile trace elements, were used as an additional tool to distinguish between the R-Basalts, N-Basalts and N-Basalts-SL. The results of the analyses for major and trace elements are presented in Appendix Table 4. Geochemically, the samples show an alkalic trend, plotting in the basanite, tephrite and trachybasalt field of the Total Alkali-Silica diagram (Le Bas et al., 1986). One sample plots in the field for basaltic trachyandesites (Fig. 4A). The SiO₂ contents ranges from 41.7 wt% to 47.5 wt% for N-Basalts and from 42.4 wt% to 52.1 wt% for R-Basalts, indicating that during the eruption of the N- and R-Basalts the magma evolved from a primitive basanitic to a more differentiated melt (Fig. 4A).

Multi-element plots for several trace elements (Fig. 4B), normalized to primary mantle composition (Sun 1980; McDonough et al., 1992), show enrichment in elements ranging from Rb to Ti as compared to N-MORB element distribution (Saunders & Tarney 1984; Sun 1980). Potassium is depleted relative to Ba, Th, and Nb. The R- and N-Basalts and N-Basalts-SL exhibit chemical signatures typical for ocean island basalts and Canary Island basalts enriched in the more incompatible elements and a negative K anomaly (Ancochea & Huertas 2003), similar to those of HIMU-type

basalts (Weaver 1991). The N-, R-Basalts and N-Basalts-SL show comparable chemical signatures, indicating that they all derived from the same mantle source (Fig. 4B). The content of lithophile elements like Na₂O, K₂O, Rb, and Nb increases with decreasing MgO content (Fig. 5). The depletion of CaO, V, and Fe_2O_3 with decreasing MgO is indicative of fractionation processes involving the formation of olivine, titanoferous magnetite and clinopyroxene (Price & Chappell 1975). The N-Basalts are generally more enriched in Na₂O, K₂O and in the incompatible elements at similar MgO concentrations compared to the R-Basalts and N-Basalts-SL (Fig. 5). This may indicate that the N-Basalts were generated as a result of lower degrees of partial melting. The trace element plot Y/Nb versus Zr/Nb separates the R-Basalts, the N-Basalts, and the N-Basalts-SL into three well defined fields (Fig. 6). The N-Basalts exhibit Y/Nb ratios <0.35, the R-Basalts show Y/Nb ratios between 0.37 -0.41 and the N-Basalts-SL display Y/Nb ratios ~0.47 (Appendix Table 2). Additionally, this plot is useful to evaluate the degree of enrichment of the mantle source (Pearce & Norry 1979; Abratis et al., 2002); hence, the N-Basalts derived from a more enriched mantle source compared to R-Basalts and N-Basalts-SL (see Fig. 6).

K-Ar age determination

Age determination resulted in an age of 300 ± 8 ka for the sample TF- 4/Amarilla (N-Basalts) and 948 ± 15 ka for the sample TF-47/Roja (R-Basalts) (Appendix Table 2, 3). Carracedo et al. (2003, 2007) presented K-Ar ages of 95 ± 5 ka for a cinder cone near La Buzanada, 323 ± 6 ka for the cinder cone Montaña Gorda, and 311 ± 6 ka for a basaltic lava flow at the Autopista Sur km 30. The cinder cone near La Buzanada comprises N-Basalts-SL while Montaña Gorda comprises N-Basalts (Fig. 2, Table 2). Based on these dates, a minimum age for the R-Basalts is between the last geomagnetic polarity reversal event (Matuyama/Brunhes) 778.7 \pm 1.9 ka (Singer & Pringle 1996) and the K-Ar age of 948 \pm 15 ka (TF-47/Roja). The eruption of N-Basalts started at a minimum age between 323 \pm 6 ka and 300 \pm 8 ka. Volcanic activity of the San Lorenzo lava field began ~ 95 \pm 5 ka ago (Fig. 7).



Fig. 4: A: Classification of the R-Basalts, N-Basalts, N-Basalts-SL, and syenite (tephriphonolite) using the TASdiagram (Le Bas et al., 1986); B: Multi-element plot for the R-Basalts, N-Basalts, and the syenite (tephriphonolite), normalized to primordial mantle (Sun, 1980; McDonough et al., 1992). The MORB-line is taken from Saunders & Tarney (1984) and Sun (1980).



Fig. 5: Incompatible and compatible elements plotted against MgO for the samples.



Fig. 6: Trace element variations between the R-Basalts, N-Basalts and N-Basalts-SL showing different mantle source characteristics; modified after Pearce & Norry (1979). EMS: enriched mantle source, DMS: depleted mantle source.



Fig. 7: Volcanic cycles documented in the Bandas del Sur and related volcanic deposits. Data source: Fuster et al. (1994), Bryan et al. (1998), Bryan et al. (2002), Huertas et al. (2002), Brown et al. (2003), Carracedo et al. (2003, 2007), and Edgar et al. (2007); * volcanic deposits that are not absolute dated; the relative age is defined by their stratigraphic position.

2.4 Characteristics of the southern rift zone

Compared to the northwest and northeast rift zones, the evolution of the southern rift zone proceeded unequally in many respects. The northwest and northeast rift zones display steep ridges built up by fissure eruptions and are characterised by a narrow chain of cinder cones and an extensional stress field, triggering flank collapses (e.g., lcod, Orotava, Güimar; Carracedo et al., 2007). Eruptive activity along the northeast and northwest rift located medial and distal of the Las Cañadas caldera mainly produced mafic lavas; felsic eruptions exclusively occurred proximal near or within the caldera (Carracedo et al., 2007).

In the southern rift zone the volcanic features are arranged in widely scattered clusters and parallel chains following the direction of the southern rift zone (Fig. 2); it does not display a distinct ridge and instead has a fan shaped distribution of the monogenetic cones (Fig. 1 in Carracedo et al., 2007). In the distal part of the southern rift zone, basaltic cinder cones occur together with two phonolitic eruption centres (Montaña Guaza and Caldera del Rey). According to Martí et al. (2004), the phonolitic centres (see Fig. 1 and Fig. 8A) represent the only manifestations of highly evolved magma outside the Las Cañadas caldera. In the tuff cone deposits of Montaña Pelada, syenitic components ("tephriphonolite" TF-P1 in Fig. 4A, B) occur as ballistic blocks ranging from a few centimetres to ~1 m in size (Fig. 8B). The syenitic components of intermediate character (Fig. 4) are composed out of Kfeldspar, plagioclase and feldspathoides (mainly nepheline) (Fig. 8C). On Tenerife, syenitic rock fragments have been described exclusively as components in ignimbrites (e.g., El Abrigo ignimbrite; Wolff et al., 2000) that derived from the Las Cañadas edifice; the tuff cone deposits of Montaña Pelada, however, do not display any components derived from reworked ignimbrites. Wolff (1987) proposed that the Tenerife syenitic components crystallised on the roof of a phonolitic magma chamber.

2.5 Discussion

Southern rift zone

According to Walter & Troll (2003), the triaxial architecture of the rift zones on Tenerife is characteristic of a volcano that is centrally supplied with magma and is experiencing increases in the instability of a sector. This results in two rift zones with intense volcanic activity (corresponding with the northwest and northeast rift zone on

Tenerife) and a less pronounced rift zone, located in the stable part of the volcano (corresponding with the southern rift zone on Tenerife). Acosta et al. (2003b) described rift characteristics of the nearby islands of La Palma and El Hierro that are comparable to the southern rift of Tenerife. These are characterised by a broad fanlike distribution of monogenetic centres. They relate this to the stress field within the rift being insufficient to trap dykes within a narrow region and/or to dyke injection and volcanism shifting laterally through time. Additionally, a low rate of magma supply produces low magma pressures, responsible for randomly orientated dyke injections. The rift zones of the Hawaiian Islands generally consist of linear and steep ridges. The toes of some Hawaiian rifts partly fan out as well perhaps as a result of low magma supply (Acosta et al., 2003b).

In the distal part of the southern rift zone, basaltic cinder cones are associated with volcanic features formed by phonolitic eruptions (Fig. 9A, B). Additionally, syenitic components (TF-P1, Figs. 4, 8B, 8C) occur as ballistic blocks in the tuff cone of Montaña Pelada. Widom et al. (1993) interpreted syenitic ballistic blocks at the Agua de Pao Volcano on the island of San Miguel (Azores) as fragments that had crystallised in the margins of a magma chamber ejected during an explosive eruption. Together with the phonolitic volcanic centres of Montaña Guaza and Caldera del Rey, I interpret the occurrence of syenitic rocks as evidence for shallow magma pockets, located in the distal part of the southern rift zone (compare to Fig. 9B).

Cyclicity of volcanic activity

The major pyroclastic deposits in the Bandas del Sur correlate with eruptions, that built up the major ignimbrite layers of the Ucanca, Guajara and Diego Hernández Formation outcropping in the caldera wall. According to Marti et al. (1994) and Bryan et al. (1998), these formations represent three volcanic cycles: each cycle started with mafic flank eruptions and culminated in an explosive, caldera-forming eruption, collectively responsible for the development of the Las Cañadas caldera (Martí et al., 1994). After Brown et al. (2003) and Edgar et al. (2007), numerous ignimbrite layers and pumice fall deposits of the Bandas del Sur give evidence for more than three caldera collapse events and a more complex development of the Las Cañadas caldera deposits within the Bandas del Sur, are separated from each other by longer periods

without significant volcanic activity, erosional disconformities and paleosoils which are discordantly overlain by basaltic lava flows. In the aftermath of periods of nonpyroclastic deposition, ascending magma in the Las Cañadas volcano probably has been responsible for increasing flank eruptive activity in the southern rift zone, producing large lava fields and cinder cones.

Zellmer et al. (2000) described volcanic eruption cycles for the Santorini volcano (Greece) with an average duration of ~180 ka; each cycle ended with a major caldera forming eruption. According to Christiansen (2001), the volcanic activity of the Yellowstone caldera volcano (Wyoming, USA) is characterised by three volcanic cycles during the last 2.1 Ma; each cycle totals to ~640 ka to 800 ka. The early stage has been dominated by plateau basalt eruptions and each cycle ended with a major caldera forming eruption. However, basaltic as well as rhyolitic eruptions accompanied the entire period of volcanic activity. The time span of major volcanic activity of the three cycles ranges from ~340 ka to 580 ka, the repose periods between the cycles from ~140 ka to 520 ka, respectively (Christiansen, 2001).



Fig. 8: A: View northward to the phonolitic dome and flow complex of Montaña Guaza; phonolitic lava flow (behind the housing) is tens of meters thick; the phonolitic lava dome of Montaña Guaza is situated centre-right of the photograph; B: Syenitic (tephriphonolitic) nodule as ballistic block in the tuff cone deposits of Montaña Pelada east of El Médano; C: Thin section micrograph of the syenitic component (Montaña Pelada) showing hypidiomorphic K-feldspar and plagioclase crystals.



Fig. 9: A: Model of the triaxial rift zone on Tenerife illustrating the distribution of cinder cones; narrow chains of cinder cones on top of the steep ridges of the northwest and northeast rift and a fan-like distribution of monogenetic volcanic structures within the southern rift zone; B: Interpretation of the occurrence of phonolitic volcanic structures in the distal part of the southern rift zone with feeder dykes and assumed magma pockets underneath the Bandas del Sur. CR: Caldera del Rey, GZ: Montaña Guaza, PL: Montaña Pelada.

Stratigraphy

Based on the dataset presented in this work and on the radiometric age dating of several volcanic units in previous literature, 4 volcanic cycles can be defined, based on the stratigraphy developed by Bryan et al. (1998), Brown et al. (2003) and Edgar et al. (2007) for the Bandas del Sur (Fig. 7). The volcanic cycles 1 to 4 depicted in Fig. 7 are defined for the volcanic succession of the Bandas del Sur Group; in the

northwest and northeast rift, due to the lack of ignimbrites, a volcanic cyclicity has not yet been identified. According to Galindo & Soriano (2005), fissure eruptions along the northeast rift have occurred since the early development of the rift up to the historical eruptions. Cycle 1 deposits are scarce in the Bandas del Sur and Cycle 1 is poorly defined in age and distribution. Pyroclastic deposits of Cycle 1 are preserved in the southwestern flank of Tenerife; however, the stratigraphic position of these units is not well defined. Additionally, the Helecho Member or Arafo Member of the Bandas del Sur Group have not been dated yet. Further dating of pyroclastic deposits and lavas is necessary to better constrain the duration of each cycle. Cinder cones belonging to Cycle 1 have not yet been found in the study area.

The alignments of Cycle 2, 3 and 4 cinder cones occur mainly along NNE-SSW trends (Fig. 2), representing the main direction of the southern rift zone (Fig. 1A, 2, 8A).The specific alignment indicates that persistent fractures acted as continuous channels for the mafic flank eruptions within the Bandas del Sur (Bryan et al., 1998; 2002). In previous literature, all the cinder cones within the study area (except the San Lorenzo cinder cones) were assigned to the Cycle 3/Series III-basalts (e.g. Fuster et al., 1968; Bryan et al., 1998; 2002; Clarke et al., 2005) with an eruption age between 690 ka and Upper Pleistocene/Holocene boundary (e.g. Bellido Mulas et al., 1978; Hernández-Pacheco & Fernández Santín 1978; Carracedo 1979) or >320-316 ka (Bryan et al., 1998).

The paleomagnetic data and K-Ar ages determined through this study indicate that a specific number of cinder cones belong to an older volcanic cycle. At least 13 cinder cones show reverse magnetization (R-Basalts; Fig. 2) and hence they must be older than the last geomagnetic polarity reversal event at 778.7 \pm 1.9 ka (Singer & Pringle 1996). The cones represent the initial stage of Cycle 2 eruptions. Bryan et al. (1998) set the beginning of Cycle 2 to a minimum age of >760 ka. Using the age of TF-47/Roja (948 \pm 15 ka) and the paleomagnetic data, the start of flank eruptive activity at the base of Cycle 2 can be set at between >948 \pm 15 ka and 778.7 \pm 1.9 ka (Fig. 7).

