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RESEARCH ARTICLE

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The volcano-tectonic evolution of Concepción, Nicaragua

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Abstract We describe the evolution of Concepción volcano by integrating regional geology, eruptive activity, morphology, stratigraphy, petrology, structure and active deformation data. This Nicaraguan volcano is set close to the back limb of the northwest-trending Tertiary Rivas anticline, a regional structure that bounds the southwest side of Lake Nicaragua. Concepción rises 1,600 m above a 1-km-thick sequence of Quaternary lacustrine mudstones. There is no record of volcanism in the lake prior to Concepción. In addition, the only nearby volcano, Maderas volcano, has not deposited material on Concepción because of the trade winds. Thus, Concepción (and Maderas, too) can be considered as pristine volcanic environments, unaffected by other centres. A topographic rise forms an annulus 20 km in diameter around the cone. The rise is created by thrust-related folds at the western base, where the trade winds have accumulated a thick sequence of tephra, and by mud diapirs at the eastern base where only lake mudstones are present. Four magmatic-eruptive episodes exist in the stratigraphic record. The first begins with primitive low-alumina basalt and subsequently evolves to dacitic compositions. The following three episodes begin with high-alumina basalts and evolve only to silicic andesites. The occurrence of the high-alumina basalt after the first episode is indicative of crystal fractionation at lower crustal depths. The first episode may be associated with a compressive phase of volcano evolution. In this phase, the edifice load compresses substrata, allowing a longer magma residence time and differentiation in a shallow reservoir (possibly located at the density contrast between the lake sediments and the Tertiary flysch). During the next three episodes the weak sediments below the volcano started to rupture and yield under its increasing load, beginning a thrusting/diapiring phase of volcano evolution. Because of outward thrusting, vertical and horizontal stresses above the chamber were reduced, allowing magma to erupt more easily and to reach a lesser degree of evolution. If we consider the future evolution of Concepción, the differentiation in the shallow reservoir has probably generated a cumulitic complex, which eventually will start to deform and spread, beginning another, this time plutonic, spreading phase. This phase, which *may* be beginning now, could allow less evolved magmas to be erupted again. Four components influence the phases of volcano evolution: (1) the regional geology that is the boundary condition of the environment, (2) the substrata rheology that controls deformation, (3) the load of the volcanic edifice and (4) the magma, which provides the input of mass and energy. Our model of volcanic evolution suggests that Concepción is a complex geologic environment. The volcanic activity, tectonics and hazards can only be constrained through a complete knowledge of the many components of this environment.

Keywords Concepción Volcano · Lake Nicaragua · Gravitational spreading · Volcanic environment · Substrata deformation · Thrusting · Diapirism

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Introduction

Concepción is a clay-footed volcano; it is an almost-perfect steep cone built on a thick sequence of sediments beneath Lake Nicaragua. Concepción is a textbook example of gravity-related spreading at a volcano built directly on a weak layer that is almost as thick as the volcano is high. At other volcanoes where spreading has been studied, the weak layer is either very thin compared to the edifice size, like at Kilauea-Mauna Loa (Borgia 1994), or it has a brittle layer above the weak, one like at

Poás (Borgia et al. 1990) and Mombacho (van Wyk de Vries and Borgia 1996), or it is strongly heterogeneous in rheology, like at Etna (Borgia et al. 1992), or it has no weak layer, like at San Cristobal (van Wyk de Vries and Borgia 1996).

Borgia (1994) proposes that, by modifying the stress field of a volcano and its substratum, spreading may control not only the structural evolution of volcanoes, but also influence magmatic evolution and volcanic activity. Concepción is a good case study in this respect as well. Significant changes in the type of volcanic activity and chemistry of the erupted products have occurred, which seem to be related to subsequent stages of structural evolution of the volcanic apparatus (van Wyk de Vries 1993).

Based on a detailed stratigraphical, structural and petrological study of Concepción, we show how loading of the weak basement by the volcano has generated an actively growing deformation belt around it. In addition, we attempt to make a correlation between structural and magmatic evolution, drawing inferences on the future potential volcanic hazard in the area. We conclude that Concepción is not a ”simple” volcanic cone. It is a complex geologic environment characterised by interactions and feed-backs among the many active geologic processes.

Regional geology

Concepción volcano (Fig. 1) is part of the Central American Quaternary volcanic belt, which is located about 40 km southwest of the Tertiary volcanic range, following the axis of the Nicaraguan Depression (McBirney and Williams 1965) (Fig. 2). The southwest border of the depression, located 20 km to the southwest of Concepción (Weinberg 1992), is formed by the sedimentary rocks of the Pliocene Rivas Anticline.

Fig. 1 Photograph of Concepción from Lake Nicaragua looking east. Note the 200-m-high ridge rising in front of the volcano (*arrowed*), which is a thrust-related fold produced by volcanic spreading

The deepest known unit in the region is the Nicoya Complex, an ophiolite suite of the Jurassic-Cretaceous age (de Boer 1979). The Nicoya Complex is overlain by the flysch of the Rivas, Brito and Masachapa formations, of the Cretaceous to Miocene ages, which are deposited in the Nicaragua Trough (Weyl 1980; Seyfried et al. 1991). In the Pliocene the thrust fault-related Rivas Anticline grew within the flysch formations (Fig. 2), forming a piggyback basin (the Nicaraguan Depression) between this anticline and the Tertiary volcanic range (van Wyk de Vries 1993). From the Pliocene onward, erosion of the growing anticline provided sand, silt and clays for the Nicaraguan Depression. Finally, during the late Quaternary and Holocene, the axis of active volcanism jumped south-westwards from the Tertiary volcanic range, building the volcanoes of Zapatera, Concepción and Maderas within Lake Nicaragua (van Wyk de Vries 1993).

Based on published data (de Boer 1979; Cruden 1989; Seyfried et al. 1991; Weinberg 1992) and our fieldwork, we constructed a regional cross section (Fig. 2B), which suggests the following: (1) the flysch formations below Concepción Volcano dip at about 2° to the west; (2) a ~1-km-thick sequence of lake sediments infills the Nicaragua Lake Depression beneath Concepción; (3) the eroded eastern limb of the Pliocene Rivas anticline lies underneath the western edge of the island of Concepción; (4) the Rivas Anticline is not presently active and has no dynamic influence on Concepción; (5) a marked density and rheological contrast occurs within the stratigraphic sequence at about 2-km depth below Concepción, between the flysch formations and the lake sediments. This contrast may favour neutral buoyancy accumulation of magmatic intrusions (Ryan 1988).

Morphology

Concepción is a 14-km-diameter stratocone that rises about 1,600 m above Lake Nicaragua. It is connected via a small isthmus to Maderas volcano, which is 25 km to the southeast, and together they form the Island of Ometepe (Figs. 2A and 3A).

Due to the prevailing trade winds, tephra deposits dominate the western sector of the cone of Concepción, while lavas mainly occupy the eastern sector. At Moyogalpa, 8 km to the west of the crater, the tephra sequence is over 50-m-thick, while at Tierra Blanca, 10 km to the northwest, it is only about 20 m thick. On the coastal plain to the north and south of the crater the tephra sequence becomes negligible. No tephra horizon that can be correlated with an eruption from the summit crater is preserved over the whole eastern base of the volcano.

None of the dacitic tephra or lava layers that characterize the older part of the volcanic sequence are found on the cone, even where there are gullies deeper than 300 m. In fact, the visible upper part of the cone was built very recently, mostly between 1883 and 1977 (Simkin and Siebert 1995). In addition, vegetation on the cone (both on lavas and tephra) is scarce, and where forest is