The basalts showing normal magnetization (N-Basalts and N-Basalts-SL, Fig. 2) belong to Cycle 3 and to the San Lorenzo lava field. The assumed onset of Cycle 3 >320 ka ago (Bryan et al., 1998) correlates with the age of the cinder cone Montaña Gorda and with a lava flow by Carracedo et al. (2003, 2007), as well as with the age of TF-4/Amarilla, presented in this study. It can be assumed that the majority of

basaltic flank eruptions at the base of Cycle 3 took place between 323 ± 6 ka and 300 ± 8 ka.

The basaltic eruptions of the San Lorenzo lava field indicate the start of a possible further volcanic cycle (Kröchert et al., 2008b). The age of the San Lorenzo lava field is given from the K-Ar age of a cinder cone near La Buzanada (Carracedo et al., 2007), defining the onset of Cycle 4 to a minimum age of >95 ka. The caldera forming eruptions of Cycle 3 have been followed by the construction of the Pico de Teide and Pico Viejo stratocones that began with non- or minor-explosive eruptions of basaltic to intermediate and phonolitic lavas inside the Las Cañadas caldera; basaltic fissure eruptions occurred concurrently along the northwest and northeast rift (Carracedo et al., 2007). The subplinian eruption of Montaña Blanca (Fig. 1) ~2 ka ago (Ablay et al., 1995) may represent a change from effusive basaltic flank eruptions and non-explosive volcanism at Pico de Teide and Pico Viejo to a more explosive phase (Bryan et al., 1998; Wolff et al., 2000), similar to the earlier volcanic cycles (Fig. 7).

The ends of the four cycles defined in this study are characterised by widespread erosional unconformities in the Bandas del Sur, by thick paleosoil development (Bryan et al., 1998) and by extended periods without explosive volcanic eruptions. The gap between Cycle 1 and 2 lasted for ~180 ka, between Cycle 2 and 3 for ~250 ka; and between 3 and 4 for ~70 ka. The period of volcanic activity of Cycle 2 lasted for ~350 ka and 180 ka for Cycle 3, respectively (compare to Fig. 7).

Geochemistry

The geochemical data reveal a magmatic evolution from primitive magma (SiO₂ 41.7 wt%) to a more evolved tephritic and trachybasaltic magma for the R-Basalts and N-Basalts, due to fractional crystallisation processes involving the removal of olivine, clinopyroxene and titaniferous magnetite (Fig. 4, 5). The N-Basalts-SL, with high MgO, Fe₂O₃, V and Cr abundances represent a primitive magma with relatively short storage periods. Rapid ascent of magma from the mantle to upper crustal levels was proposed by Neumann et al. (1999) based on the presence of ultramafic xenoliths in the cinder cones and dykes of Tenerife. The range in the trace element abundance of R-Basalts and N-Basalts (Fig. 4) could be explained by fractional crystallisation processes, assimilation or different degrees of partial melting of the mantle source. Lower alkali (Na₂O+K₂O), Rb and Nb contents of the R-Basalts at similar MgO

content in comparison to the N-Basalts and N-Basalts-SL (Fig. 5) may suggest a higher degree of partial melting. Immobile trace element plots for Y/Nb versus Zr/Nb (Pearce & Norry 1979) show that the basalts plot into three different fields. The N-Basalts with Y/Nb ratios <0.35 indicate that they derived from a more enriched mantle source compared to the R-Basalts (Y/Nb: 0.37 – 0.41) and the N-Basalts-SL (Y/Nb: ~0.47). But these ratios could also be influenced by magma mixing and mingling processes, characteristic for magma compositions on Tenerife (Ablay et al., 1998; Bryan et al., 2002; Bryan, 2006). Fractional crystallisation in periodically refilled magma chambers and the assimilation of syenite and amphibolite are also processes, present on Tenerife, which can change element ratios/abundances (Neumann et al., 1999; Simonsen et al., 2000) and may overprint primary mantle source characteristics. However, the Y/Nb versus Zr/Nb plot combined with the paleomagnetic data appears to be a good tool to determine the stratigraphic position of cinder cones within the Bandas del Sur.

2.6 Conclusions

1. In contrast to the northwest and northeast rift zones on Tenerife, the southern rift zone comprises a number of characteristics with respect to the morphological features and the geochemistry of the volcanic deposits. It does not display a distinct ridge and has a fan shaped distribution of monogenetic cones. Together with phonolitic volcanic structures, the occurrence of syenitic rocks can be interpreted as evidence for shallow magma pockets, located in the distal part of the southern rift zone.

2. Four volcanic cycles can be identified in the volcanic succession of the Bandas del Sur; cycles 1 to 3 commenced with intense mafic flank eruptions and culminated in a series of explosive phonolitic eruptions. However, the formation of phonolitic volcanic structures outside the caldera as well as caldera forming eruptions occurred over a longer period and are not necessarily restricted to the final stage of each cycle.

3. The end of each cycle is defined by the occurrence of erosional unconformities, paleosoils and longer periods without volcanic activity. The gap between Cycle 1 and 2 lasted for ~180 ka, between Cycle 2 and 3 for ~250 ka; and between 3 and 4 for ~70 ka.

4. The cinder cones within the Bandas del Sur can be split into three different age groups, belonging to the Cycle 2, 3 and 4 episodes of basaltic flank volcanism.

5. The Cycle 2 cinder cones have a wide distribution in the Bandas del Sur Formation and were erupted between >948 \pm 15 ka and 778.7 \pm 1.9 ka.

6. The main eruptive activity of the Cycle 3 basalts occurred between 323 ± 6 ka and 300 ± 8 ka.

7. The basaltic eruptions which formed the San Lorenzo lava field ~95 ka ago, may define the start of a fourth volcanic Cycle.

3. Uplift markers on Tenerife

3.1 Introduction

Positive vertical movements of volcanic islands can generally be caused by major earthquakes, ascending magma or mass loss as a consequence of giant land slides. According to Pirazzoli et al. (1982) and Kontogianni et al. (2002), major earthquakes can enforce vertical movements of tectonic blocks resulting in a symmetric or asymmetric uplift of entire islands.

Amelung et al. (2000) detected widespread uplift on the Galápagos Islands enforced by ascending magma; positive vertical movements enforced by magma injection have also been described for the Nisyros volcano (SE Aegean Sea) by Stiros et al. (2005). Significant uplift of volcanic islands as the result of giant land slides and flank collapses with concomitant mass loss have been described in detail by Smith & Wessel (2000) for the Hawaiian Island.

On the western Canary Islands, submarine series presently expose at the surface have been described as evidence for significant uplift of La Palma by Staudigel & Schmincke (1984). Uplifted and re-incised conglomerate terraces give further indication for a persistent uplift of this island (Hildenbrand et al., 2003). In contrast to the central and eastern Canary Islands, La Palma is still in the shield building stage associated with an intense magma intrusion and high effusion rates.

On the eastern islands Lanzarote, Fuerteventura, and Gran Canaria, uplifted fossil beaches have been described by Lecointre et al. (1967); Klug (1968); Meco & Stearns (1981) and Zazo et al. (2002, 2003a). The topographically highest fossil beach deposits were discovered by Klug (1968) on Gran Canaria, 100 m ASL. On Tenerife, planar cross-bedded sandstones near the high tide level on the coast between the Punta Roja and El Médano (South Tenerife) were interpreted as delta deposits by Hausen (1955). González de Vallejo et al. (2003, 2005) described sandstones with paleoliquefaction features positioned 15 m ASL at the same locality. Bravo (1952) and Palacios et al. (1996) have both recorded marine deposits on the coast of the Orotava valley, while Talavera et al. (1978, 1989) and Zazo et al. (2003b) have done so on the Playa del Tachero (NE Tenerife). Further fossil beaches have been depicted by Zazo et al. (2003a) near Igueste de San Andrés.

Rothe (1966) interpreted volcanic rocks in the Anaga and Teno mountains as pillow lavas. Fuster et al. (1968) reinterpreted these rocks as volcanites with structures of spheroidal weathering. These rocks should not be interpreted as submarine

formations and accordingly do not represent uplift markers. On a general map of the Canary Islands Carracedo (1999) recorded two locations with pillow lavas on Tenerife. These pillow lavas are situated at an altitude probably influenced by Pleistocene sea-level changes. Carracedo (1999) concluded that the Canary Islands have experienced neither uplift nor subsidence since their emergence above sea-level. The development of pillow lavas and fossil beaches on Tenerife was ascribed to Pleistocene sea-level highstand based on former literature. As a result, stable conditions for Tenerife without uplift or subsidence have been assumed (e.g. Talavera et al., 1978; Palacios et al., 1996; Carracedo, 1999). Zazo et al. (2003a,b) even assumed a slight subsidence of Tenerife since the upper Pleistocene.

The intention of this part of the study is to re-evaluate the known fossil beaches of Tenerife as well as to identify further fossil beaches as potential uplift markers. In addition a further investigation was carried out to determine whether tuff cones developed within the range of the sea-level. An overview of the study area is depicted in Fig. 10.



Fig. 10: Position of Tenerife Island and the northern and southern study area. Arrows point to localities studied in this work: bold type: predominantly studied localities; light face type: re-examined localities; italic type: compiled from literature. PV: Pico Viejo; PT: Pico de Teide; after Ablay & Martí (2000) and Hürlimann et al. (2001), modified.

3.2 Methods

Age dating

For K/Ar age determination of Montaña Amarilla Pelada and Montaña Roja, unweathered samples of a pyroclastic bomb and basaltic lava, respectively, have been used. The age determinations were carried out at the Laboratoire des Sciences du Climat et l'Environment (Gif-sur-Yvette). The materials used were whole rock samples, crushed to particle sizes varying between 0.250 and 0.125 mm, and ultrasonically washed in HC₂H₃O₂. The converted ages were calculated using the following constants: ⁴⁰K/K = 1.167 10⁻⁴ g/g; $\lambda_{\epsilon} = 0.572 \ 10^{-10}/a$; $\lambda'_{\epsilon} = 0.0088 \ 10^{-10}/a$; $\lambda_{\beta} = 4.962 \ 10^{-10}/a$. The error margin for the age is 2 σ .

Fossil beaches between El Médano and Punta Roja have been dated by thermoluminescence methods and presented in González de Vallejo et al. (2003, 2005). Age determinations for the locations of Igueste de San Andrés and Playa de la Tachero were carried out on fossil shells by using aminostratigraphy, U-series (Zazo et al., 2003a), and paleontological methods (Talavera et al., 1989, Zazo et al., 2003a,b). Montaña Pelada has been relative dated by paleomagnetic methods (Carracedo, 1979).

Sedimentary petrography

Fossil beaches are generally subdivided into foreshore and backshore area (Nichols, 1999). Foreshore deposits are characterised by the occurrence of horizontal, weakly seaward dipping strata, containing marine macro fossils. According to Pirazzoli et al. (1985) and Pirazzoli (1991, 1996) the most common sea-level indicators are marine organisms, for instance barnacles, calcareous algae and limpets. On Tenerife, foreshore sediments typically comprise calcareous algae, the marine gastropod *Patella sp.* and the cephalopod *Spirula spirula*. Regarding sedimentary structures, backshore deposits of the backbeach and the affiliated coastal dunes exhibit planar and cross bedded strata; on Tenerife the landsnail *Hemicycla sp.* occasionally occurs whereas marine macro fossils are lacking in these very well-sorted sandy deposits.

Backshore deposits can occur tens of meters above the sea-level whereas foreshore deposits directly indicate the position of the shoreline. Accordingly, in this study I exclusively use foreshore deposits with an unambiguous content of marine macro fossils as uplift markers. The classification of the fossil content has been carried out at the Museum für Naturkunde, Stuttgart.

3.3 Localities

Northern area

Punta del Draguillo (UTM 28384745 E/ 3162118 N)

The succession of beach deposits has a lateral expansion of ~30 m and reach to a maximum of 2.5 m ASL. Deposits of wave-cut benches are situated at the basis, discordantly overlain by sandy beach sediments of the foreshore area. The deposits of the wave-cut benches consist of clast-supported breccias with a maximum thickness of 1.5 m. Numerous shells and shell fractions of marine gastropods and cephalopods (predominantly *Patella candei, Patella lowei, Strombus bubonius* and *Spirula sp.*) as well as components overgrown with serpulits are evidence of a highly energetic marine milieu (Fig. 11A). The beach sediments mainly consist of weakly cemented fine and middle sands. Sometimes horizontal bedded foreshore deposits can be observed. Numerous shells of various marine gastropods are preserved in this unit. The well sorted sands contain mineral fragments of olivine and pyroxene as well as micritic fragments of red algae and mafic lithoclasts. At the top of the beach sediments a paleosoil can be observed covered by mighty breccias of slope alluvium and further interbedded paleosoils. Similar beach deposits can be tracked over a distance of 200 m.

Roque de las Bodegas (UTM 28382158 E/ 3160828 N)

The beach sequence at this location possesses a maximum thickness of 4.5 m; the basis lies 6 m ASL. The beach deposits consist of weakly cemented fine and middle sands featuring horizontal bedding. The petrographical properties as grain size distribution and grading are comparable to the fossil beach deposits of Punta del Draguillo, as well as the occurrence of a similar marine fauna at both localities (Fig. 11B). West of Roque de las Bodegas, fossil beaches at the Playa del Tachero (Fig. 11C) have been described by Talavera et al. (1989) and Zazo et al. (2003b), reaching to a height of 1-2 m ASL. The sediments at the Playa del Tachero have been relative dated to the OIS 5e and feature the same petrographical and paleontological characteristics as the deposits of Punta del Draguillo and Roque de las Bodegas (compare Fig. 11B, C).

Igueste de San Andrés (UTM 28387756 E/ 3155593 N)

The volcanic units of the old basaltic series are prevalently overlain by paleosoils. At the outcrop of Igueste de San Andrés paleosoils are followed by marine conglomerates with a maximum thickness of 2 m and by breccias of slope alluvium. The conglomerates mostly lay approximately 0.5-2.8 m ASL (Fig. 11D). Numerous fragments of different bivalves and marine gastropods (as well as *Strombus bubonius*) can be found between the well cemented components of the conglomerates. These multitudinous marine organisms demonstrate highly energetic conditions (e.g. serpulids and limpets). Accordingly, this unit can be interpreted as fossil wave-cut bench deposits. An age of 131 \pm 1.60 ka correlating with oxygen isotopic stage 5e (OIS 5e) was ascertained by absolute U-series dating of marine fossils (Zazo et al., 2003a) from this location.