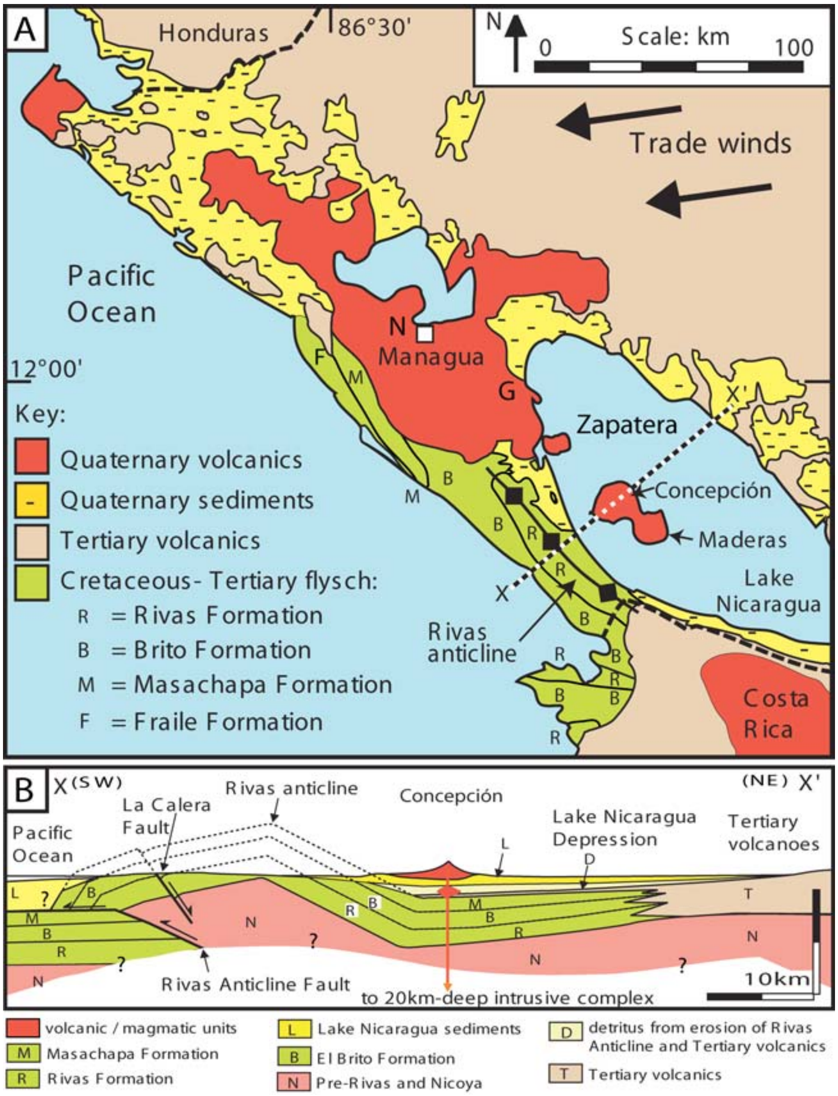

Fig. 2 A Schematic geological map of western Nicaragua, indicating the location of Concepción and Maderas volcanoes (X-X' is cross section in **B**). **B** Balanced retro-deformable cross section showing a possible reconstruction of the upper-crust structure in southwestern Nicaragua. Note the large Pliocene Rivas Anticline, which has formed the Lake Nicaragua depression to the east. Also note the location of a proposed intrusive complex at the density contrast between the Tertiary flysch formations and the Quaternary infill of the Nicaragua Depression

developed it is not the mature jungle found on the neighbouring Maderas volcano. Finally, the absence of faulting on the cone of Concepción is in striking contrast to all surrounding lowland areas and to the cone of Maderas, all of which are substantially faulted. Thus, the cone has a morphology essentially controlled by constructional processes (van Wyk de Vries et al. 2000).

A wide topographic rise forms an annulus 20 km in diameter around the cone of Concepción (Fig. 3). The rise is made of lake sediments blanketed by tephra. Deformed beds and raised beaches are common to the west and east. There is a trough between the rise and the cone that is partially filled in by lahars and lava flows. The rise is larger on the western and eastern sides; in contrast, to the north and the south there are two 3-km-wide stretches with no rise. On the north shore there are petroglyphs on ancient lava blocks that are now below water, suggesting perhaps a small amount of subsidence.

The topographic rise to the west is composed of a series of north-trending ridges (Fig. 4) that reach over 160 m above lake level. These ridges consistently have their steepest slopes facing away from the volcano. The most westerly escarpments intersect the lake on the north shore, but those inland swing to a more easterly direction in the north, converging to produce a marked 100-m-high single scarp. The western rise protects the coastal area from the descending lahars and lavas, which pond behind or are diverted to the north and south.

Volcanic activity

Concepción is a high-alumina basalt-dacite volcano that had many eruptions from 1883 to 1999 (Simkin and Siebert 1995; GVN 2000). Before 1883 there is only one questionable report of activity, even though Indian artefacts are found within the topmost layers of the tephra sequence, indicating substantial activity over the last few thousand years (Alta Gracia Museum, Ometepe). The historic activity up to 1977 was characterised by mild Strombolian or small Plinian eruptions of basalt to silicic andesite about every 10 years and silicic andesite lava

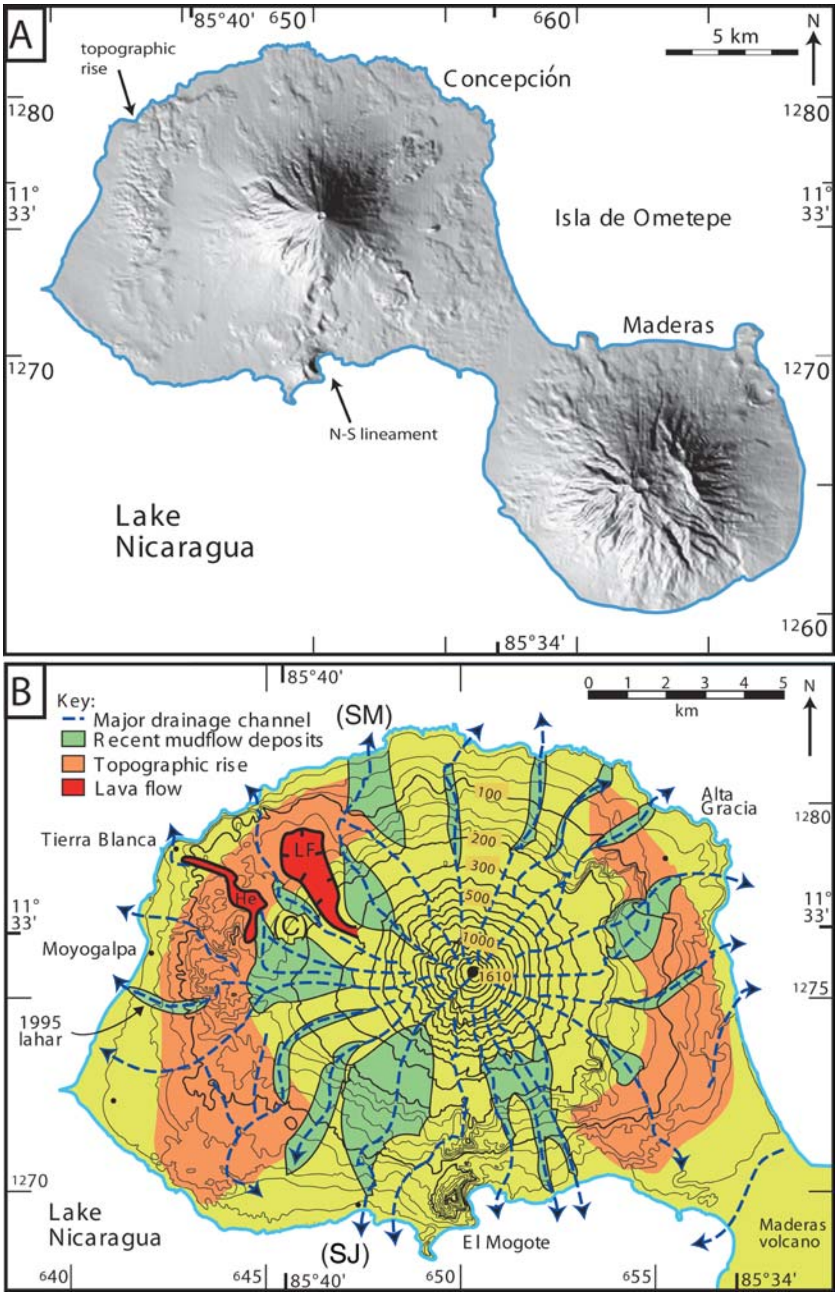

Fig. 3 **A** Digital elevation model of Ometepe Island, provided by Instituto Nicaragüense de Estudios Territoriales, showing the main morphologic features of the island, including the topographic rise. **B** Drainages (*dashed lines*) with corresponding mudflows that descended in the past decade from Concepción. Hills form two arches that surround the western and eastern base of the cone. The western ridge protects the coastal area from the descending lahars and lavas, which are diverted or pond behind it [see the La Flor lava flow (*LF*) that terminates behind the rise]. The only lava flow (*He*) to breach the western rise was erupted from a satellite vent at La Concepción village (see Fig. 4A); this lava can be mapped both downhill and uphill from the vent (located at the *e* of *He*), suggesting that the southern uphill part of the flow has been uplifted since its emplacement. Villages threatened by lahars at present are La Flor (*LF*), San Marcos (*SM*), Concepción (*C*) and San Juan del Sur (*SJ*)

flows about every 20 years. This activity has built most of the visible part of the cone. Since 1977, only minor ash eruptions and degassing episodes have been recorded, the latest being in December 1999 (GVN 2000).

The earliest volcanic activity is recorded in lake sediment strata as surge deposits and ash layers of basaltic and andesitic composition. Subsequent prehistoric activity is characterised by basaltic to dacitic Plinian, sub-Plinian and Strombolian eruption deposits and by lava flows and domes. Satellite vents have created a number of maars, pyroclastic cones and associated lava flows. These are concentrated close to the base of the volcano, particularly on a north-south trend through the cone.

Stratigraphy

The preliminary geological survey presented in this paper uses four main lithostratigraphic units as field-map units, namely lacustrine sediments, tephras, lavas and lahar deposits (Fig. 5). While it is possible to establish correlations within each of the units, the present data set allows only a preliminary correlation between units, because markers are few and unconformities not yet fully surveyed. Despite this inconvenience, the stratigraphy is already sufficiently well understood to define unambiguously the volcano-tectonic structures and the phases of volcanic evolution.

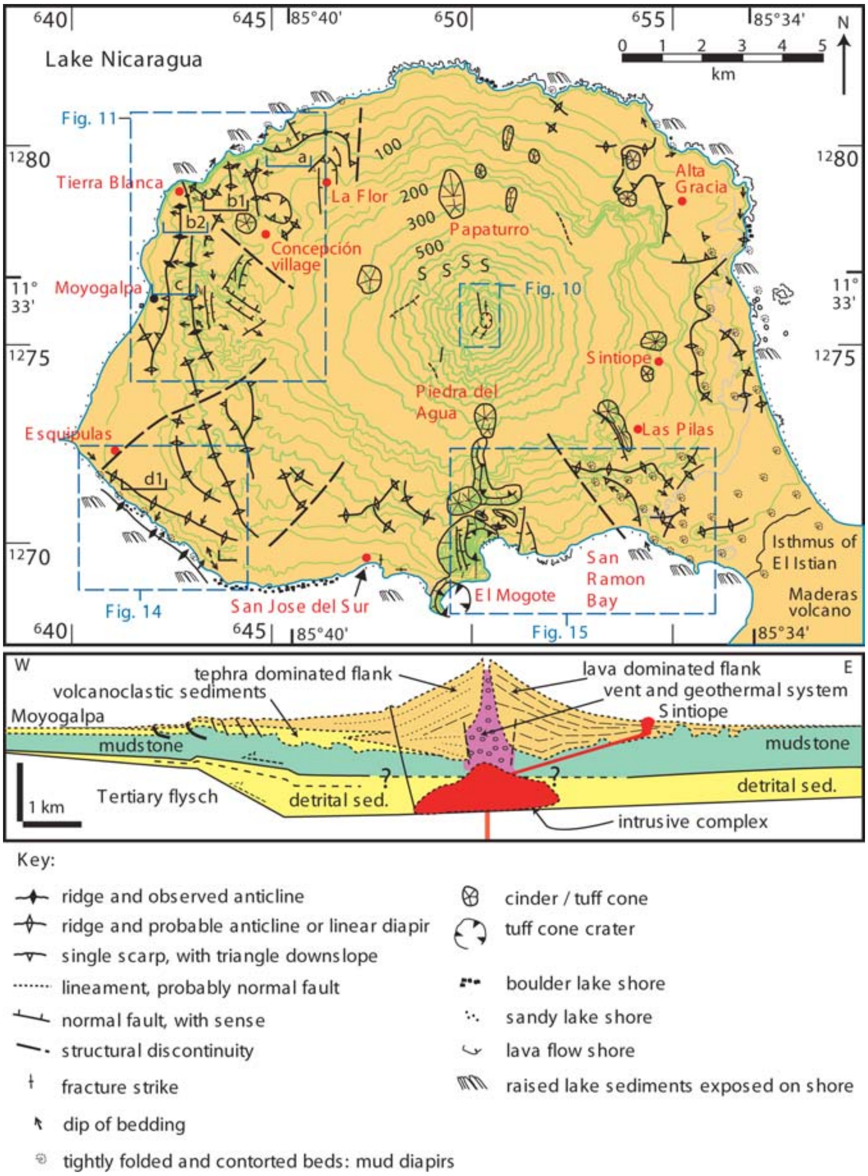

Fig. 4 Structural map of Concepción and east-west interpretative geological section through the summit. Contours are spaced every 20 and every 100 m below and above 200 m a.s.l., respectively. Location of villages and other sites mentioned in the text are shown. Note the compressional structures to the west, the mud diapirs to the east and southeast, and the north-trending zone of extension that cuts through the cone, which is the site of most parasitic vents. On the flanks of the cone we observed only one fault that cuts the edge of a gully in the southwest at about 800 m elevation, and strikes 010°. In the 1957 aerial photographs this fault is a low, sharply defined scarp, with apparent downthrow toward the crater, which has now been eroded into a major gully, a tributary to the southwest gully. Further downhill a similarly oriented gully has a discrete fracture zone cutting a lava flow. These fractures contain white alteration products, which are often associated with low temperature fumaroles. Other lineations have been mapped from aerial photographs, but have not been verified in the field. A distinct set of shoulders (*s*) characterise the radial ridges around the north side of the cone. These features were interpreted as a buried caldera edge related to the Tierra Blanca eruption (van Wyk de Vries 1986, 1993). However, field investigation indicates that the shoulders are the apex of lava fans. Thus, they are more probably related to differential erosion between the upper, more-erodible, scoria-dominated portion of the cone and the lower, less-erodible portion

Lacustrine sediments

The lower stratigraphic units outcropping on Concepción are the Pleistocene-Holocene finely-bedded sand- silt- and clay-stones of Lake Nicaragua. These sediments become more clay-rich towards the top part of the sequence. With the beginning of the volcanic activity, however, a significant fraction of fresh volcanic ash is mixed with the clays, particularly in the western stratigraphic sections, downwind of the volcano, and mudflows become interbedded with the lacustrine sequence. To the east of the volcano lava blocks are found within the mudstones where flows have disaggregated and sunk into the clayey sediment. A 5-m-thick surge deposit (Snowball

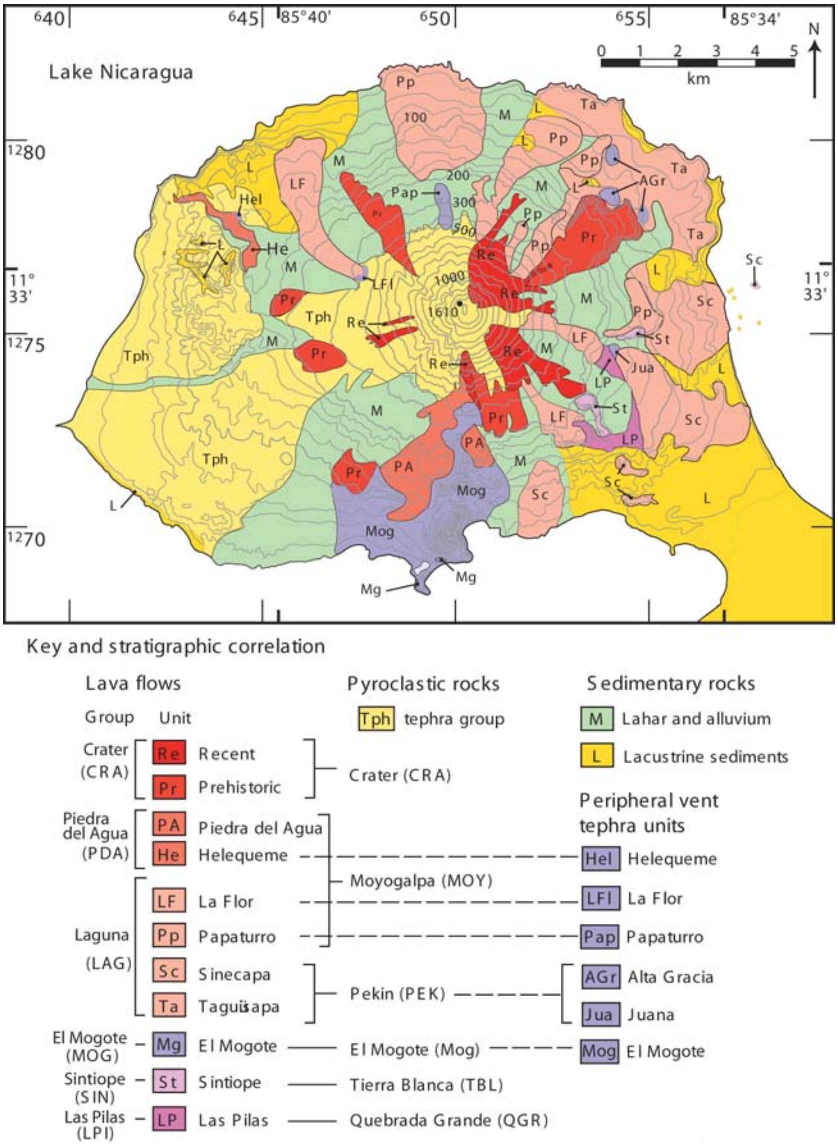

Fig. 5 Preliminary geologic map of Concepción, showing the main stratigraphic units and their correlation. Note that the western segment is covered mainly by tephra (the distinct tephra groups cannot be shown in map view, but are indicated in the key for correlation). The eastern side of the volcano is dominantly lava covered, with the exception of several lahar fans. Lacustrine sediments are found uplifted to 160 m above the lake level on the western and eastern sides

Surge, see Figs. 6, 11) is the deepest volcanic horizon found. It is followed upward by coarse volcanoclastic sandstones, which grade southwards and eastwards into laminated sands and silts; these are occasionally interbedded with basaltic tephras.

Pyroclastic deposits

The earliest record of volcanic activity is found on the northwest and southeast shores lying directly on mudstone sequences. The most distinctive deposit is a massive breccia, containing mudstone inclusions, often rounded and encased in concentric layers of ashy material, as in accretionary lapilli. Higher levels of the deposit become crossbedded. There are massive black, non-vesicular, aphyric lapilli and bombs with cauliflower or angular surfaces. Similar deposits are found in maars on the south shore of Concepción (El Mogote). From these features we interpret this deposit as a surge deposited on the lake bottom. We call this distinctive deposit the Snowball Surge because of the great balls at its base. Above the surge lacustrine sands are found, with thin scoria layers (the Quebrada Grande unit; Figs. 6, 7).