Fig. 11: Cross section and lithostratigraphic logs including fossil content of study sites in the northern working area; PSL: present sea-level.

Playa de Gordejuela and Playa de San Juan (compiled from Palacios et al. (1996) and Bravo (1952))

At the Playa de Gordejuela (Fig. 11E), Palacios et al. (1996) described two horizons of Pleistocene beach deposits at 3 m and 18.5 m ASL, respectively (Fig. 11E). However, Palacios et al. (1996) did not mention the occurrence of marine fossils in the sandy sediments. The Pleistocene beach deposits directly overlay collapse breccias ("Mortalon") of the ~540-690 ka (Cantagrel et al., 1999) Orotava flank

collapse (Fig. 10). Bravo (1952) depicted shell fragments of marine organisms at ~8 m ASL at the Playa de San Juan (Fig. 10).

Conclusions for the northern area

The fossil beaches in the Anaga mountains (Fig. 10) are located close to the present sea-level and are exposed up to an elevation of 10.5 m ASL. Sedimentological, petrological and paleontological criteria point to deposits of fossil wave-cut benches and sand beaches. An age of ~131 ka can only be specified for the deposits near lgueste de San Andrés. The occurrence of *Strombus bubonius* in the fossil beach deposits of Punta del Draguillo is indicative of the deposition during the OIS 5e; *Strombus bubonius* exclusively existed on the Canary Islands during the interglacial period OIS 5e (Meco et al., 2002). Talavera et al. (1989) and Zazo et al. (2003b) described fossil beaches of the OIS 5e at the Playa del Tachero (in the West of Roque de las Bodegas; see Figs. 11B, C) reaching to a height of 1-2 m ASL and featuring the same petrographical and paleontological characteristics as the deposits of Punta del Draguillo and Roque de las Bodegas. At the Playa de Gordejuela, Pleistocene beach deposits are exposed up to an elevation of 18.5 m ASL. Due to the lack of faunal content, these sediments can only be dated by stratigraphical methods to a maximum age of ~540-690 ka.

Southern area

Montaña Pelada (UTM 28350552 E/ 3104740 N)

The tuff cone Montaña Pelada has an expansion of 1.5×1.3 km and a maximum height of 80 m ASL. In a paleomagnetic study, Carracedo (1979) placed the tuff cone into the Bruhnes (778.7 ± 1.9 ka, Singer & Pringle, 1996). On its southern flank marks of coastal erosion can be observed between the recent sea-level and 30 m ASL (Figs. 12B, 13A). Fossil beach deposits with a maximum thickness of 2 m are arranged above the marks of coastal erosion at a height of 35 m ASL (Fig. 13A, B). The beach sediments consist of well cemented middle sands with a high fraction of biogenic components (red algae, bryozoans, and planktonic foraminifera, see Fig. 13C, D). The lower section of the beach is made up of coarse grained debris deriving mainly from the tuff cone. On the southern flank there is also a second fossil beach horizon which can be noticed in the range of the recent sea-level.



Fig. 12: Simplified geological map (A) and cross-section (B) of Montaña Pelada east of El Médano; PSL: present sea-level.



Fig. 13: A: Marks of coastal erosion and the present abrasion platform at Montaña Pelada east of El Médano; dashed line marks position of the horizon of fossil beach deposits; B: horizon of fossil beach deposits overlaying marks of coastal erosion; C and D: fossil beach deposits predominantly containing red algae and bryozoans.
Coastal segment between El Médano and Punta Roja (UTM 28348449 E/ 3101724 N)

The cinder cone Montaña Roja at the Punta Roja has an age of 948 ± 15 ka (Kröchert & Buchner; 2008). The rocks of the coastal segment between El Médano and Punta Roja consist of ignimbrites of the Arico formation (Brown et al., 2003), discordantly overlaying the scoria of Montaña Roja. The ignimbrite was dated by Brown et al. (2003) at ~668 ka using K/Ar method. Fossil sandy beach deposits on top of the ignimbrite can be subdivided into a lower and an upper unit (Fig. 14A, B) separated by pumice deposits and/or paleosoils (for readability I use FBD 1 for the lower unit and FBD 2 for the upper unit of the fossil beach deposits in the following). The FBD 1 are constricted to a small area in the southwest of the coastal segment (Fig. 14A) and are partially covered by 2 m thick pumice deposits. The FBD 2 featur a greater distribution than FBD 1. The boundary between the ignimbrite and beach sands is always represented by an erosional disconformity. In places a marginal thick layer with reworked ignimbrite material and marine gastropods separates the younger sands from the ignimbrite. The fossil beaches of FBD 2 also occur on Montaña Roja's southeastern flank. They either lay directly on the volcanic scoria or on breccias made up of scoria material and beach sediments. In the range of the recent sea-level, fossil beaches are additionally divided by beach rock deposits from Montaña Roja's scoria. Large parts of the area are covered by colluvium deposits (Fig. 14A, B).

Fossil beach deposits 1 (FBD 1):

The sequence of FBD 1 consists of weakly cemented, moderately sorted middle to coarse sands showing horizontal and planar cross bedding. The altitude of the sandy deposits ranges from a few meters to 15-20 m ASL. The maximum thickness of the beach profile reaches up to 3 m. The beach sands are composed of biogenic components (red algae, marine gastropods and sea urchins), lithoclasts (scoria and mafic rock fragments) and fragments of minerals (olivine, plagioclase, pyroxene). The deposition in a submerged position in the foreshore area is reasonable considering the sedimentary structures, moderate sorting and the coarse sand fraction mentioned.



Fig. 14: Simplified geological map (A) and lithostratigraphic logs (B) of the coastal segment between El Médano and Punta Roja; FBD: fossil beach deposits.

Fossil beach deposits 2 (FBD 2):

The sequence of FBD 2 consists of weakly cemented, well to moderately sorted, middle to coarse sands mainly featuring horizontal and planar cross bedding. The maximum thickness of the beach succession totals 5 m overlaying scoria of Montaña Roja from the present intertidal zone to a height of more than 65 m ASL. The sands consist of biogenic components (predominantly micritic red algae) and lithoclasts as well as fragments of pyroxene, olivine and plagioclase. The sands of FBD 2 are only cemented with thin circum granular cement of microcrystal calcite and aragonite needles comparable to the lower beach sequence.

In the study area FBD 2 is cut into two areas, A and B (see Fig. 14A):

Area A:

In certain places very well preserved shells of marine gastropods and *Spirula sp.* can be found in the sandy beach deposits. Tube–like concretions (Fig. 15A, B), appearing perpendicular and partly branching, are characteristic for the beach deposits in area A. Single tubes can reach a length of 1.2 m and a diameter of 20 cm. A few of them

are hollow or secondarily filled by fine grained sands. These tube-like concretions can be interpreted as rhizoconcretion (Fig. 15A, B). Further characteristics of area A are 2 - 5 cm thick sedimentary dykes with lengths of up to 10 m (Fig. 15A). A layer with reworked components has developed at the sand's basis in the area of contact with the ignimbrite. The processed horizon can lay up to 11 m ASL (compare to Figs. 14B2, 15C). It reaches a thickness of up to 20 cm and mainly consists of rounded, 5–10 cm big lithoclasts and middle to coarse sands. The layer presents itself in some places as a dark brown horizon which has a thickness of more than 30 cm and holds marine gastropods (especially *Patella sp.*; Figs. 14B, 15D). The basal layer with reworked components and marine gastropods (*Patella sp.*) represents a development in the high-energetic foreshore area. The main parts of the sands were deposited in the backshore. The fossil beach in area A was dated via thermoluminescence (González de Vallejo et al., 2003, 2005). The ascertained age of the dating adds up to 10.081 ± 933 .



Fig. 15 A and B: Concretions (tubes and dykes) in fossil beach deposits of the coastal segment between El Médano and Punta Roja; C: layer with reworked components of the fossil beach deposits (FBD 2, see Fig. 14) on top of the ignimbrite; D: layer including reworked components with *Patella sp.*.

Area B:

In area B, fossil beach sands lie on top of the southeastern flank of Montaña Roja and are generally coarser than in area A. Towards the top they wedge out against Montaña Roja. The topographically lowest deposits mainly show planar and cross bedding. Horizontal bedding is mainly formed from a height of 6-7 m ASL up to a maximum height of 65 m ASL. In these higher areas rounded pumices and coarse sands to fine gravel are interconnected with the scoria of Montaña Roja and the sandy deposits. The occurrence of fine gravel components suggests sedimentation near the foreshore area. Due to the lack of marine fossils, it is not possible, to separate foreshore from backshore deposits at this locality. Accordingly, sandy deposits of area B are not regarded as sufficient uplift markers.

Costa del Silencio (UTM 28339165 E/ 3099308 N)

In the study area, the 73 m high tuff cone Montaña Amarilla Pelada is located on the coast and its crater is open towards the northeast. On this tuff cone a small cinder cone developed on the northeastern flank later on. Both volcano constructions are surrounded by extensive lava fields (Fig. 16A). South and east of Montaña Amarilla fossil beach deposits (Fig. 16A, B) can be found. The rocks of the crater and parts of the beach deposits are covered by pyroclastic deposits with a maximum age of 179 \pm 11 ka (Bryan et al., 1998).

Tuff cone:

The well preserved tuff cone of Montaña Amarilla Pelada (Figs. 17A, B) consists of strongly consolidated tuff and lapilli layers with xenoliths, ballistic blocks and some single pyroclastic bombs. Several lithic blocks consist of sandy deposits that contain marine fossils (Fig. 17D). All the tuff deposits show intensive palagonitisation. The ballistic blocks and pyroclastic bombs strongly deformed the underlying layers during the impact (Figs. 16B, 17B). Slumps are generally formed in the deposits of the tuff cone up to a height of ~15 m ASL, requiring a water saturation of the affected layers (Figs. 16B, 17B). The tuff cone of Montaña Amarilla Pelada was dated by Kröchert & Buchner (2008) at an age of 300 ± 8 ka using the K/Ar method.



Fig. 16: Geological map (A) and cross section (B) of Montaña Amarilla Pelada at the Costa del Silencio; PSL: present sea-level.

Fossil beach deposits:

The fossil beach deposits (Fig. 17C) consist of weakly cemented middle sands. Parts of the fossil beach deposits lay beneath the sea-level, the highest areas are located 35 m ASL. The maximum thickness of the sands is 5-6 m. Petrographical investigations revealed a composition of lithoclasts (mafic fragments of rocks), biogenic components mainly of micritic fragments of red algae (Fig. 16B) and mineral fragments. Well preserved shells and fragments of the land snail *Hemicycla incisogranulata* and other species of the genus *Hemicycla* can also be found, especially in the cross bedded units, where they locally occur in large quantities. With regard to the sedimentary structures, planar, trough cross and horizontal bedding can be observed. The predominant portion of these sediments has to be regarded as backshore deposits (Fig. 17C); however, it is not possible to clearly separate foreshore from backshore deposits at this study site. Accordingly, the fossil beach deposits of this location are not useable as uplift markers.



Fig. 17: A: Tuff cone of Montaña Amarilla Pelada, overlain by fossil beach deposits near the present shoreline; B: tuff layers with slumps and deeply invaded volcanic bombs and ballistic blocks (top right); C: fossil back shore deposits (dunes) near the present shore line; D: thin section picture of a lithic block which derived from the tuff cone deposits consisting of sandy deposits with marine fossils (red algae and bivalves), transmitted light.

Figure 18A-E shows an overview of the development of the Costa del Silencio. In the first stage a tuff cone came into existence beneath a remote shallow submersion during a phreatomagmatic eruption (Bellido Mulas et al., 1978; Clarke et al., 2005) (Fig. 18A). Because of deeply invaded bombs, deformed pyroclastic deposits and numerous slumps on the slope of the tuff cone, one can assume an intensive water saturation of the underground area. The successive development of the scoria cone occurred in the terrestrial area (Fig. 18B). The deposition of coastal dunes on the tuff cone's southern flank can be explained either by a declining sea-level or an uplift of the tuff cone (Fig. 18C). The younger pyroclastic deposits originating from the island's centre and the slope debris, developed during terrestrial conditions (Fig. 18D, E).



Fig. 18 A-E: Schematic illustration of the development on the Costa del Silencio; A: submarine development of the tuff cone; B: uplift and an associated relative regression with subsequent development of the scoria cone; C: development of beaches with adjacent dunes; D: plinianic volcano eruption in the hinterland (Cañadas-Caldera?) as source of pyroclastic depositions in the tuff cone and its flanks; E: development of slope debris.

Conclusions for the southern area

The fossil beach sands of the southern area reach up to a maximum height of 65 m ASL. Marks of coastal erosion can be observed up to an altitude of 30 m ASL. The examined beach profiles comprise deposits of the foreshore with adjacent dunes. Layers with reworked components belonging to fossil foreshore deposits generally report the altitude of the fossil shoreline. Today, in the coastal segment between El Médano and Punta Roja these deposits are located at a height of 11-15 m ASL (Fig. 14A, B). According to Bellido Mulas et al. (1978) and Clarke et al. (2005) the tuff cone of Montaña Amarilla Pelada most probably developed at least partially during shallow marine submersion. This volcano represents the typical morphology of a tuff cone. Verwoerd & Cherollier (1987) and Wohletz & Sheridan (1983) determined that a shallow body of standing water favours the development of tuff cones. Additional arguments for submarine development (White, 1996) are, slumps, strongly

consolidated tuff deposits showing intensive palagonitisation and the lack of surge deposits (e.g. climbing dunes, antidunes, lenses of coarse grained pyroclastica). Several lithic blocks in the tuff layers consist of sandy deposits that contain marine fossils (Fig. 17D); the components represent sediments, deposited under shallow water submersion and ejected during the explosive phreatomagmatic eruption of Montaña Amarilla Pelada. Slumps and deformation structures can be observed up to an altitude of ~15 m ASL.