A sharp unconformity separates the lake sediments and the Quebrada Grande unit from the main overlying tephra sequence (the Tierra Blanca Sequence), which is most complete just east of Moyogalpa (Fig. 6C1). There, the lowest part of the sequence is characterised by scoria of basaltic-andesite composition separated by thick ash and soil horizons. A deposit similar to these ash horizons has built up from the small- to medium-sized eruptions over the last century. By analogy, we infer that the ash layers in the sequence record growth phases of the cone between major explosive events.

Further upward, the sequence becomes more silicic and lithic-rich, culminating in the climactic Tierra Blanca Plinian deposit, which is younger than 2720±60 years B.P.

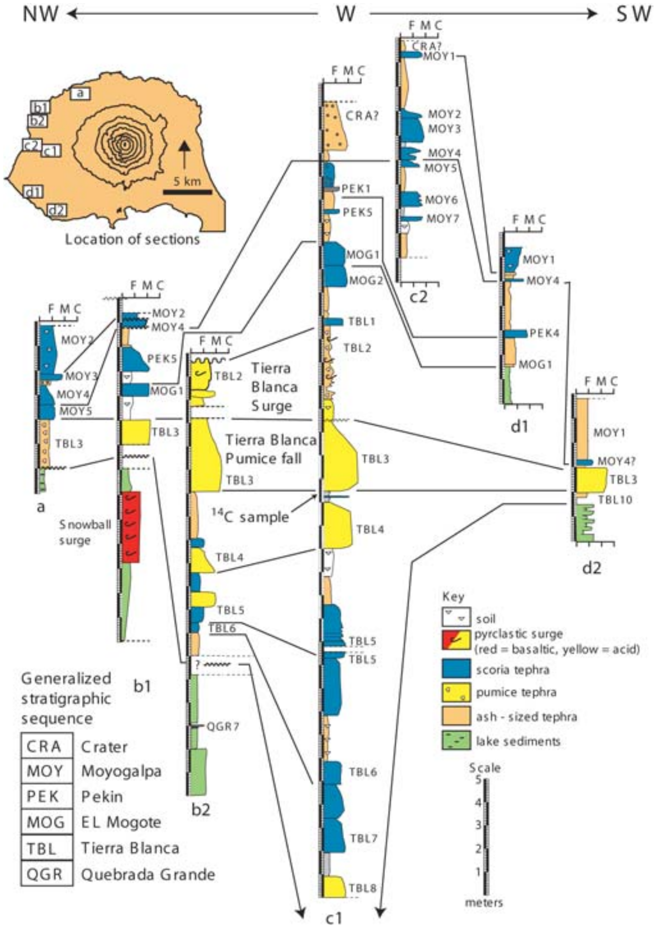

Fig. 6 Tephra stratigraphy of Concepción. Sections indicating thickness and correlations between layers. See *insert map* for locations and a general stratigraphic column is provided. Note the major unconformity below the Tierra Blanca layers, and the thick ash and soil horizons that could indicate cone construction periods. Observed tephra eruptions under normal trade wind conditions deposit relatively narrow falls from wind-controlled plumes (van Wyk de Vries 1986). For this reason, many deposits are found in only one of the sections. Only the largest eruptions, or the ones erupted during low winds are present throughout. The position of a leaf and wood sample from soil under the Tierra Blanca Pumice Fall is shown on section *c1*. This sample was dated at 2720±60 B.P. by standard radiocarbon dating procedures at Beta Analytic Inc., Florida (acid wash pretreatment, reduction of carbon to graphite, with standards and backgrounds, followed by ^{14}C measurement and calculation in an accelerator-mass-spectrometer). The numbering of each unit relates to its stratigraphic position within its parent group, as determined in the field

from radiocarbon dating of the soil below it (Fig. 6) and in the Tierra Blanca Surge deposit (Figs. 6, 7). Both layers, which are the thickest in the section, can be traced over most of the western part of the island. They may be correlated with dacitic lava flows and domes of similar composition and petrography found on the eastern side of Concepción (Fig. 5, Las Pilas and Sintiope units). The Tierra Blanca Pumice and some of the layers immediately below contain abundant amphibole and cognate xenoliths of gabbroic and granitic composition (which also contain amphibole).

A thick, high-alumina basaltic tephra follows the Tierra Blanca Surge. It can be correlated by stratigraphy and chemical composition with a major basaltic sequence that forms the parasitic maars and tuff rings of El Mogote (Figs. 6, 7) on the south side. El Mogote is in turn followed by the Pekin group, a sequence of basaltic to andesitic tephra layers, that correlate with the Tagüiasapa and Sinecapa lava flows (Figs. 5,7). Individual units tend to be compositionally, zoned with a range that becomes greater higher in the sequence. The Moyogalpa group follows the Pekin, with a series of banded scoria deposits, best exposed at Moyogalpa (Fig. 6C2). The Moyogalpa group is followed by ash layers, which thicken towards the cone, becoming scoriaceous. These interleave with the most recent lavas (Crater group; Figs. 5, 6). Parasitic centres of El Mogote, Alta Gracia, Helequeme and Papaturro have erupted high-alumina basalts and are correlated with the stratigraphy in Fig. 5. The most recent eruptions from the main crater range from 48 to 61 wt% SiO_2.

Lava flows

Apart from historic lava flows, the stratigraphy of the lavas is based wherever possible on superposition criteria. Many outcrops, however, may be correlated only using other qualitative and less accurate means, such as soil and vegetation cover, or the amount of tectonic deformation. Thus, it is not possible to detail the stratigraphic position of all the lavas down to the level of single eruption units. Taking into account this limitation, six major groups of lava flows may be distinguished.

The earliest group of lavas are exposed close to Las Pilas (Figs. 5, 7) and are basaltic to andesitic in composition. They form a suite of flows that are totally dismembered by post-emplacement deformation and are mostly found as blocks within contorted mudstones or rafts of more coherent lava surrounded by mudstone. Individual flows cannot be identified nor their place of eruption.

The second group is made up of a set of dacitic flows and domes that occur close to Sintiope (Figs. 5, 8). The Sintiope flows are dismembered in a similar way to those of Las Pilas, while the domes have conserved their plug-like morphology. We have separated them from the older sequence, as they can be correlated with the Tierra Blanca Pumice that has identical composition and petrography.

The lava flows from El Mogote form a single unit of basaltic composition (Figs. 5, 7). Unlike all the other lava groups, they maintain a very narrow compositional range. They were erupted from north-south trending parasitic vents at the southern base of the volcano. The tephra associated with these flows have similar composition.

The following group forms a set of flows that outcrop all around the western side of the cone descending into the lake (Laguna group on Figs. 5, 7). They are divided into four minor units, each in a different sector of the cone. On the north side of the volcano the Papaturro

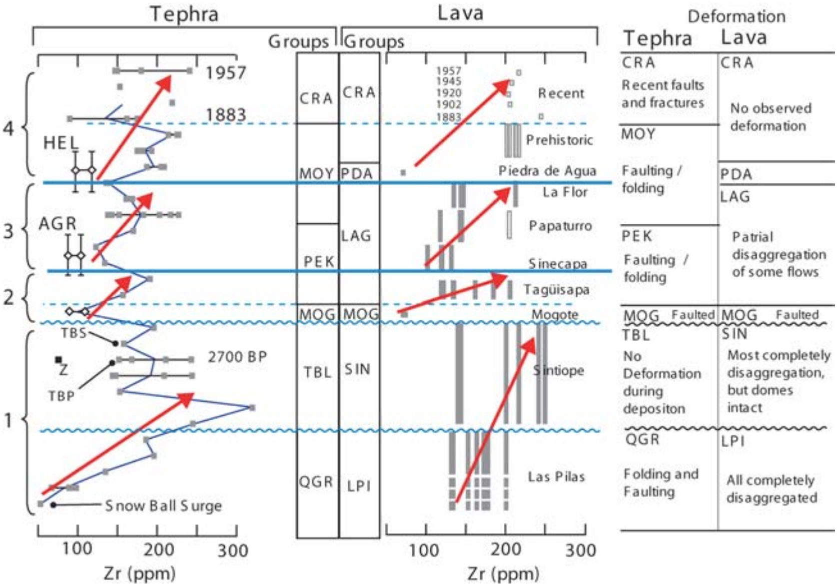

Fig. 7 Composite stratigraphy of Concepción showing the main stratigraphic units, Zr compositional variation in lavas and tephras, and deformation correlated with each unit. Note the four episodes that characterise the volcanic activity of Concepción. It appears that the recent eruptions form part of the end of the fourth episode

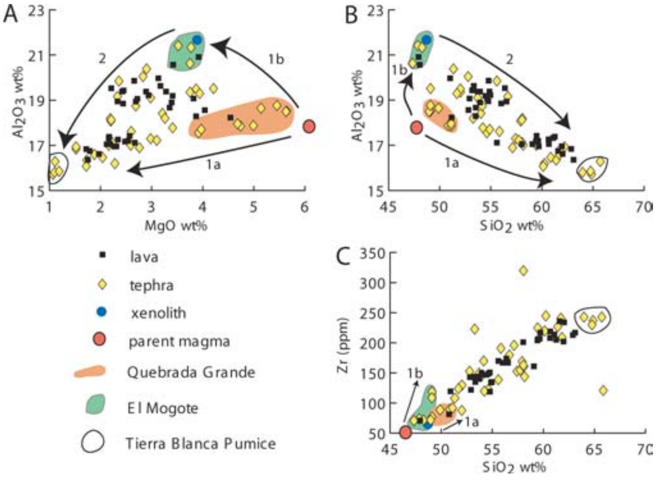

Fig. 8 Magma compositions at Concepción: **A** Al_2O_3 vs. MgO, **B** Al_2O_3 vs. SiO_2 and **C** Zr vs. SiO_2. *Shaded areas* indicate low-alumina, high-magnesium basalts from the early Quebrada Grande stage, the Tierra Blanca Pumice and the high-alumina basalts of El Mogote stage. *Arrows* indicate magma evolution pathways: *1a* low-pressure magma evolution from near-primitive, high-magnesium, low-alumina basalt for the first cycle; *1b* high-pressure magma evolution that forms the high-alumina basalt; *2* low-pressure trend from high-alumina basalt for the following episodes. All samples were prepared by the methods set out in van Wyk de Vries (1993) and were analysed on ARL 8420+ wavelength dispersive XRF at the Open University, UK

(Fig. 5) lavas were erupted from north trending fissures. The La Flor lava was erupted from the northwest base, but similar lavas are found to the sourthwest and are included in the La Flor unit. The Sinecapa group occupies the area to the south west of El Mogote, and the Tagüisapa group covers the area around Alta Gracia.

The Piedra del Agua group forms distinctive units of thick lavas erupted from the El Mogote lineament and the distinctive Helequeme lava, near La Concepción village. The lavas are high-alumina basalts, very similar in composition to the El Mogote unit.

Following the Piedra del Agua group a number of recent prehistoric and historic lava flows (the Crater group) were erupted from the main crater. These are divided into those erupted since 1883, and a prehistoric set (Fig. 5). All of these are silicic andesites, even though accompanying tephras range from andesite to basalt.

Lahars and alluvium

Most of the outcropping lahar deposits (Fig. 3) were emplaced during the past 100 years. Major damaging lahars were first recorded in 1957 (Ferrey and Williams 1971), and probably had not begun before the 1940s, when photos of the volcano show little erosion (Masaya Volcano Museum). Active mudflow fans follow the drainage throughout and tend to infill the moat around the cone to the west or collect around mudstone-cored hills elsewhere. Older mudflows attest to other major episodes of cone degradation. These are found particularly around the south, underlying the Piedra del Agua lava group, and lying against the Moyogalpa hills, underlying the Laguna lava group, but overlying the Tierra Blanca Pumice. No debris avalanche deposits, such as would indicate sector collapse events, have been observed.

Petrology

We analysed samples in thin sections and for major and trace elements from all major units (Table 1) and used additional data from van Wyk de Vries (1993). Phenocrysts are, in order of abundance: plagioclase, clinopyroxene, othopyroxene, olivine and magnetite. Amphibole

Table 1 Representative whole-rock analyses of lava and tephra from Concepción

Sample wt%	CL41	C2	C1b	C5a	C7a	CL30	CL27	C1b	GAB1
SiO_2	47.34	49.09	65.71	61.71	52.78	51.68	58.66	54.61	48.70
TiO_2	0.83	1.319	0.478	0.873	0.999	1.13	0.92	0.895	1.021
Al_2O_3	20.63	18.52	16.29	16.60	20.05	19.30	16.93	17.71	21.67
Fe_2O_3t	10.40	11.10	3.87	6.35	8.88	9.82	7.68	8.83	9.31
MnO	0.15	0.24	0.18	0.18	0.17	0.18	0.18	0.201	0.151
MgO	3.75	5.64	1.11	1.88	2.83	3.94	2.1	3.97	3.89
CaO	12.38	11.09	3.12	4.46	8.4	9.50	6.47	8.43	12.41
Na_2O	2.30	2.99	5.04	4.79	2.98	2.68	4.14	3.54	2.53
K_2O	0.58	0.64	2.60	2.54	1.46	1.00	1.73	1.33	0.57
P_2O_5	0.14	0.104	0.185	0.411	0.394	0.034	0.39	3.66	0.292
LOI	0.01	–0.1	1.99	0.25	1.71	0.44	0.7	0.18	–0.05
Total	98.51	100.65	100.58	100.06	100.68	100.00	99.91	100.34	100.53
Trace elements (ppm)									
Ni	13	16	4	3	7	13	8	13	11
Rb	12	31	51	58	32	23	32	26	13
Sr	681	783	425	463	616	644	537	611	730
Y	18	20	30	43	31	27	32	28	17
Zr	71	72	243	241	153	124	161	123	65
Description	Scoria from El Mogote (Mog)	Snowball surge	Tierra Blanca pumice (TBL3)	Recent tephra (1957 top)	Recent tephra (1957 base)	Alta Gracia bomb (Agr)	Piedra del Agua lava (PA)	Tephra (TBL 5)	Gabbro Xen. from TBL3

is present in the Tierra Blanca Surge, the Sintiope dacite domes and in gabbro xenoliths from the Tierra Blanca pumice fall. Megacrysts of anorthite are common from El Mogote and later units, except for the andesites (van Wyk de Vries 1993).

Primary magma brought to the base of the crust below Concepción is probably similar to basalts erupted 30–60 km to the northwest, at Zapatera and Managua (Fig. 2). This is a near-primitive low-alumina basalt with ~8% MgO, and ~16% Al_2O_3 (Walker 1984; van Wyk de Vries 1993). Despite occasional xenoliths of baked mudstone, $^{87}Sr/^{86}Sr$ isotope ratios are around 0.704 and $^{230}Th/^{232}Th$ ratios are 2.3–2.4, precluding even small amounts of crustal contamination (McDermott and Hawkesworth 1991).

The majority of Concepción's lavas and tephras are high-alumina basalts to high-alumina andesites (Fig. 8). Only during the earliest Quebrada Grande sequence were low-alumina, high-magnesium basalts erupted (e.g., Snowball Surge, Table 1). Only following the Quebrada Grande unit, during the Tierra Blanca period do compositions evolve to dacite (Fig. 7, Table 1). In fact, the low-alumina Quebrada Grande basalts are also richer in magnesium (MgO=4–6 wt%), and in olivine and clinopyroxene phenocrysts (but have no anorthite megacrysts) compared to the later high-alumina basalts (Al_2O_3<18 wt %) that have MgO<4 wt% and abundant anorthite megacrysts (Fig. 8, Table 1). Interestingly, the composition of amphibole-bearing gabbroic xenoliths found in the Tierra Blanca Pumice is also high-alumina basalt (Table 1). This indicates that such magma was forming in the system before the first high-alumina basalt eruption at El Mogote.

The Quebrada Grande low-alumina basalts can be modelled as the parental magmas of all other compositions (van Wyk de Vries 1993). Clearly, the distribution of erupted products on a MgO/Al_2O_3 plot is spread out, with compositions having different proportions of the three end members: (1) a low-alumina parent, (2) a high-alumina composition and (3) the most evolved rocks (Fig. 8A). This pattern is also observed on a Al_2O_3/SiO_2 plot (Fig. 8B), where the high MgO rocks have slightly higher SiO_2 contents than the alumina-enriched rocks. A plot of incompatible elements such as Zr/SiO_2 produces a straight trend, although above 60 wt % of SiO_2 there appears to be some Zr fractionation (Fig. 8C).

Two trends are evident in the data (Fig. 8). In the first trend, found in the early erupted products (Quebrada Grande to Tierra Blanca), magma evolves from high-magnesium, low-alumina basalt to dacite and has no alumina-enrichment. This trend is similar to that of other areas of Nicaragua, where fissures erupt small volumes of magma, which has fractionated in a reservoir at upper-crustal levels (Walker 1984; van Wyk de Vries 1993). In the second trend there is an early alumina enrichment of the most basic magmas, which presumably occurs at lower crustal levels as they plot above 8 kbar on the phase diagrams of Baker and Eggler (1983), Carr et al. (1982) and van Wyk de Vries (1993). This second trend begins with the high-alumina El Mogote basalts of the second episode and continues with all the products of the subsequent episodes.