3.4 Discussion

In the literature available, neither uplift nor considerable subsidence has ever been agreed on Tenerife. The fossil beaches have been interpreted as the result of Pleistocene sea-level fluctuations (Carracedo, 1999; Acosta et al., 2003a). In the Central Atlantic during the past 500 ka the sea-level has been situated in the time periods ~400 ka with 18-20 m, ~300 ka with 3 m and ~125–130 ka with 6-10 m ASL (Hearty & Kaufmann, 2000) (Fig. 19A). Quaternary sea-level curves of high-resolution cover only the last 500 ka years. However, characteristics of the δ^{18} O curve (Augustin et al., 2004) consistently match the sea-level fluctuations during this period; the maximum sea-level highstand at ~400 ka (+20 m ASL) is clearly expressed as δ^{18} O minimum. The δ^{18} O curve for the last 800 ka indicates that the sea-level did not exceed +20 m ASL significantly (compare to Fig. 19A, B).

Marine deposits up to 18.5 m ASL located on the Playa de Gordejuela (Fig. 20) were explained as the result of sea-level changes by Palacios et al. (1996). As their maximum sedimentation age ranges between ~540-690 ka, these deposits can truly be the result of an eustatic sea-level highstand at ~400 ka. On the other hand, absolute dating of the oldest fossil beach deposits on Tenerife yield an age of 131 \pm 1.60 ka according to Zazo et al. (2003a). Thus the relatively high age of 400 ka for the deposits of Playa de Gordejuela is possible but rather improbable due to this fact and to the high erosional rates, especially on the northern cliff coast. In conclusion, an uplift of the Playa de Gordejuela site of about ~8.5 m can be assumed. However, I am not able to calculate exact uplift rates for this study site due to the uncertainties regarding the age of the marine deposits of this locality.



Fig. 19: A: Sea level curve slightly modified after Hearty & Kaufmann (2000) for the last 500 ka, including position above the present sea-level (PSL) and age of uplift markers; B: δ^{18} O curve for the last 900 ka after (Augustin et al., 2004).

The mentioned marine deposits at Igueste de San Andrès (131 \pm 1.60 ka) are situated at a height of 0.2 and 0.75 m ASL according to Zazo et al. (2003a). They assumed that the fossil beaches were deposited at a maximum of 2 m ASL (Fig. 11D) during two sea-level highstands in the interglacial period ~130 ka ago. From the deviation difference between the sea-level at that time (+2 m) and the location of the fossil beaches up to +0.2 and +0.75 m, Zazo et al. (2003a) calculated a subsidence rate of -0.0011 mm/a and 0,0074 mm/a (Zazo et al., 2003b) respectively. However the fossil beaches which were investigated by Zazo et al. (2003a) locally reach up to 2.8 m ASL according to my own diagnostic findings (Fig. 20). Therefore, the mentioned deposits lie in the area of the sea-level fluctuations of that time. From this point of view this result indicates stable conditions without significant uplift or subsidence in the southern Anaga Mountains during the last 131 ka.

Due to their paleontological, petrographical and sedimentological properties, the fossil beaches in the north of the Anaga Mountains (Fig. 20) are probably of the same age. Marine deposits (+2 m) on the Playa del Tachero described by Talavera

et al. (1978) have been dated at an age of 6 ka by biostratigraphical methods. The deposits are the result of the Holocene Mellahian-Versilian transgression (+2 m) (Talavera et al., 1978). More recent dating of the fossil beach deposits by Talavera et al. (1989) and Zazo et al. (2003b) yield a depositional age within the OIS 5e. The topographical highest deposits in the northern Anaga Mountains reach a height of 10.5 m ASL. During the OIS 5e two sea-level highstands with a maximum of +10 m ASL were estimated by Hearty & Kaufmann (2000; Fig. 19A). Consequently, the fossil beaches in the northern Anaga mountains indicate stable conditions, with no subsidence or uplift since OIS 5e.



Fig. 20: Position of uplift markers on Tenerife at studied sites; the altitudes above sea level of the fossil beaches at the Playa de Gordejuela originate from Palacios et al. (1996), the ones for Playa de San Juan from Bravo (1952) and for the Playa del Tachero from Talavera et al. (1978).

In the southern study area fossil beaches reach up to a height of 65 m ASL. Additionally, a submarine formed tuff cone represents an uplift marker there. Marks of coastal erosion can be observed up to an altitude of 30 m ASL at the Montaña Pelada. The fossil beaches of this location can be noticed up to 35 m ASL. Due to the age of the Montaña Pelada being a maximum of ~778 ka the marks of coastal erosion and the fossil beach deposits probably formed during the +20 m sea-level highstand ~400 ka ago (Hearty & Kaufmann, 2000). Accordingly, a minimum uplift rate of 15 m during the last ~778 ka can be assumed for this section.

On the coast between El Médano and the Punta Roja the fossil beach deposits were dated via thermoluminescence methods (see González de Vallejo et al., 2003, 2005) with an age of 10.081 ± 933, respectively. Those segments of beach deposits formed under shallow water reach up to 15 m ASL. This results in uplift rates of about 1.5 mm/a for the past ~10 ka. According to Faure & Elouard (1967) and Pirazzoli (1996) the sea-level was situated about 30 m beneath today's mean sea-level ~10 ka ago. This amount must be included in the uplift rate, thereby resulting in an uplift rate of 4.5 mm/a. Ignoring the dates presented in Gonzalez de Vallejo et al. (2003, 2005) and presuming no significant uplift of Tenerife, the beach deposits only could have developed during a sea-level highstand ~400 ka ago. The relatively high age of the deposits mentioned is unlikely due to intensive weathering on Tenerife's coasts.

The tuff cone on the Playa del Silencio at least partially developed under shallow water submersion. This volcanic structure features the typical internal structures, morphometry, and properties of a shallow marine developed tuff cone (e.g. the tuff cone in the Jinzai Formation, Japan, described by Kano, 1998). After Kröchert & Buchner (2008), the K/Ar age of Montaña Amarilla Pelada is ~300 ka. At that time the sea-level exceeded today's level by 3 m (Fig. 19A) according to Hearty & Kaufmann (2000). The present topographical position of the tuff cone deposits reach from recent sea-level to 73 m ASL. If the entire tuff cone had formed under water, an uplift of 70 m in the southern study area of Tenerife would have been acquired. Distinct indications for submarine development can be observed in the lower ~15 m of the volcano. Volcanic deposits above 15 m ASL indicate that a submarine development is presumable but outcrop conditions do not allow a definitive statement. Accordingly, an uplift of ~12 m can be considered reliable on the Playa del Silencio with respect to a slightly higher sea-level (+3 m) 300 ka ago.

The varying uplift amounts at the different localities induce an asymmetrical uplift of Tenerife Islands. Mass loss caused by flank collapse events (e.g. near Guimar, Orotava and Taganana), earthquakes with adjoining local offset at faults, or ascending magma are possible reasons for local uplift. The Orotava flank collapse event could have been responsible for considerable uplift of Tenerife in the time span

between ~540-690 ka, potentially documented by fossil beach deposits above the present sea level at the Playa de Gordejuela and Playa de San Juan. At the localities of Costa del Silencio and Montaña Pelada, a considerable uplift since 300 ka and <778 ka, can be ascertained. The uplift could be possibly linked with the giant flank collapse events of Orotava (~540-690 ka, Cantagrel et al., 1999), Güimar (~287 ± 7 ka, Brown et al., 2003), or Icod (~170 ka; Masson & Watts, 1995). According to presented results, the uplift of Tenerife has been asymmetric and preferably affected the southern part of the island. Due to the fact that none of the giant flank collapses is located in the South of Tenerife, a direct association between land slides and uplift rates is improbable. In particular, no remarkable flank collapses occurred during the uplift of the El Médano area since ~10 ka. Accordingly, in the southern part of Tenerife, none of the flank collapse events correlate convincingly, neither by time nor by geographical position, to uplift of the localities investigated in this study. Faults with minor offsets were depicted by González de Vallejo et al. (2003, 2005) in the area of El Médano; however, faults with considerable offsets have not been described in the study areas. Minor offsets of 1.2 m mentioned by González de Vallejo et al. (2003, 2005) are not sufficient to explain the uplifts ascertained in this study. Amelung et al. (2000) detected widespread uplift on the Galápagos Islands enforced by ascending magma. Positive vertical movements enforced by magma injection have been described for the Nisyros volcano (SE Aegean Sea) by Stiros et al. (2005); uplift rates total 1.7 mm/yr during the last 2,000-3,000 years. I determined the highest uplift rates in the volcanically active zone of Bandas del Sur (south coast) with numerous eruption centres and scoria cones. Accordingly, ascending magma could be responsible for the uplift of southern Tenerife.

The tuff cone on the Playa del Silencio with its topographic elevation of 73 m ASL and an age of ~300 ka coincides chronologically with the beginning of the stratigraphic Cycle 3 (Fig. 1B). During the course of Cycle 3, numerous basaltic eruptions occurred within the Bandas del Sur culminating in the third caldera collapse of the Las Cañadas volcano (Bryan et al., 1998). Ascending magma was probably responsible for the concurrence of considerable uplift and volcanic activity during Cycle 3 ~300 ka ago. Further remarkable uplift (+45 m) took place on the coast between El Médano and Punta Roja and may indicate ascending magma during the last ~10 ka.

3.5 Conclusions

1. In the Anaga mountains in the northeast of Tenerife, the position of fossil beaches indicate stable conditions without remarkable subsidence or uplift since the OIS 5e (~130 ka).

2. In the north of Tenerife, marine deposits are located up to 18.5 m ASL. These deposits can point to significant uplift of ~10 m of Tenerife Island associated with the Orotava flank collapse event (~540-690 ka) or can be alternatively explained as the result of an eustatic sea-level highstand at the time of ~400 ka.

3. The uplift rates in the south (Bandas del Sur) amount to a minimum of 15 m since \sim 778 ka. However, the effective uplift rate probably exceeded this amount, given by the detected uplift rate of 45 m since the last 10 ka.

4. The asymmetrical uplift of Tenerife is the result of varying regional uplift rates. The uplift in the south could be caused by seismic activity or mass loss due to flank collapse events. However uplift due to ascending magma is more plausible.

5. The enforced uplift of Costa del Silencio coincides with the beginning of Cycle 3 ~300 ka ago. The uplift of the area near El Médano since ~10 ka may indicate an adjoining magma load for Tenerife.

4. The interpretation of sedimentary deposits in southern Tenerife

4.1 Introduction

Sedimentary deposits on Tenerife predominantly consist of slope alluvium, paleosoils, and fossil beach deposits. The latter were described at different elevations above the present sea-level by Bravo (1952), Talavera et al. (1978, 1989), Palacios et al. (1996), González de Vallejo et al. (2003, 2005), Zazo et al. (2003a,b) and recently by Kröchert et al. (2008b). In southern Tenerife, between the township of El Médano and Punta Roja (Figs. 10 and 21), Hausen (1955) described planar cross-bedded sandstones near the high tide level and interpreted these sedimentary rocks as delta deposits. Carracedo & Day (2002) recognised conspicuous sediment structures in the sandstones and interpreted these features to be the result of hot ignimbrites that flowed over wet beach sediments; according to this theory, boiling water in the beach sands erupted and, subsequently, unconsolidated sands were ejected through fractures. Martin & Nemeth (2004) interpreted the features as dewatering pipes caused by fast accumulation of beach sediments above a hot and still degassing ignimbrite. González de Vallejo et al. (2003, 2005) redescribed these sediments as fossil beach deposits that exhibit concretionary tubular vents and sedimentary dykes; they interpreted the concretions as paleoliquefaction features and, accordingly, suggested a paleoearthquake with an intensity of IX (moment magnitude of M=6.8) for the region in the Holocene (about ~10 ka ago) that would have been responsible for the formation of the proposed seismites. Kröchert et al. (2008b) described the sandy deposits as fossil beaches with adjacent dunes. The aim of this part of the study is to determine the genesis of these sedimentary structures discussing a volcanic, seismic, or biotic origin.

4.2 Study area

The study area is situated between the widely eroded remnant of the cinder cone of Montaña Roja to the southwest and the township of El Médano in the northeast. According to a K-Ar dating study by Kröchert & Buchner (2008), the age of the cinder cone of Montaña Roja accounts is 948 ± 15 ka. The scoria of Montaña Roja is discordantly overlain by ignimbrites that blanket a wide area of the coastal segment between Punta Roja and El Médano (Fig. 21A). The fossil beach deposits on top of the ignimbrite can be subdivided into a lower (Fossil Beach Deposits 1) and an upper

unit (Fossil Beach Deposits 2); for readability the term FBD1 for the lower unit of fossil beach deposits and FBD2 will be used in the following text (Fig. 21B). The units are separated from each other by pumice deposits and/or paleosoils (Figs. 21B and 22).

The Sequence FBD1 is restricted to a small area in the southwest of the study area and are partially covered by 2 m thick pumice deposits (Fig. 21A, B); the sandy deposits consists of weakly cemented, moderately sorted middle to coarse sands showing horizontal and planar cross bedding. Sequence FBD1 reaches a maximum thickness of 3 m and was predominantly deposited in the foreshore area (Kröchert et al., 2008b).

Sequence FBD2 predominates over FBD1 in the study area. The boundary between Sequence FBD2 and the ignimbrite is characterised by an erosional disconformity; reworked components and some marine gastropods occur at the basis of FBD2. Sequence FBD2 also appears on the southeastern flank of Montaña Roja and consists of moderately sorted middle to coarse grained sands showing horizontal and planar cross bedding. The beach sands are composed of biogenic components (predominantly red algae, marine gastropods, and sea urchins), lithoclasts (scoria and mafic rock fragments), and fragments of minerals (olivine, plagioclase, and pyroxene). In certain places, well-preserved shells of Spirula spirula and marine gastropods (such as Patella sp.) can be found in Sequence FBD2 (Fig. 21B). The thickness totals up to 5 m in the area of Montaña Roja. The sands of Sequence FBD2 exhibit high porosity and are weakly cemented by thin circum-granular cement of microcrystalline calcite and aragonite needles (without intergranulare cement). According to Kröchert et al. (2008b), the sands of Sequence FBD2 that feature tubular like concretions and sedimentary dykes were deposited in the fore- and backshore area and were dated at an age of 10081 ± 933 a by thermoluminescense methods (see González de Vallejo et al., 2003, 2005; Kröchert et al., 2008b).