In summary, the early ascent of magma reaches the surface directly, erupting low-alumina basalts and starting the growth of a lower-crustal and an upper-crustal magma reservoir. Subsequent magmas appear to reside significantly in the lower-crustal reservoir, where the near-primitive basalts are converted to the high-alumina basalts (Fig. 7, MOG, AGr and HEL) by pyroxene >olivine>plagioclase>magnetite crystal fractionation and redistribution (van Wyk de Vries 1993). The residence time of magma in the upper-crustal reservoir appears to

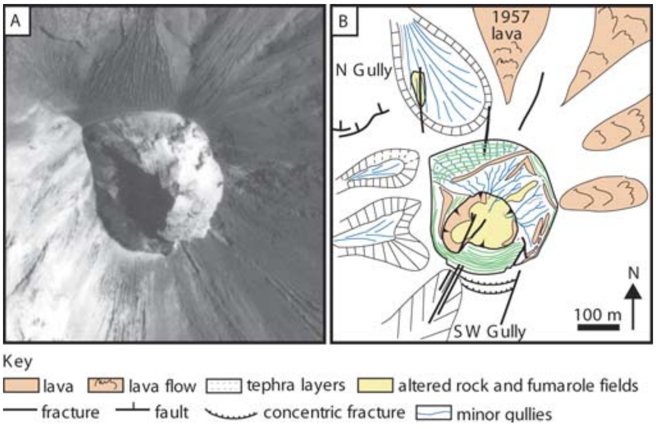

Fig. 9 Non-orthorectified aerial photograph (**A**) and map of the summit crater area of Concepción (**B**), showing recent fractures and fumaroles. The crater has narrow, deep fractures that cut its northern and southern rim. The southern fractures strike about 30° and extend into the southwest gully, which is remarkably deep (400 m). The northern fractures strike due north, and about 50 m below the summit, form the site of low temperature fumaroles that are visibly more active during eruptive episodes (GVN 1986). There are a few tangential faults on the southeast side downthrowing toward the summit. In the crater walls we did not observe faulting (GVN 1993)

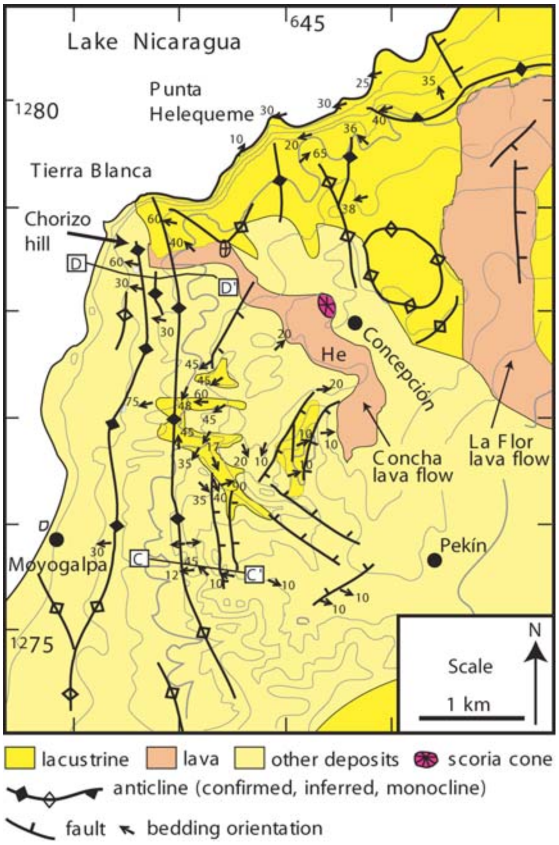

Fig. 10 Geological and structural map of the western province (see Fig. 4 for location). Sections *D-D'* and *C-C'* are shown in Fig. 11 and Fig. 12, respectively. The western side of Concepción is characterised by ridges produced by anticlines that verge westwards. In some areas strata dips have strong divergence from the main trend. A few times fold axes become radial to the cone, thrust faults strike east and beds are not homogeneously oriented (NE sector). These structures are clear in the older sedimentary sequence, and are not found in the layers above the unconformity that exists after the Quebrada Grande tephra (Fig. 6). These features indicate an early deformation phase that is more complex and that suggests some component of diapiric tectonics

decrease after the Tierra Blanca eruptions, since magma never again reaches a dacitic composition.

As discussed above, because of the sharp density and rheological contrasts, the deep reservoir should form an intrusive complex at the base of the crust and differentiate magmas with a high pressure assemblage (Carr et al. 1982). In addition, the shallow reservoir would form an intrusive complex at the density contrast between the Tertiary flysh and the overlying detrital and lake sediments (Fig. 2A). This position would have been about 1 km below the surface at the onset of volcanism, and 2–2.5 km after the volcanic edifice had developed. Such a depth is feasible in view of evidence from eroded volcanic areas: basic to acidic intrusions are found at shallow levels in volcanic complexes in the Tertiary of Nicaragua (Ehrenborg 1996; McBirney and Williams 1965), and in other areas such as NW Scotland (Skye, Mull and Ardnamurchan: Richey 1961), Namibia (Messum crater: Korn and Martin 1954) and the USA (Bearpaw Mountain: Reeves 1925; SW Utah: Merle et al. 1993).

Four episodes of magma evolution become evident once the data is set in stratigraphic order (Fig. 7). In all episodes, there is a progression to more evolved compositions, as indicated by the increase in Zr content of the volcanic products. In addition, though, toward the end of each episode, the erupted products are generally characterised by a wider range of compositions. These episodes are clearly evident in the tephra sequence and less clearly in the lava groups, probably because lava stratigraphy is not known with equal accuracy.

The first episode is of unknown duration, extending from the first eruptions, such as the Snowball Surge, up to the Tierra Blanca Pumice. The time was long enough for both a deep chamber to develop, produce high-alumina basalt as well as to allow the shallow differentiation of basalts to dacites. The three following episodes are marked initially by eruption of high-alumina basalts, recorded mainly at the base of the cone and then magmas ranging from basalt to silicic-andesite (60% SiO_2). Taking the ^{14}C date below the Tierra Blanca Pumice into account (Fig. 6), these latter episodes occurred in about 2,500 years. This period is similar to the time scales recently proposed for fractional crystallisation of a basic-intermediate magma in a shallow magma chamber (Hawkesworth et al. 2000) and for source to surface transport times gained from ^{226}Ra-^{230}Th sytematics (Turner et al. 2001).

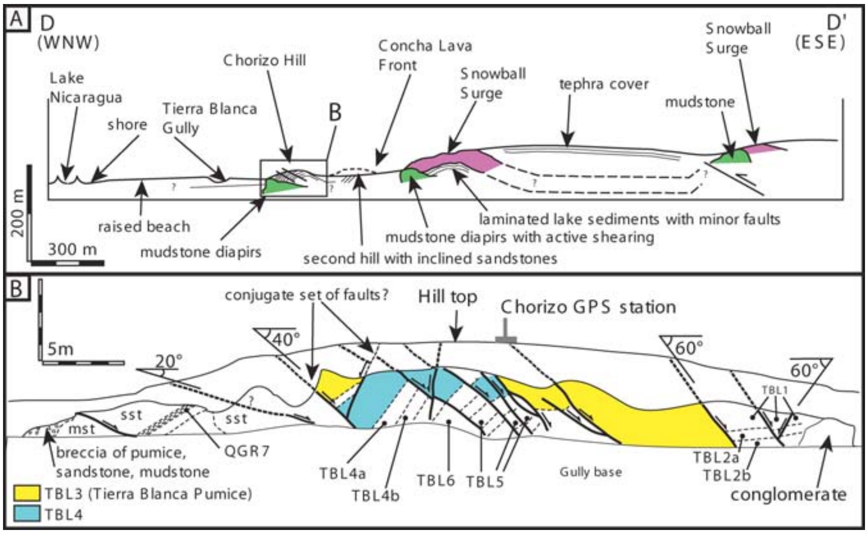

Fig. 11 Structural section at Tierra Blanca. **A** Section from Lake Nicaragua 2 km inland (D-D' in Fig. 10, sequence b2 in Fig. 6). The land rises gently over a raised beach to a set of low anticlinal ridges (Chorizo hill), then there is a flat area before the main scarp. At the base of the scarp, fissured, chaotic mudstone bulges into the gully and is in contact with soil and alluvium. Many of the fissure surfaces of the mudstones glisten with striations, indicating recent deformation. On the scarp immediately above the mudstone is the Snowball Surge. This forms the bulk of the scarp, which intersects the lake 2 km to the north of the Tierra Blanca section. Beneath the Snowball Surge, sandstones and mudstones generally dip at 20–30° west and southwest. They are cut by many small thrusts, normal faults and irregular folds. **B** Detail of complex structure at Chorizo hill. At the base of the hill a chaotic breccia is exposed, made of pumice, sandstone and mudstone fragments embedded in clay. An irregular west-sloping contact separates this from unbedded fissured mudstone, which intrudes through 45° westerly dipping sandstone and scoria layers. A steeply dipping tephra sequence sits on top of the sediments. This sequence dips at 40–60° W and is cut by three sets of normal faults. The order and dip progression of the faults suggest that the first generation has been rotated with the bedding by about 50°, while the second (a conjugate set) was rotated by only 30°

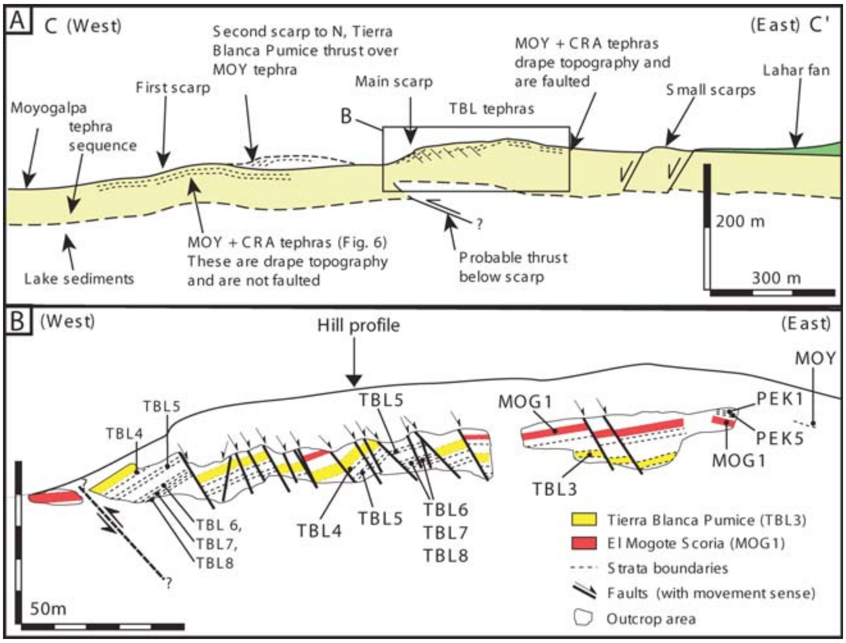

Fig. 12 Structural section of the Moyogalpa Hills (the hills seen in Fig. 1). **A** General section from Moyogalpa eastward (C-C' in Fig. 10). Just east of Moyogalpa, there is a slight rise, where the uppermost Moyogalpa and Crater units are exposed, dipping at 10–20° to the west, without faulting or fractures. These beds drape the existing uplifted and eroded topography. In contrast, 500 m along strike to the north, the lower Tierra Blanca Pumice is thrust over tephra of the younger Moyogalpa sequence. **B** Detail through the main escarpment. The Tierra Blanca Pumice sequence is well exposed, dipping at up to 45° W. It is cut by many east-dipping normal faults, spaced 3–10 m apart. Eastwards, this bedding flattens out with a corresponding decrease in faulting and finally it dips at 10° toward the volcano. Here, the Moyogalpa and Crater sequences crop out again on two west-dipping fault scarps

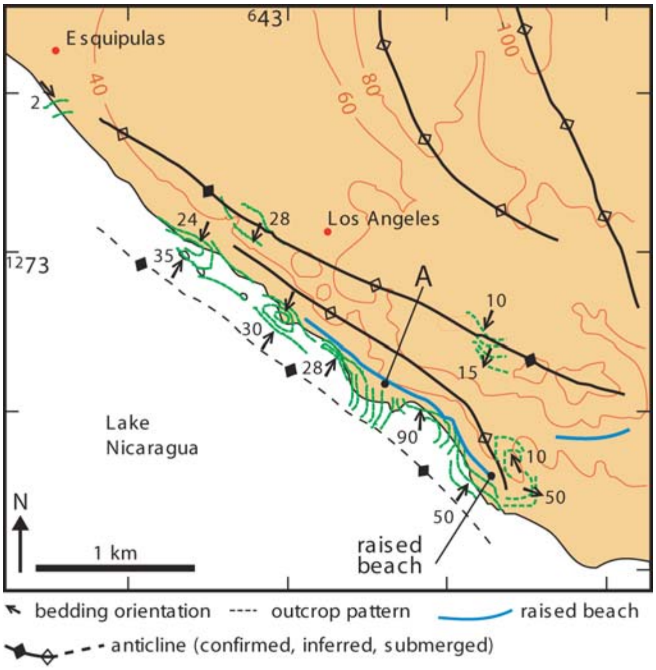

Fig. 13 Structural map of southwest Concepción shore and interior, showing the location of four low ridges, which rise gently toward the volcano (see Fig. 5 for location). The topographic relief of the ridges is less pronounced than in the west (see Fig. 3) with the highest summits a little less than 100 m above the lake. Exposure is best along the coast, where alternating sand-, silt- and claystones form elongate domes, with strikes that average northwest. Dips vary from 0° to 90°, mostly clustering around 30° to 40°, and dome elongation is 300 to 500 m. Other ridges inland appear to be produced by similar structures. A raised beach (a terrace) stands along the central portion of the coastal reach, attaining about 2 m above the highest lake level. A small stone-and-concrete water container, of the type found along the lake shore, is stranded on this terrace, suggesting recent uplift (A)

Structure

We made a detailed mapping survey that led to the maps and sections shown in Figs. 9, 10, 11, 12, 13, 14. In areas of good outcrop, we were able to define a direct relationship between surface morphology and structure. We use this relationship to give a structural interpretation to morphological features in areas where outcrop is limited and where the structure is not dissected by erosion.

In general, the structures on Concepción show a distinct pattern of outward thrusting at the western side of the volcano and diapiric rise at the eastern side. There is a zone of subsidence and extension in between that compensates the deformation of the two sides. The different structural styles of the two sides correlate directly with the different substrata compositions: the lake sediments in the west having a higher percentage of sand relative to those in the east. Also, the back limb of the Rivas Anticline may tend to block the westward propagation of the thrusts, forcing them to break upwards to the surface (Figs. 2B, 4). In contrast there is no such barrier in the east and the diapiric deformation of the substrata may spread outwards over a much longer distance.

In view of the large amount of deformation seen around the base, the cone of Concepción has remarkably few outcropping structural features. The crater (Fig. 9) has narrow, deep fractures that, striking roughly north, cut both northern and southern rims. These fractures could perhaps continue in the vents associated with the El Mogote and Papaturro eruptive centers (Fig. 4), which are northerly-aligned, indicating some structural control on their eruption location.

Below 300 m, structures become more common (Fig. 4). The western side of Concepción is characterised by ridges that mimic anticlines verging westwards (Fig. 10). The Tierra Blanca section (Fig. 11; trace D-D' in Fig. 10) and the Moyogalpa section (Fig. 12; trace C-C' in Fig. 10) show a correlation between the dips of these anticlines and the topographic slope. In addition, the frontal base of the folds is often occupied by convoluted, folded mudstone that probably masks a dêcollement. Significant extensional deformation indicated by closely spaced normal faults downthrowing to the east is superimposed on the anticlines. The faults close to western edge of the folds tend to be less steeply dipping, and may have been rotated (Fig. 11). The close spacing of the faults and the possibility that they are cogenetic with the steeply dipping strata indicate that, as at Tierra Blanca, they pass into a ductile layer a few tens of meters below the tephra outcrop (i.e., clayey lake sediments). The geometry of the structures is critically influenced by the presence of relatively thick layers that show viscous deformation, thus it is not possible to accurately reconstruct a balanced cross section following standard rules.

An inspection of dips in Fig. 10 indicates that they frequently diverge from the main radial trend. A few times fold axes become radial to the cone, thrust faults strike east and beds become variably oriented (Fig. 10, NE sector). These structures are evident in the older sedimentary sequence, and are not found in the layers above the unconformity that exists after the Quebrada Grande unit (Fig. 6). Therefore, they indicate an early deformation that is more complex than that observed in the later products, suggesting some early component of diapiric tectonics.

The southwest area of Concepción is characterised by four low ridges, which rise gently toward the volcano (Fig. 13). Along the coastal ridge, alternating sand-, silt- and claystones form elongate domes, up to 500 m long, that strike northwest. The south part of the island (Fig. 14) is characterised by tuff rings, normal north-oriented faulting and drowned shorelines. Further east, diapiric uplift becomes evident again with a long lake terrace uplifted more than 20 m above the shore. The pattern of diapiric rise of mudstones covered by isolated rafts of dismembered lava flows continues around the east side of the island up to the north. The youngest lavas, even if they are not obviously deformed, have begun to sink into the lake sediments.

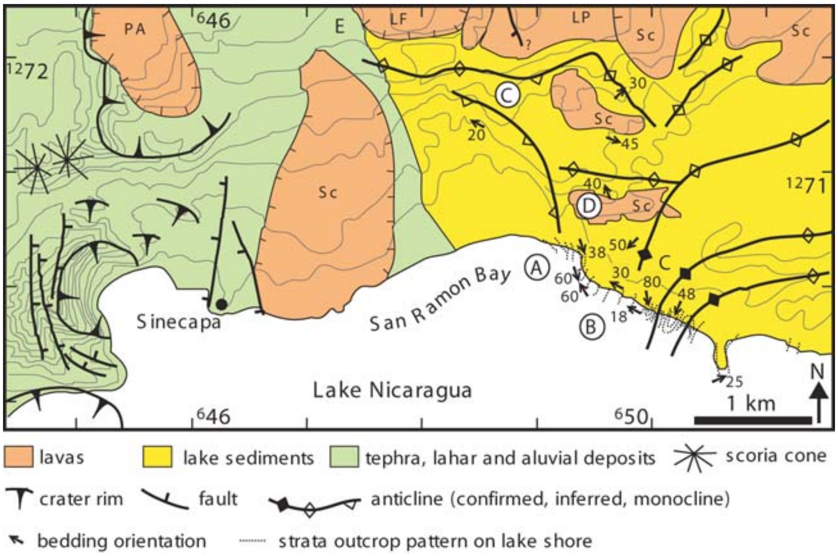

Fig. 14 Structural map of southeast Concepción, showing the north-trending normal faults, El Mogote tuff rings, drowned shorelines where lavas have entered the lake, mudstone ridges, and lava rafts (see Fig. 4 for location). At the eastern end of the San Ramon bay, there is a raised lake terrace, and unconsolidated massive mudstones crop out at the shore (**A**). Similar mudstones are found just a few metres offshore, directly underneath the soft lake bottom, suggesting that the outcrops may be the same, recently uplifted, deposits. Further eastward, a lake terrace rises to 20 m above lake level, creating cliffs of laminated mudstone and occasional volcanoclastic material. They are highly contorted, with occasional stretches of gently inclined, but otherwise undeformed beds. Dips are generally toward or away from the volcano. A 3-m-thick massive bed of layered ash and small bombs (**B**) is correlated with the Snowball Surge deposits found northwest of Concepción (Fig. 11A). This terrace rises gently inland (**C**), becoming steeper and merging with another east-west trending scarp. Rootless rafts of lava up to 1 km across have slid down the scarp (**D**). Within the mudstones of the ridges found at higher elevation there are blocks of lavas of different compositions, which presumably originated by dismembering and sinking of lava flows into soft sediments

The north-trending normal faulting on the volcano is perhaps also influenced by the present regional east-west direction of extension. In fact, van Wyk de Vries and Merle (1996, 1998) show that under extensional or strike-slip regimes, spreading structures will tend to align themselves along regional trends. Accordingly, the extensional zone is also a source of voluminous eruptive activity, with the Mogote, Piedra del Agua and Papaturro eruptive centers (Fig. 4).