Fig. 21: Geological map of the study area between El Médano/Punta Roja; modified after Kröchert et al. (2008b).

4.3 Tubes and dykes

In contrast to Sequence FBD1, tubular like concretions and dykes frequently occur in Sequence FBD 2 (see Figs. 21A, B and 22). The tubes show variable diameters from less than 1 cm to 20 cm in maximum and reach a length of up to ~1.20 m (Fig. 23A, B). Some tubes occur throughout the entire vertical extent of Sequence FBD2 (Fig. 22). The tubes are always perpendicular to the bedding planes, often branching, whereas the bifurcations show a decrease in diameter from second to third order branches; the branches are orientated downward or horizontal. The tubes occur as single features or as coalesced concretions with multiple openings (Fig. 23D). Most tubes are hollow or contain a secondary fill of unconsolidated sediment. Primary sediment structures (horizontal lamination, cross bedding) remained unaffected by the concretionary processes that produced the tubes (Fig. 23A, B).



Fig. 22: Photograph and sketch of tubular concretions with bifurcation system in cross-bedded sandy deposits at the El Médano site (see Fig. 21A).

The dykes reach a length ranging from a few dm to up to ~10 m and a variable thickness of 2 to 15 cm; in some cases, the dykes are cut or widened by the tubes. Occasionally, dykes obviously emanate from single tubes (Fig. 23C). The lateral extension of the dykes is mostly straight whereas some dykes exhibit a trend of curving and/or branching (Fig. 23E).

Similar to the sands of Sequence FBD2, components of the concretions are made up of either biogenic material (predominantly red algae), or lithoclasts and mineral fragments. In cross section, the degree of cementation increases from the outer to the inner rim of the tubes (Fig. 24A), whereas the observed frequency of grain contacts decreases towards the inner parts of the concretions (Fig. 24B-D). In the innermost parts of the tubes, some isolated mineral grains are surrounded by cements mainly composed of micrite and/or clay minerals. In the innermost zone of the tubes, cements may also consist of a single phases like calcite or clay minerals (Fig. 24A).



Fig. 23: Photographs of concretionary sediment structures (tubes and dykes) within the fossil beach deposits (FBD2); A: tubular concretions with bifurcation system in cross-bedded sandy deposits; B: concretions cutting unaffected primary sediment structures; C: tubes and dykes; some dykes emanate from single tubes (arrows); D: tubular concretions with multiple openings; E: curving and ramifying dykes.



Fig.24: A: cross section of a concretionary tube showing characteristic features of rhizoliths; B: micrograph of a thin section of the inner part of the tubule, showing single grains within the cement, plain polarizers; C: micrograph of a thin section of the middle part of the tubule showing increasing frequency of grain contacts, plain polarizers; D: micrograph of a thin section of the outermost part of the tubule, showing compact bedding, plain polarizers.

4.4 Discussion

The genesis of concretions in beach deposits between El Médano and Punta Roja has been variably interpreted as either the result of the interaction between hot ignimbrites with wet beach sands (Carracedo & Day, 2002; Martin & Nemeth, 2004) or an effect of paleoliquefaction of beach sands during an intense seismic event (González de Vallejo et al., 2003, 2005).

Interaction of hot ignimbrites with wet beach sands?

Carracedo & Day (2002) interpreted the tubes and dykes as the product of hot ignimbrites that flowed over wet beaches; boiling water dissolved many shell

fragments and subsequently ejected them through fractures. The cooling water percolated back into the beach sands and reacted with the sand in the walls of the fractures, producing dykes and tubes. However, the sands of Sequence FBD2 are not overlain by remnants of ignimbrite but by colluvium (Fig. 21A, B) and recent beach/dune deposits. In particular, dewatering processes in wet beach sands and the concomitant development of tubular sedimentary structures caused by hot ignimbrites seems to be implausible, due to chronologically differing depositional ages. Whereas the youngest ignimbrites in the Bandas del Sur were dated at a minimum age of ~170 ka (Bryan et al., 1998; Brown et al., 2003; Edgar et al., 2007), the beach sands are of Holocene age (10081 ± 933 yr.; see González de Vallejo et al., 2003, 2005). Erosional disconformities (Fig. 21B), as well as paleosoils that are intercalated between the ignimbrite and Sequence FBD2 (Fig. 21B), are further arguments for a significant difference in the depositional ages of the ignimbrite layer and Sequence FBD2. Additionally, paleosoils (Figs. 21B and 22) do not show any indications of dewatering and degassing processes and appear to be completely unaffected by the influence of thermal heat emanated from a hot ignimbrite body.

Martin & Nemeth (2004) interpreted the concretions as dewatering structures, sand volcanoes, gas escape pipes, and fluidisation channels, respectively; according to this model, the generation of the sediment structures was induced by the accumulation of beach sands on the top of a hot and continuously degassing ignimbrite deposited shortly before sedimentation of the sands. However, the ignimbrite layer in the study area does neither show any lapilli pipes, nor any further evidence for intense degassing. As specified above for the model of Carracedo & Day (2002), the depositional model by Martin & Nemeth (2004) is unlikely due to chronologically differing depositional ages of ignimbrites and sandy deposits of Sequence FBD2 in the Bandas del Sur.

Seismites?

González de Vallejo et al. (2003, 2005) interpreted the tubes and dykes as seismites, generated by a major Holocene earthquake with an estimated intensity of IX and a moment magnitude of M=6.8. According to Montenat et al. (2007) water-saturated sediments that are covered by an impermeable layer are required for the generation of seismites. González de Vallejo et al. (2003, 2005) argued that Sequence FBD2 consists of two distinguishable layers (water-saturated sands overlain by well-

cemented sandstones). Due to the intense interstitial pressures during seismic activity, water and sand were transported to the surface and ejected during hydraulic fracturing or lateral spreading in sand volcanoes. During field work, however, I did not recognise any criteria for the subdivision of Sequence FBD2 into two different layers as proposed by González de Vallejo et al. (2003, 2005). Sequence FBD2 has the same grain size distribution and degree of cementation over its entire vertical extent; the deposits homogeneously provide weakly cemented sandstones, causing high porosity over the entire unit (Fig. 21B); this would rather preclude high interstitial pressures within the sedimentary body. Some of the tubes penetrate the entire Sequence FBD2 unit (Fig. 22). According to the interpretation of González de Vallejo et al. (2003, 2005), the dewatering process responsible for seismite formation should be expected in a sediment body situated underneath Sequence FBD2; however, these deposits overlie paleosoils or ignimbrite. The compact ignimbrites and the clayey paleosoils must be considered as unsuitable for dewatering. If the dewatering had occurred within the paleosoils, then clayey material of the paleosoil should have been injected into the tubes and dykes; however, this was not observed in the field.

Moretti (2000) studied seismites in fossil aeolian sands near Brindsi (southern Italy) and noted that upward deformation of primary sediment structures - with special regard to liquefaction features - are essential characteristics of dewatering structures. The undisturbed primary sediment structures in Sequence FBD2 in southern Tenerife are a further argument against formation by intense dewatering processes, such as caused by an earthquake or volcanic activity. In summary, the sediment structures in fossil beach deposit depicted in this study do not meet the crucial criteria diagnostic for seismites (according to the classification of seismites in different settings by Montenat et al., 2007) for the following observations: 1. The formation of tubes and dykes in question did not affect the primary sediment structures as required for dewatering processes; 2. Ignimbrites and paleosoils that underlie the fossil beach deposits including tubes and dykes must be considered as unsuitable for dewatering; 3. there are no criteria's given for the subdivision of Sequence FBD2 into two different layers; the deposits homogeneously provide weakly cemented sandstones, causing high porosity over the entire unit; this would rather preclude high interstitial pressures within the sedimentary body.

Rhizoliths?

In light of the fact that the primary sediment structures are not destroyed but rather are unaffected by the tubes, a non-spontaneous process for the generation of the concretions should be taken into account. Regarding shape, size, as well as the orientation of the tubes, these features are characteristic for rhizoliths. Further arguments for the interpretation of the tubes as rhizoliths are: (1) Distinct bifurcation systems with decreasing diameter from second to third- and fourth-order branching; (2) the intensity of cementation that increases from the outer to the inner rim (see Fig. 24); (3) single grains that are surrounded by cements in the centre of the features, which is characteristic for roots with root hairs (for details see Klappa, 1980); (4) In some single cases, calcified roots are preserved in the centre of the root tubes (Fig. 25). Considering all these points, the tubes should be interpreted as root tubules. According to the model by Klappa (1980), cementation processes occur within the rhizospheres and is subsequently followed by the decay of the roots. Consequently, root tubules can either contain relicts of the roots or remain as hollow tubes.

Roots that occupied pre-existing fractures and joints in the substrate widened and enlarged these potential pathways, which resulted in branching and curving of some of the dykes (Fig. 23C, E). Hence, small and straight fractures and joints exist in the ignimbrite that underlie the sediments of Sequence FBD2 (~180-190°; González de Vallejo et al., 2003, 2005), following the dominant tectonically induced trend of the southern rift zone on Tenerife (e.g., Bryan et al., 1998; Kröchert & Buchner 2008). However, the strike direction of the dykes (~145°) does not correspond to the joints strike direction in the ignimbrite (González de Vallejo et al., 2003, 2005). Therefore I take into account that the dykes formed during a seismic event as open fractures subsequently occupied by plants.

Krejci-Graf (1961) provided photographs of rhizocretions (tubes and dykes) in fossil beach deposits on the islands of Madeira, Porto Santo, and Sal/Cap Verde Islands, showing the same characteristic features (tubes and dykes) observed in the study area on southern Tenerife. Meco et al. (1997, 2006) described similar features (tubes) in Quaternary deposits in Lanzarote as rhizocretions. In addition, Matteucci et al. (2007) described root tubules in aeolian deposits of southern Somalia that are comparable to the rhizocretions of southern Tenerife



Fig. 25: Photograph of a concretionary tube with the calcified root preserved in the centre of the feature; note the considerable dimensional discrepancy between the filigree root and the resulting root tube.

4.5 Conclusions

1. Sediment structures in the fossil beach deposits of the area between El Médano and Punta Roja, Tenerife, were previously interpreted as dewatering (paleoliquefaction) features caused by the interaction between hot ignimbrites with wet beach sands or by paleoearthquakes, respectively; however, the concretions exhibit features incompatible with this interpretation.

2. With respect to the sedimentary characteristics of root tubules and their orientation, size, branching system, and style of cementation, the sediment structures are in general accordance with the properties of rhizocretions.

3. The root tubes originated from cementation of sandy beach deposits within single rhizospheres, whereas the dykes are most likely the result of cementation along roots that occupied and widened pre-existing fractures and joints within the slightly cemented fossil beach deposits. The dykes formed during a seismic event as open fractures subsequently occupied by plants.

5. Seismotectonic evolution of southern Tenerife

5.1 Introduction

The study area in southern Tenerife (Fig. 21A) comprises a suite of volcanosedimentary rocks that are best studied in the El Médano site (e.g., González de Vallejo et al., 2003, 2005; Kröchert et al., 2008a,b; Kröchert & Buchner, 2008). The volcano-sedimentary units are part of the southern rift zone of Tenerife and exhibit prominent tectonic features as well as conspicuous sediment structures. The sediment structures have been explained as dewatering structures caused by earthquake-induced paleoliquefaction in fossil beach deposits (González de Vallejo et al., 2003, 2005). Kröchert et al. (2008a) reinterpreted tubular features in these deposits as rhizocretions; however, they took into account that "dykes" in the fossil beach deposits could be regarded as indications for a intense Holocene paleoearthquake in the El Médano site, as postulated by González de Vallejo, 2003, 2005). The aim of this part of the study is to investigate the possible seismo-tectonic origin of the fault systems in the study area and to evaluate their significance with respect to the volcanic evolution of the southern rift zone and their hazard potential for Tenerife Island.

5.2 Rift zones on Tenerife

Tenerife Island is characterised by a three-armed rift zone geometry typical for ocean island volcanoes (Carracedo, 1994, 1999). This triple fracturing (with angels of 120°, Fig. 1A) is typical for volcanoes with a central supply of magma that results in a reduced stability of one sector (Walter & Troll, 2003) with the consequence of two active rift zones with intense, and an underdeveloped rift zone with weak volcanic activity. On Tenerife Island, the two active rift zones are represented by the northeast and the northwest rift with continuous volcanic activity since the middle Pleistocene (Carracedo et al., 2007). These rift zones, displaying steep ridges built up by fissure eruptions, are characterised by narrow chains of cinder cones and an extensional stress field, triggering major landslides like the flank collapses of lcod, Orotava, and Guimar (Carracedo et al., 2007). A detailed description of the eruptive and structural history of the northeast and northwest rift is given by Carracedo et al. (2003, 2007). The southern rift does not display a distinct ridge, and the volcanic features show a fan-like distribution of monogenetic cones, arranged in widely distributed clusters and

parallel chains, following the direction of the southern rift (Kröchert & Buchner, 2008). With regard to the volcanic alignments (Fig. 2), the main structural trend of the southern rift zone follows a NNE-SSW direction (Bryan et al., 1998; Kröchert & Buchner, 2008).

The volcanic rocks of southern Tenerife are the product of four major volcanic cycles (Cycle 1 to 4); each cycle started with basaltic flank eruptions of the Las Cañadas volcano and terminated by violent plinian eruptions that produced extensive ignimbrite deposits in southern Tenerife. Basalts of the first cycle were not previously reported from the study area. Hence, the lavas and cinder cones exposed in the southern rift are divided into three different stratigraphic units representing intervals of enhanced basaltic eruptional activity. Cinder cones and lavas of the first two units were generated between ~0.948-0.779 Ma (Cycle 2 basalts; Fig. 7) and ~0.323-0.300 Ma (Cycle 3 basalts; Kröchert & Buchner, 2008; Fig. 7). The youngest volcanic eruptions of the southern rift building up the San Lorenzo lava field (Fig. 1) with a constructional age of ~0.095 Ma (Carracedo et al., 2003, 2007), were combined to the Cycle 4 basalts (Kröchert & Buchner, 2008; Fig. 7). Evidence for Holocene magma loading beneath the southern rift zone is given by Kröchert et al. (2008b), due to asymmetric uplift of Tenerife Island during the last ~11 ka. A detailed description of the genesis of the southern rift is given by Bryan et al. (1998), Carracedo et al. (2007), and Kröchert & Buchner (2008).

5.3 Geology of the study area

The study area is bounded between the eroded remnants of the cinder cone of Montaña Roja in the southwest and the township of El Médano in the northeast (Fig. 21). Montaña Roja belongs to the Cycle 2 basalts with a formation age of 948 ± 15 ka (Kröchert & Buchner, 2008). Together with Montaña Callao and Montaña Ifaro in the northeast, Montaña Roja is part of a linear chain of cinder cones that strictly follow the structural trend of the southern rift (Fig. 2). At the basis of Montaña Roja, the volcanic rocks are discordantly overlain by ignimbrites (Fig. 21B) of the Arico Formation with a depositional age of ~668 ka (Brown et al., 2003).

The fossil beach deposits on the top of the ignimbrite can be sub-classified into a lower (Fossil Beach Deposit 1; FBD1) and an upper (Fossil Beach Deposit 2; FBD2) unit. Here I use the term FBD1 for the lower and FBD2 for the upper unit of fossil beach deposits in what follows. FBD1 and FBD2 are separated from each other by

pumice deposits and/or a paleosoil horizon with a maximum thickness of 2 m (Fig. 21B). The FBD1 are restricted to a small area of the coastal segment (Fig. 21A) and consist of weakly cemented middle- to coarse-grained sands showing horizontal and planar bedding. The occurrence of the FBD1 ranges from a few meters to 15-20 m above the present sea level. According to Kröchert et al. (2008b), the FBD1 were deposited in a submerged position of the foreshore area.

The sequence of FBD2 feature a greater distribution than FBD1; the boundary between FBD2 and the ignimbrite is generally characterised by an erosional disconformity (Fig. 21B). In some places in the study area, a paleosoil is intercalated between the ignimbrite and the FBD2 (Fig. 21B). The Sequence of FBD2 consists of well to moderately sorted middle to coarse sands that are weakly cemented by thin circumgranular cements of microcrystal calcite and aragonite needles, providing a high porosity; the sands exhibit horizontal and planar cross bedding and contain shells of *Spirula spirula*, marine gastropods (predominantly *Patella sp.*), further biogenic components (predominately red algae), lithoclasts, and mineral fragments.

González de Vallejo et al. (2003, 2005) explained conspicuous sediment structures in the FBD2 as dewatering structures ("dykes" and "tubular vents"); Kröchert et al. (2008a) reinterpreted the tubular features as rhizocretions; the "dykes" (Fig. 26A) consist of the same material as the FBD2 (composition, size and sorting), featuring a higher degree of cementation (calcite, aragonite, and clay minerals), that results in a reduced porosity and an increased stability. The tubes (Fig. 26B) and "dykes" display distinct morphological features that are partly or completely filled by fine-grained aeolian deposits. A detailed description of the concretionary features is given by Kröchert et al. (2008a). The sedimentation of the FBD2 in the fore- and backshore area was proposed by Kröchert et al. (2008b). The sands of FBD2 were dated by thermoluminescense methods at an age of 10,081 \pm 933 a (González de Vallejo et al., 2003, 2005).



Fig. 26: A: Open faults in sands of FBD2 in the study area stabilized by an increased degree of cementation and partly colonized by rhizocretions; the occurrence of the root tubules concentrates in intersection points of the fractures (centre and right-most position of the photograph); B: Photograph of a concretionary tube with the calcified root preserved in the centre of the feature.

5.4 Seismic activity on Tenerife Island

According to Mezcua et al. (1992), only two moderate earthquakes with an intensity of I=VII are known for the historic period on Tenerife since seismic surveillance began. Both earthquakes were related to volcanic activity in the years 1706 and 1909. The largest earthquake known for the entire Canary Archipelago, with an intensity of I=X, took place on Lanzarote Island in the year 1730 (González de Vallejo et al., 2003, 2005). Prior to seismic surveillance, only one intense earthquake with a magnitude of M=5.3 was detected on Tenerife in May 1998 (Carracedo & Valentine, 2006). However, numerous low magnitude earthquakes have been detected along the seafloor between the islands of Tenerife and Gran Canaria showing a maximum magnitude of M=5.2 on May 9, 1989 (Mezcua et al., 1992).

5.5 Tectonic features in the El Médano site/Tenerife

In the volcano-sedimentary suite of the El Médano site (Fig. 21), faults and fractures are arranged in two well-defined strike directions (Fig. 27A). The NNE-SSW strike direction (Fig. 27A, left) precisely coincides with the fault system of the southern rift zone (e.g., Bryan et al., 1998; Gonzalez de Vallejo et al., 2003, 2005; Kröchert & Buchner, 2008; compare Fig. 1A,2). Penetrating the FBD2 as an exception, fractures of this strike direction generally intersect the ignimbrite of the Arico formation (Fig. 27B-E), forming joint sets that are extremely straight. The most prominent tectonic

feature of this distinct fault system can be observed over a considerable distance in the El Médano site (Fig. 27) connecting a chain of cinder cones (Fig. 2) that is terminated by Montaña Ifaro in the North (Fig. 27D) and by Montaña Roja in the South (Fig. 27E). The ~948 ka formation age of Montaña Roja (Kröchert & Buchner, 2008) marks the beginning of volcanic activity in this section of the southern rift zone that resulted in the formation of the chain of cinder cones and the concomitant extensional rift-associated fault system. In the study area, this prominent tectonic feature not only intersects the ignimbrite but also intercuts the sands of FBD2 in places appearing as straight, narrow (few centimetres in width), and unbranched single faults at the surface (Fig. 28A).

Fractures showing a competing strike direction approximately perpendicular to the southern rift fault direction (Fig. 27A, right) are restricted to the sedimentary rocks of FBD2 (Figs. 28B, C, 29, 30) and do not occur in the ignimbrite. This type of open fractures (Figs. 28B, 29A) appears as broad cracks up to 30 cm in width and generally exhibits intense branching (Figs. 28B, C, 29, 30). As the formation of the cracks is predominantly erratic and corrugated, pinnate fractures can be developed as straight and narrow, geometrically arranged tectonic features (Figs. 29, 30).

The rims of the fractures of both strike directions are stabilized by an increased degree of cementation (e.g., Fig. 28B); open cracks are filled by poorly-consolidated, fine-grained aeolian deposits and were partly colonized by plants forming rhizocretions. The occurrence of root tubules concentrates in intersection points of open fractures (Fig. 26A).



Fig. 27: A: left: Strike direction of faults measured in the ignimbrite of the Arico Formation (depositional age of ~668 ka) in the study area which strictly follow the structural trend of the southern rift (compare Fig. 2); right: Strike direction of faults in the FBD2 (depositional age of ~11 ka) predominantly run more or less perpendicular to the structural trend of the southern rift; B: The most prominent fracture of the southern rift fault system in the study area; C: The identical open fault straightly intersects ignimbrite of the Arico formation; D: The fault in ignimbrite strictly follows the southern rift fault system trending to Montaña Ifaro that terminates the chain of cinder cones to the North (compare Fig. 2); E: The same fault in ignimbrite straightly trends to Montaña Roja that terminates the chain of cinder cones to the South (compare Fig. 2).



Fig. 28: A: Fractures in sands of FBD2 following the southern rift fault system are straight, narrow, and unbranched; B: Fractures in sands of FBD2 running perpendicular to the southern rift fault system are often broad, open, and tend to branch; C: Fault in sands of FBD2 perpendicular to the southern rift fault system with synthetic Riedel shear structures.



Fig. 29: A: Broad and open crack in sands of FBD2 perpendicular to the southern rift fault system with synthetic (R) and antithetic (R') Riedel shear structures; B: Earthquake shaking model of Hamamura & Ogawa (1993) for poorly-consolidated sediments; the earthquake wave produces synthetic (R) and antithetic (R') Riedel shear structures (after Brothers et al., 1996, slightly modified).



Fig.30: A: Synthetic (R) and antithetic (R') Riedel shear structures in sands of FBD2 in the study area; B: Model for basic Riedel shear structures by Katz et al. (2004); R and R' are synthetic and antithetic shear bands.

5.6 Seismically induced ground effects in Nicoya/Costa Rica

On March 25, 1990, a large earthquake (M=6.8) occurred at the entrance of the Nicoya Gulf in one of the seismically most active regions in Costa Rica. Husen et al. (2002) interpreted a subducted seamount as an asperity whose rupture caused the Gulf of Nicoya earthquake producing considerable damage in central Costa Rica (e.g., Protti et al., 1995); the consequences of the earthquake (e.g., landslides, collapse of buildings, tsunami) were compiled by Ambraseys & Adams (2001) in detail. In order to compare with fractures and faults in the El Médano site on Tenerife Island, non-durable seismically induced ground effects in unconsolidated beach deposits affected by the intense Nicoya earthquake will be presented in the following. These ground effects (Fig. 31, 32B) were reported and photographed minutes after the earthquake and subsequently destroyed by the following high tide few hours later (Seyfried, H., personal communication, 2008). The open seismogenic cracks at Nicova are erratic, tend to branch, and exhibit slight vertical displacement (Fig. 31, 32B); their direct relation to the intense earthquake and their alignement parallel to the shoreline strongly suggest that these seismic features are produced by gravitational sliding. This process produces linear cracks orientated parallel to the seashore and normal to the slope gradient, showing the initial stage of slope failure (e.g., Rajendran et al., 2001).

In unconsolidated and water-saturated sediments, lateral spreading represents a further process that may be triggered by an intense earthquake. This mode of ground failure is a principal cause of liquefaction-related earthquake damage: ground shaking-triggered liquefaction in a subsurface layer of sand produces differential

lateral and vertical movement in overlying unliquified (or less liquified) sand or silt deposits (e.g., Taboada-Urtuzuastgui & Dobry, 1998; Okamura et al., 2001). Lateral spreading is commonly accompanied by the occurrence of characteristic dewatering structures like sand volcanoes (e.g., Rajendran et al., 2001); these dewatering features were not observed in the wet beach deposits of Nicoya.



Fig. 31: Seismically induced ground effects generated by an intense earthquake in unconsolidated beach sands (wet beach deposits) affected by an intense earthquake in Nicoya/Costa Rica (M=6.8) in the year 1990. The open erratic seismogenic cracks exhibit slight vertical displacement and were produced by earthquake-induced gravitational sliding parallel to the shoreline; the photo was taken minutes after the earthquake (Photograph: H. Seyfried).



Fig. 32: A: Open seismogenic cracks in sands of FBD2 in the study area; B: open seismogenic cracks in unconsolidated beach sands (wet beach deposits) in Nicoya/Costa Rica (M=6.8) in the year 1990 (Photograph: H. Seyfried); at both locations, the formation of the cracks is erratic, fractures tend to branch and the cracks were most probably produced by earthquake-induced gravitational sliding.

5.7 Discussion

Rift-associated fault system

In the study area, faults striking parallel to the southern rift zone (Fig. 27A) are common, clearly defined, and extremely straight features that predominantly occur in the ignimbrite of the Arico formation (González de Vallejo et al., 2003, 2005). The most distinct tectonic feature of this strike direction connects a chain of cinder cones (Kröchert & Buchner, 2008; Fig. 2) that is terminated by Montaña Ifaro in the North (Fig. 27D) and by Montaña Roja (~948 ka; Kröchert & Buchner, 2008) in the South (Fig. 27E), and must be considered as a rift-associated main fault that formed contemporaneously with the chain of cinder cones. According to Brown et al. (2003), the ignimbrite of the Arico Formation has a depositional age of ~668 ka; for the reason that joint sets of extensional rift-associated faults are common in the ignimbrite layer, rift activity must have continued after the ignimbrite deposition. The

most prominent tectonic feature of this distinct fault system (Fig. 27B-E) cuts the young sediments of FBD2 (Fig. 28A) that were dated to ~10 ka (González de Vallejo et al., 2003, 2005); this suggests that the extensional tendency along the main rift fault continued during the Holocene and potentially continues to date in the study area. Due to the long lasting activity and the morphological properties of the faults that match the NNE-SSW strike direction, these faults can be interpreted as an extensional, rift-associated fault system. A single but intense seismic event proposed by González de Vallejo et al. (2003; 2005) that could have been responsible for the formation of these faults is implausible for the reasons mentioned.

Seismically induced ground effects

Faults and open cracks in the study area striking perpendicular (Fig. 27A, right) to the NNE-SSW rift-associated fault system, display further distinct tectonic features that are widely-spaced, open, erratic, and commonly branched (Figs. 29A, 30A). Faults of this strike direction do not occur in the ignimbrite and are restricted to the young sediments of FBD2.

González de Vallejo et al. (2003; 2005) interpreted the distinct morphological features in the FBD2 (Figs. 26A, 28, 29, 30) as sedimentary dykes that are caused by paleoliquefaction of water-saturated sandy deposits triggered by an intense Holocene paleoearthquake (M=6.8); likewise, single tubes in FBD2 (Fig. 26B) have been interpreted as paleoliquefaction features (seismites) by González de Vallejo et al. (2003; 2005), whereas the diagnostic sedimentological criteria for dewatering processes were not observed in the sandy deposits of the study area. Kröchert et al. (2008a) reinterpreted the sedimentary structures in question (in particular the tubes) using the general criteria diagnostic for rhizocretions and root tubules with respect to their orientation, size, branching system, and style of cementation and, thus, considered them, to be of biogenic origin (Kröchert et al., 2008a). However, Kröchert et al. (2008a) took into account that the "dykes" formed during a seismic event as open fractures subsequently occupied by plants. In contrast to the root tubules, the "dykes" do not display any sedimentological differences when compared to the surrounding FBD2, with the exception of a more intense degree of cementation.

In the FBD2, the open cracks are accompanied by straight and narrow thin tectonic features in many cases (Figs. 29, 30); these small faults are arranged in certain tectonic patterns that strongly resemble Riedel structures (Figs. 29, 30) displaying

synthetic and antithetic Riedel shear bands (e.g., Eisbacher, 1991). According to Katz et al. (2004), Riedel structures are networks of shear bands, commonly developed in zones of simple shear during the early stages of faulting that were first reported by Riedel (1929) in clay-cake experiments, and were realized to be a fundamental structure within shear-zones. Studies of macro-scale fault systems have associated these structures with strike-slip displacement that can be typically induced by earthquakes (e.g., Tchalenko, 1970; Katz et al., 2004). An earthquake shaking model of Hamamura & Ogawa (1993) for poorly-consolidated sediments produced tectonic patterns that are depicted in Fig. 30B; the earthquake wave produces synthetic (R) and antithetic (R') Riedel shear structures (Brothers et al., 1996) that are developed in the poorly consolidated sandy sediments of FBD2 (Fig. 30A).

Earthquake-induced gravitational sliding (e.g., Cinti et al., 2000; Salamon, 2004) is a further earthquake-related process in the FBD2 which produced open seismogenic cracks with vertical movements. As an actualistic example, seismogenic cracks produced by earthquake-induced gravitational sliding parallel to the shoreline formed during an intense earthquake (M=6.8) in wet beach sands of the Nicoya peninsula in Costa Rica in 1990. The open cracks depicted in Fig. 31 and 32B were filled and garbled by the following high tide a few hours after the earthquake. According to Cinti et al. (2000), Krinitzsky & Hynes (2002), and Salamon (2004), earthquake-induced gravitational sliding not only occurs in unconsolidated wet beach sands, but potentially forms in poorly-consolidated sediments of manifold inclined site. In the study area, the seismogenic cracks remained open after the earthquake, subsequently stabilized by cements and filled by fine-grained aeolian deposits (Fig. 32A). When the earthquake occurred, the sediments of FBD2 were out of tidal influence and must have been consolidated to a certain degree. As the sandy deposits have been at least poorly-consolidated and as the FBD2 do not exhibit any indications of liquefaction-induced dewatering structures (Kröchert et al., 2008b; Kröchert & Buchner, 2008), the possibility that the liquefaction-related process of lateral spreading was responsible for the formation of the open cracks in the FBD2 can be excluded.

In summary, the faults and open cracks striking perpendicular to the rift-associated fault system should be interpreted as earthquake-induced seismogenic ground effects for the following reasons: (1) The seismogenic features are restricted to the FBD2; (2) The occurrence of synthetic and antithetic Riedel structures; (3) The

indications of earthquake-induced gravitational sliding in the FBD2 comparable to gravitational sliding effects in unconsolidated beach deposits affected by an intense earthquake in Nicoya/Costa Rica. In agreement with the formation age of the FBD2 of $10,081 \pm 933$ a (González de Vallejo et al., 2003, 2005), the paleoearthquake must have occurred during the Holocene.

Fossil seismogenic cracks: rare features?

Earthquake-induced seismogenic dewatering effects are commonly preserved in the form of characteristic sediment structures (e.g., flame structures, destruction of the primary sediment structures, sand volcanoes) in fossil sediments (e.g., Obermeier et al., 2005). The occurrences of liquefaction-induced features are regarded as a primer for the analysis of paleoseismic shaking. However, water-saturated sediments that are covered by an impermeable layer are required for the generation of seismites (Montenat et al., 2007). According to Kröchert & Buchner (2008) and Kröchert et al. (2008a,b), at least the second precondition is not realized in the El Médano site leading to an absence of dewatering structures in the FBD2 (Kröchert & Buchner, 2008). The occurrence of the root tubules as well as of the "dykes" are restricted to an area in which the FBD2 are underlain by ignimbrite; they are not to be observed in regions where the FBD2 are superimposed on the porous deposits of the Montaña Roja cinder cone. The formation of the root tubules at the ignimbrite-FBD2 boundary leading to an occasional supply of groundwater in this area.

Seismically induced ground effects produced by gravitational sliding can be estimated to have a low preservation potential. Open cracks will be immediately refilled and erased by aeolian or tidal processes, depicted in the form of the nondurable open cracks in wet beach deposits of Nicoya/Costa Rica (Fig. 31, 32B). In the study area in southern Tenerife, the following environmental circumstances lead to the formation and subsequent preservation of the open seismic cracks: (1) at the time of the earthquake, the FBD2 have been at least poorly-consolidated; (2) they superimposed a thick layer of ignimbrite that is well-consolidated and functioned as a "vibrating table"; (3) the FBD2 have been out of the tidal influence; (4) ground water ascending from the ignimbrite-FBD2 boundary efficiently increases the degree of cementation and stabilized the rims of the open cracks; (5) plants, that occupied the cleavages, advanced the stability further on. Earthquake-induced fossil seismogenic
cracks are predominantly known from solid rocks (e.g., Jiang et al., 2002); reports of open seismogenic cracks produced by gravitational sliding in poorly-consolidated sediments and subsequently preserved are sparsely mentioned in the literature; they can be regarded as rare sedimentological phenomena.

Magnitude of the paleoearthquake

González de Vallejo et al. (2003, 2005) first proposed an intense paleoearthquake to be responsible for the generation of the paleoliquefaction structures in sandy sediments of FBD2, estimating the earthquake magnitude by evaluation of the paleoliquefaction intensity. Kröchert et al. (2008a) showed that the conspicuous sediment structures of the El Médano site are concretions that exhibit features incompatible with this interpretation. With respect to the sedimentary characteristics, the concretionary features are in general accordance with the properties of rhizocretions, discarding the possible relation of seismites originated by liquefaction in past with intense seismic activity. Hence, the estimation of the paleoearthquake magnitude of M=6.8 by González de Vallejo et al. (2005) appears misconceived. According to Carracedo & Valentine (2006) and Mezcua et al. (1992), paleoearthquakes with a magnitude of M=5.3 have been detected for the Canary Islands since seismic surveillance began. The geodynamic setting of Tenerife excludes high magnitude seismic activity (Carracedo & Valentine, 2006), which was occurrence has been alleged only on the basis of the apparent seismites by González de Vallejo et al. (2003, 2005).

Gravitational sliding in unconsolidated wet beach deposits of the peninsula of Nicoya/Costa Rica was produced during an intense earthquake with a magnitude of M=6.8 in 1990 (Fig. 31, 32B). Cinti et al. (2000) described intense seismogenic ground effects (gravitational sliding) caused by an earthquake of the magnitude M=5.7 in Umbria/Italy in the year 1997. In 2004, an earthquake at the northeastern Dead Sea of the magnitude M=5.2 produced seismically induced ground effects including gravitational sliding of poorly-consolidated sediments, slumps, and collapses of sea cliffs, as well as open seismogenic cracks within a distance tens of kilometres away from the epicentre (Salamon, 2004). An earthquake of this magnitude in the seismically active seafloor between the islands of Tenerife and Gran Canaria (Mezcua et al., 1992), with an epicentre approximately 30 km away from the El Médano site, would probably be sufficient to generate seismically induced

ground effects in the FBD2; the earthquake magnitude might have been less intense in the event of an epicentre more proximal to the study area.

Hazard potential of the volcanic activity in southern Tenerife?

Rift-associated faults in ignimbrite of the Arico formation (~668 ka) and young fossil beach deposits (~10 ka) of the El Médano area suggest that rift-associated extensional movements in the rocks of southern Tenerife are still ongoing. As these rift-associated faults are common in the ignimbrites, but rare in the young sediments of FBD2, rift activity in the El Médano site seems to have decreased since the formation of the associated chain of cinder cones ~948 ka ago. As formerly proposed (González de Vallejo et al., 2003, 2005), the formation of seismically induced ground effects in fossil beach deposits of the El Médano site require an intense paleoearthquake. However, a relatively moderate earthquake (~M=5) would be probably sufficient to generate these seismogenic ground effects; furthermore, a paleoearthquake offshore between the islands of Tenerife and Gran Canaria of a magnitude of about M=5.2 could have been responsible for the observed ground effects. Kröchert et al. (2008b) described an asymmetrical uplift of Tenerife that is the result of an intense regional uplift of the southern part of the island. The vertical movements in the South could have been caused by ascending magma; seismic activity or mass loss due to flank collapses are further possible reasons. The results underline that the southern part of Tenerife is latently endangered by volcanic activity; on the other hand, there are no indications speaking of currently increasing volcanic activity in this part of the island (Kröchert & Buchner, 2008; Kröchert et al., 2008a,b).

5.8 Conclusions

1. A chain of cinder cones terminated by Montaña Roja in the South and Montaña Ifaro in the North is linked with a prominent fault system in the El Médano area, which belongs to the southern rift zone; the formation age of Montaña Roja (~948 ka) marks the initial volcanic activity in this part of the southern rift zone. Open fractures in ignimbrites (~668 ka) and fossil beach deposits (~10 ka) of the El Médano area suggest that the rift-associated fault system has been seismically active in the aftermath and is probably still active.

2. Typical patterns of Riedel shear fractures and indications of gravitational sliding in fossil beach deposits (~10 ka) of the El Médano site provide evidence for a young paleoearthquake in this area; the patterns are comparable to ground effects of gravitational sliding in unconsolidated beach deposits affected by an intense earth quake (M=6.8) in the peninsula of Nicoya/Costa Rica (March 25, 1990).

3. For the paleoearthquake in the El Médano site, a moment magnitude of M=6.8 was previously proposed; the analyses of seismic induced ground effects of different earthquakes lead to the assumption that an earthquake of M=5.2 offshore or an even less intense earthquake with an epicentre more proximal to southern Tenerife is sufficient to produce the observed seismogenic open cracks.

4. The initially open seismogenic cracks and faults caused by gravitational sliding, as well as Riedel shear structures, probably provided fluid pathways and were consequently occupied by plants that formed the conspicuous rhizocretions in the fossil beach deposits of the El Médano site. The formation of the seismically induced ground effects as well as the exceptional preservation of the fossil seismogenic cracks is due to the specific environmental conditions in the study area and, hence, they can be indicated as rare and unusual fossil sediment structures.

6. Summary and Conclusions

Within the southern part of Tenerife, four volcanic cycles can be identified. Cycle 1 to 3 commenced with intense mafic flank eruptions and culminated in a series of explosive phonolitic volcanic eruptions. The mafic flank eruptions of Cycle 2 (Cycle 2 basalts) erupted between >948 ± 15 ka and 778.7 ± 1.9 ka. Eruptive activity of the Cycle 3 basalts occurred between 323 ± 6 ka and 300 ± 8 ka. The basaltic eruptions of the San Lorenzo lava field ~95 ka ago may define the start of a fourth volcanic cycle. The end of the cycles 1 to 3 can be defined by the occurrence of erosional unconformities, paleosoils, and longer periods without volcanic activity. The recurrence time between the cycles 1 to 3 lasted for about 180 ka, 250 ka, and 70 ka. Based on the analysis of marine deposits, Tenerife has undergone asymmetrical uplift. In the Anaga mountains, the position of the fossil beach deposits indicate stable conditions with a slight uplift since the last 130 ka. In the North of Tenerife, marine deposits are located up to 18.5 m ASL; this position can be induced by an uplift of ~10 m of this part of Tenerife, associated with the Orotava flank collapse, or can alternatively be explained as the result of an eustatic sea-level highstand ~400 ka ago. The uplift of the Costa del Silencio site ~300 ka ago coincides with the start of Cycle 3 and ascending magma was probably responsible for the concurrence of considerable uplift and volcanic activity during Cycle 3. Remarkable uplift of up to 45 m took place on the coast between El Médano and Punta Roja and may also indicate ascending magma in this part of the island during the last ~10 ka.

The fossil beach deposits of the El Médano site exhibit conspicuous sediment structures (concretionary tubes and dykes) that have been described as paleoliquefaction features caused by the interaction of hot ignimbrites with wet beach sands, or as the result of an intense paleoearthquake. However, characteristics of the tubular shaped concretions are in general accordance with the properties of rhizocreations, whereas the dykes are most likely the result of cementation along roots that occupied pre-existing open fractures and joints within the slightly cemented fossil beach deposits. Parts of the dykes show typical patterns of Riedel shear fractures and indications of gravitational sliding of the fossil beach deposits, comparable to ground effects in unconsolidated beach deposits of the peninsula of Nicoya/Costa Rica, induced by an earthquake (M=6.8) on March 25, 1990. Accordingly, these dykes provide evidence for a young (>10 ka) paleoearthquake

within the El Médano site. The analysis of seismically induced ground effects of different earthquakes lead to the assumption that an earthquake of M=5.2 offshore or an even less intense earthquake with an epicentre more proximal to southern Tenerife is sufficient to produce the observed seismogenic cracks and, hence, an earthquake with a moment magnitude of M=6.8, previously proposed in the literature, is probably overvalued.

Some of the open cracks do not exhibit Riedel shears and are commonly straight. These cracks also occur in the ignimbrite (~668 ka) but are much more frequent there. The strike direction of these open cracks coincides with the orientation of the chain of cinder cones terminated by Montaña Roja (~948 ka) in the South and Montaña Ifaro in the North, which is linked with a prominent fault system in the El Médano area, that belongs to the southern rift zone. This suggests that the rift-associated fault system has been seismically active in the aftermath of the formation of the cinder cones.

Volcanic hazard assessment

In comparison with the northeast and the northwest rift zone, the southern rift zone is characterised by a relatively weak volcanic activity, observable in the fan-like distribution of cinder cones and the absence of a distinct ridge. The youngest basaltic eruptions of the southern rift zone formed the San Lorenzo lava field ~95 ka ago and may define the start of a further long-lasting volcanic cycle; however, vertical movements, caused by magma loading in the southern part of Tenerife, are currently not observable. Rift-associated faults are common in the ignimbrite (~668 ka) of the El Médano site, but rare in the Holocene fossil beach deposits, indicating that the rift-associated extensional movements decreased in the study are since the formation of the chain of cinder cones ~948 ka ago. The results accentuate that the southern part of Tenerife is latently endangered by volcanic and seismic activity; however, there are no indications speaking for a currently increasing volcanic activity in this region.

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Appendix

Table 1: Results of the paleomagnetic measurements for each cone and associated lava flows. M.P.: magnetic polarity, +: normal polarity, -: reverse polarity, LM: low magnetic signal, N/A: no adequate material available.

Locality	Sample-1	Sample-2	Sample-3	Sample-4	Sample-5	Sample-6	Sample-7	Sample-8	M.P.
TF-4/Amarilla	+	+	+	+	+	+			+
TF-7.1/Malpasito1	+	+	+	+	+	+			+
TF-7.2/Malpasito	+	+	+	+	+	+			
TF-8.1/Chargo	+	+	+	+	+	+			+
TF-8.2/Chargo	+	+	+	+	+	+			
TF-9/Negra	+	+	+	+	+	+			+
TF-10/Majano	+	+	+	+	+	+			+
TF-11/Callao	-	-	-	-	-	-			-
TF-12/Ifaro	-	-	-	LM	-	LM	-	-	-
TF-13/NN	-	-	-	-	-	-			-
TF-17/Erales	+	+	+	+	+	+			+
TF-18/Chimbesque	-	-	-	-	-	-	-		-
TF-19/Lucena	+	+	+	+	+	+			+
TF-20/Estrella	+	+	+	+	+	+			+
TF-21/Casablanca	-	-	-	-	-	-	-		-
TF-22/Montanita	-	-	-	-	-	-			-
TF-23/Tabaibas	-	-	-	-	-	-			-
TF-24/Conde	+	+	+	+	+	+	+	+	+
TF-25/NN	+	+	+	+	+	+			+
TF-26/GordaGrande	+	+	+	+	+	+			+
TF-28/Laguneta	-	-	-	LM	-	-	-		-
TF-29/Cambada	+	+	+	+	+	+			+
TF-30/Buzanada	+	+	+	+	+	+			+
TF-31/NN	+	+	+	+	+	+			+
TF-32/VinaVieja	LM	LM	LM	LM	LM	LM			?
TF-33/Chinama	-	-	-	LM	LM	-	LM	-	-
TF-34/Gorda	+	+	+	+	+	+			+
TF-35/Garanana	+	+	+	+	+	+			+
TF-36/Tileta	LM	LM	-	LM	+	LM	LM		?
TF-37/Pozo	+	+	+	+	+	+			+
TF-38/Coto	+	+	+	+	+	+			+
TF-39/DonaCandida	+	+	+	+	+	+			+
TF-40/NN	+	+	+	+	+	+			+
TF-41/Listones	+	+	+	+	+	+			+
TF-42/Pinos	+	+	+	+	+	+			+
TF-43/Vica	-	-	-	+	-	-	-	-	-
TF-44/Funes	+	+	+	+	+	+			+
TF-45/Mesas	+	+	+	+	+	+			+
TF-46/Coloradas	-	-	-	-	-	-			-
TF-47/Roja	-	-	-	-	-	-			-
TF-48/Yaco	-	-	LM	LM	LM	-	-		-
TF-49/Acojea	LM	LM	LM	LM	LM	LM			?
TF-51/Chozas	+	+	LM	+	+	+			+
TF-52/Tea	+	+	+	+	+	+			+
TF-100/NN	+	+	+	+	+	LM			+
TF-101/Pelada	N/A								?

Sample	UTM-Coordinates (WGS84)	Polarity	Y/Nb	Zr/Nb
TF-4/Amarilla	3099631N/28339167E	N	0.31	3.83
TF-7.1/Malpasito1	3100424N/28339243E	Ν	0.31	3.89
TF-7.2/Malpasito2	3100930N/28339122E	Ν		
TF-8.1/Chargo	3101784N/28339781E	Ν	0.35	4.17
TF-8.2/Chargo	3101848N/28339746E	Ν	0.32	4.06
TF-9/Negra	3101323N/28339139E	Ν	0.31	3.85
TF-10/Majano	3101965N/28339564E	Ν		
TF-11/Callao	3107521N/28349389E	R	0.37	5.23
TF-12/Ifaro	3108275N/28349783E	R	0.40	4.56
TF-13/NN	3108853N/28349792E	R		
TF-17/Erales	3103005N/28339988E	Ν	0.27	3.50
TF-18/Chimbesque	3105512N/28341186E	R	0.39	3.93
TF-19/Lucena	3105895N/28341054E	Ν		
TF-20/Estrella	3105291N/28340923E	Ν	0.34	3.53
TF-21/Casablanca	3105832N/28345242E	R	0.41	4.35
TF-22/Montanita	3106482N/28345360E	R	0.41	4.45
TF-23/Tabaibas	3106695N/28345314E	R	0.39	4.39
TF-24/Conde	3105889N/28345834E	Ν	0.33	3.58
TF-25/NN	3100703N/28333485E	Ν		
TF-26/GordaGrande	3100131N/28333752E	Ν		
TF-28/Laguneta	3100490N/28334116E	R		
TF-29/Cambada	3106140N/28338455E	Ν		
TF-30/Buzanada	3105855N/28338316E	Ν	0.47	3.66
TF-31/NN	3105609N/28337416E	Ν		
TF-32/VinaVieja	3104627N/28342152E	?		
TF-33/Chinama	3109934N/28343101E	R		
TF-34/Gorda	3108543N/28344013E	Ν		
TF-35/Garanana	3108762N/28341601E	Ν		
TF-36/Tileta	3111472N/28340945E	?		
TF-37/Pozo	3113370N/28339108E	Ν		
TF-38/Coto	3115207N/28338612E	Ν		
TF-39/DonaCandida	3114317N/28337397E	Ν		
TF-40/NN	3114554N/28337076E	Ν		
TF-41/Listones	3114666N/28336272E	Ν		
TF-42/Pinos	3115154N/28336571E	Ν		
TF-43/Vica	3116005N/28336960E	Ι		
TF-44/Funes	3112318N/28336055E	Ν		
TF-45/Mesas	3115013N/28340697E	Ν		
TF-46/Coloradas	3114371N/28341470E	R		
TF-47/Roja	3101247N/28348249E	R	0.41	3.84
TF-48/Yaco	3107799N/28346504E	R		
TF-49/Acojea	3111293N/28345288E	?		
TF-51/Chozas	3111752N/28343973E	Ν		
TF-52/Tea	3112486N/28343864E	Ν		
TF-100/NN	3108473N/28342523E	Ν		
TF-101/Pelada	3104740N/28350552E	?		

Table 2: UTM-Coordinates, magnetization, and trace element ratios for the cinder cones in the study area. XRF-data are recalculated to anhydrous conditions.

Sample	⁴⁰ Ar%	⁴⁰ Ar 10 ⁻¹³ moles/g	Weighted mean 10 ⁻¹³ moles/g	K%	Age ka
TF-4/Amarilla	4.902	8.033	8.247	1.586	300±8
	5.306	8.444			
TF-47/Roja	9.628	2.730	2.731	1.660	948±15
	12.956	2.732			

Table 3: K/Ar radiometric age.

Table 4: Major and trace element data.

SiO2 42,84 44,28 47,14 47,33 44,27 49,78 43,44 46,62 41,48 41,38 42,05 42,86 43,54 40,34 41,58 40,37 Al2O3 15,1 15,49 16,56 16,6 15,52 16,38 14,94 16,15 12,08 13,75 14,8 15,07 15,37 13,06 12,89 13,38 MnO 0,21 0,21 0,21 0,22 0,21 0,19 0,18 0,19 0,2 0,21 0,19 0,19 0,2 0,21 0,19 0,19 0,2 0,21 0,19 0,19 0,2 0,21 0,21 0,19 0,19 0,2 0,21 0,21 0,19 0,19 0,2 0,21 0,21 0,19 0,19 0,2 MgO 5,57 4,71 4,33 4,52 4,65 3,04 5,62 3,92 8,65 5,74 5,83 5,36 4,62 7,53 8,94 7,58 CaO 9,49 9,18 8,48 8,76 9,04 6,81 9,7	50,41 20,07 0,16 1,25 4,43 7,18 3,2 1,28 0,4 5,37
Al ₂ O ₃ 15,1 15,49 16,56 16,6 15,52 16,38 14,94 16,15 12,08 13,75 14,8 15,07 15,37 13,06 12,89 13,38 MnO 0,21 0,21 0,2 0,19 0,21 0,22 0,21 0,19 0,18 0,19 0,2 0,21 0,19 0,19 0,2 MgO 5,57 4,71 4,37 4,52 4,65 3,04 5,62 3,92 8,65 5,74 5,83 5,36 4,62 7,53 8,94 7,58 CaO 9,49 9,18 8,48 8,76 9,04 6,81 9,7 8,33 12,16 11,25 9,86 9,47 9,34 12,28 12,13 11,47	20,07 0,16 1,25 4,43 7,18 3,2 1,28 0,4 5,37
MnO 0,21 0,21 0,21 0,22 0,21 0,19 0,18 0,19 0,2 0,21 0,19 0,19 0,2 MgO 5,57 4,71 4,37 4,52 4,65 3,04 5,62 3,92 8,65 5,74 5,83 5,36 4,62 7,53 8,94 7,58 CaO 9,49 9,18 8,48 8,76 9,04 6,81 9,7 8,33 12,16 11,25 9,86 9,47 9,34 12,28 12,13 11,47	0,16 1,25 4,43 7,18 3,2 1,28 0,4 5,37
MgO 5,57 4,71 4,37 4,52 4,65 3,04 5,62 3,92 8,65 5,74 5,83 5,36 4,62 7,53 8,94 7,58 CaO 9,49 9,18 8,48 8,76 9,04 6,81 9,7 8,33 12,16 11,25 9,86 9,47 9,34 12,28 12,13 11,47	1,25 4,43 7,18 3,2 1,28 0,4 5,37
CaO 9,49 9,18 8,48 8,76 9,04 6,81 9,7 8,33 12,16 11,25 9,86 9,47 9,34 12,28 12,13 11,47	4,43 7,18 3,2 1,28 0,4 5,37
	7,18 3,2 1,28 0,4 5,37
$Na_2U 3, 79 3, 73 4, 25 4, 24 3, 83 4, 62 3, 25 4, 8 2, 07 3, 97 3, 2 3, 42 3, 39 2, 78 3, 06 2, 65 3, 97 $	3,2 1,28 0,4 5.37
K ₂ O 1,7 1,78 1,97 1,89 1,83 2,21 1,59 2,35 1,11 2,04 1,57 1,76 1,9 1,6 1,45 1,35	1,28 0,4 5.37
TiO ₂ 3,3 3,36 3,1 3,13 3,4 2,03 3,89 2,94 3,24 4,3 4,11 4,05 3,55 4,1 3,81 3,76	0,4 5.37
$P_2 O_5 0.95 0.99 0.96 1.02 0.96 1.08 0.81 0.78 0.63 1.06 0.98 0.98 1.17 0.95 1.23 1.18 0.18$	5.37
Fe ₂ O ₃ 11,97 12,2 11,87 11,75 12,33 9,05 12,96 9,68 12,66 12,5 13,25 13,28 12,47 13,62 14,12 13,07	2,21
ppm	
V 167,22 171,88 195 190 188,99 62,23 251,94 187,13 270,12 308,21 249,66 238 208,47 315,93 321 257,42	24,4
Cr 70,68 25,98 18 18 3,7 3,15 19,14 10,84 447,56 69 2,23 0,89 158,57 268 138,15	4,6
Co 38,51 46,77 27 25 49,62 19,83 64,85 58,89 56,08 61,51 45 52,72 83,76 90,87 50 51,8	26,07
Ni 8 7 1,28 1,71 163,35 21,81 71,27 92 61,77	
Cu 37,38 30,56	
Zn 112,66 115,39 124 122 121,95 111,39 117,77 109,48 96,75 112,67 108,37 110,26 121,73 112,11 116 104,84	83,04
Ga 20,14 21,25 20 21 21,38 19,21 20,32 20,94 17,35 21,59 20,12 20,25 21,26 19,83 18 18,57	25,41
Ge 0,09 0,53 0,73 0,19 0,17 0,16 1,1 0,07 0,27	1,05
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Br 14,95 0,92 1,12 0,48 0,99 1,47 0,71 1,58 0,9 0,01 0,85 0,95 3,14	1,27
Rb 40,61 42,61 43 40 44,09 36,42 34,15 52,74 19,42 43,29 31,77 34,06 37,57 36,05 24 27,27	70,23
Sr 1035,94 976,7 992 1006 990,63 1369,24 925,2 986,61 782,98 1158,97 976,41 978,04 1064,3 1018,22 1124 1016,55	1674,48
Y 30,85 31,95 38 35 32,49 35,27 31,69 32,77 23,88 33,27 31,26 31,81 33,77 29,61 36 29,36	30,24
Zr 382 395,8 454 439 400,95 493,54 360,67 423,95 243,34 350,35 329,44 345,48 378,75 325,02 282 272,95	540,31
Nb 99,64 101,74 109 108 104,06 94,41 79,01 121,16 61,95 99,25 75,73 77,59 86,35 90,74 77 71,05	164,02
Mo 2,87 2,97 2,5 2,06 2,33 3,28 0,44 2,99 1,87 1,92 2,2 2,24 1,93	3,09
Ag 3,77 1,35 0,25 3,05 1,33 0,74 0,04	
Cd 0,33 0,02	
Sn 1,36 1,06 1,31 1,11 1,74 0,08 1 0,49 1,31 0,56	0,6
Sb 0,52 0,43 0,48 0,15	0,06
Te	
1 0,55 2,23	
Cs	0,92
Ba 481,5 521,3 554 571 535,2 981,9 546,6 872,7 360,26 621,1 462 476,7 519,4 540,4 526 431,2	481,55
La $01,42$ /8,00 32 40 84,58 97,55 /2,4 101,51 45,81 /2,01 56,20 54,16 69,94 58,42 54 65,45	94,25
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Na 03,13 03,55 00,95 87,08 58,03 07,48 43,55 74,5 02,99 00,07 70,02 09,04 00,94 Sm 15,40 8,54 6,90 10,20 14,02 7,70 6,21 19,76 7,17 8,01 12,01 13,06 15,54	10.22
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Ph 5 4 038 045 4	0.37
Bi 0.82 1.47 0.78 1.25 0.65 1.12 2.89 1.76 1.8 1.11 1.67 2.29 2.21	0.43
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U 5.13 4.85 3.9 3.93 3.08 4.9 2.33 5.44 4.35 5.74 5.31 3.35 2.58	16.62

Curriculum Vitae

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SCHULBILDUNG				
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	Abschluss: Fachgebundene Hochschulreife			
1990 - 1996	Theodor-Heuss-Realschule Kornwestheim			
	Abschluss: Mittlere Reife			