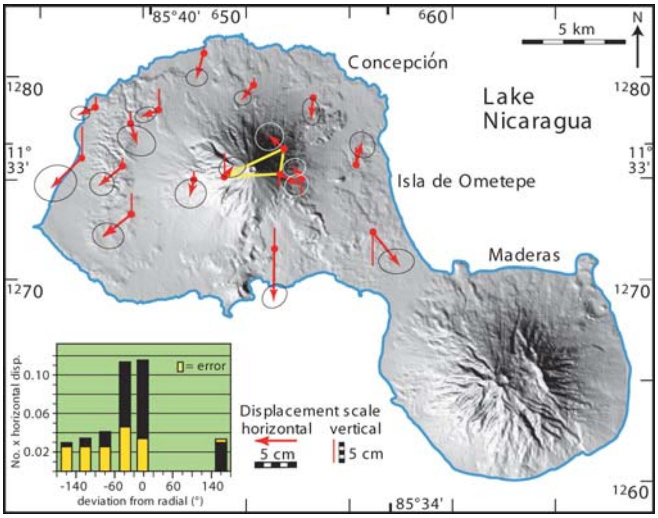

Fig. 15 Results of the GPS survey displayed on the digital elevation model of Ometepe to show the main morphologic features. Displacements cover a 2.5-year period (November 1994–May 1997). *Inset* shows cumulative frequency plot of the radial variance of GPS data. The three central stations used for averaging are shown joined by a *triangle*

Deformation monitoring

A GPS network on Concepción was surveyed in November 1994 and again in May 1997, giving a 2.5-year interval. The 20 stations are spaced between 2 and 5 km apart and are placed around the base and half-way up the cone (Fig. 15). Surveys were carried out with Leica 299 dual-frequency GPS receivers and processed with the SKI software. The surveys use a central station to measure the displacement of all other points. In addition, many other lines were surveyed to increase the robustness of the network. Due to the short baselines and limited time available compared with the large number of lines to measure, Rapid Static Techniques were used, rather than Static, for baselines shorter than 10 km. This generally gives detection limits of less than 1.5 cm over 5 km (Leica 1993), while setting-up errors amount to less than 0.5 mm. Atmospheric effects, such as the passage of large thunderstorms that cause strong perturbations in the measurements, were reduced by multiple occupations and discarding measurements where these effects were obviously relevant. Humidity caused problems with the receivers, and measurements taken with excessive humidity were also discarded.

Accuracy and consistency was tested by re-surveying lines several times on the same, as well on different days. This produced horizontal differences of less than 1.5 cm (1.1 cm average) and vertical differences of less than 7.9 cm (3.7 cm average). Also, co-ordinate differences of one single station were checked around a triangle or circle. For ten triangles of about 15 km, maximum horizontal differences were 2.5 cm (1.3 cm average) and maximum height differences 6.7 cm (3.3 cm average). The 30 km loop around the cone was closed with 2.1 cm horizontal difference for the first survey and 3.1 cm for the second. Error ellipses are shown in Fig. 15.

Results of the GPS surveys are calculated relative to the average of the displacement of the three stations on the cone of Concepción (Fig. 15). In fact, the geology shows that the cone does not move horizontally relative to the substrata, because, if it moved, there would be a trail of older craters (and cones) in the opposite direction to the displacement, as seen in many Indonesian volcanoes (van Bemmelen 1949).

The maximum horizontal movement of a station is 5.5 cm, but most are less than 2 cm, which is close to, or within, the error ellipses (Fig. 15). As a first-order approximation, these motions are roughly radial to, and away from, the cone, with larger relative displacement at the base of the western slope of Concepción. The stations to the north and northeast of Concepción do not fit this, but they are barely larger than their error ellipses.

With a data set so close to detection limits we decided to test its validity by investigating the data pattern. We expected a radial distribution of movement because of spreading. We took the angular difference between the azimuth of each survey station relative to the summit crater and the displacement vector. Thus, we normalised to the vector magnitude. The resulting cumulative frequency plot is shown in the inset in Fig. 15. It shows that there is a significant component of non-radial motion. This is because the stations on the western side all have a general and significant displacement to the southwest. Non-radial displacement, resulting from eccentric strike-slip faulting, frequently accommodates the general radial motion of brittle materials, as observed at Etna (Borgia et al. 2000a) and on lava domes (Fink and Griffiths 1998). This displacement is perpendicular to the ridge that parallels the coast on the southwest side (Fig. 15), showing that, as observed from the morphology, thrusting and uplift in this area is still active. The southeastern side also shows active radial displacements. On the other hand, the eastern side of the cone has one large downward motion, possibly related to the lava flow sliding off and sinking into a mud diapir. Another station has upward motion and is sited on the top of a major diapir.

Evolution of the Concepción Volcanic environment

A general concept emerges from the study of spreading volcanoes: coupling and feedback between multiple processes are crucial in determining their life cycle. Processes that may be coupled through the rheology of rocks include regional and local strain evolution, intrusion, differentiation, cooling and eruption. The interaction between these processes becomes particularly evident on Concepción volcano.

Concepción was born on sedimentary strata, away from previous Tertiary volcanic rocks, thus making it an ideal setting for studying the evolution of a pristine volcanic environment. Borgia (1994) proposed that volcanoes tend to have a “life cycle” that begins with an early growth phase. This growth is characterised by the eruption of primitive magma during the initial cone construction. The construction leads to loading and flexure of the substratum, compression in the volcanic edifice, magma accumulation within the crust and explosive eruptions of more differentiated products. At some point in this phase, the mass of the volcano increases enough to cause the substratum to yield and the volcano begins to spread, becoming characterised by extension in the cone and thrusting at the base, accompanied by the renewed eruption of less differentiated products.

Concepción, having such clear evidence of spreading in a reasonably simple geological environment, appears to be almost unique. Here, integrating our data set, we attempt to reconstruct the time and spatial evolution of this geological environment, which is characterised by four general components: (1) regional geology and structure, which form the boundary of the volcanic environment determining the regional stress field; (2) sedimentary substrata of low strength and viscosity, which facilitate large, relatively rapid strains. Variation in substrata rock composition (and rheology) causes either spreading by thrusting or by diapirism; (3) volcano construct, which provides the load for gravitational spreading, a sediment source for the substrata, and is part of the deforming system itself; (4) magma, which is an additional stress source that interacts with the regional stress field. Magma also provides a structural element, by producing an intrusive complex at shallow depth, and the rocks of the volcanic edifice, both of which cause additional stresses.

At Concepción these components appear to have evolved and interacted according to the following qualitative history (Fig. 16).

Pre-volcanic environment (pre-Quebrada Grande)

Flat-lying lacustrine sediments (claystone and siltstone) accumulated to a probable thickness of 1,000 m in the piggyback basin formed by the growing Rivas anticline. They are deposited above the detrital erosion products of the anticline itself and the Pliocene terrestrial and shallow marine rocks of El Fraile formation. The back limb of the

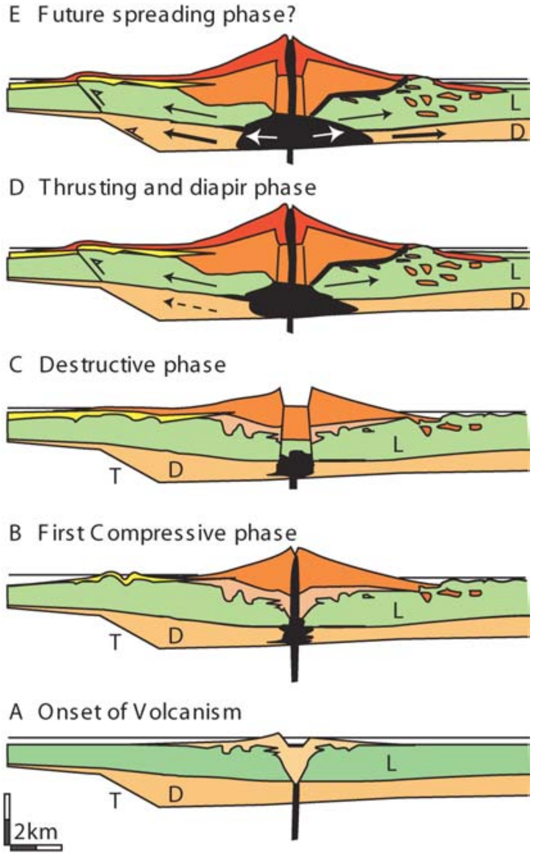

Fig. 16 Interpretative cross sections of the evolution of the volcanic environment at Concepción. **A** Onset of volcanism: initial emplacement of hydromagmatic products and beginning of volcanoclastic sedimentation in the western area. **B** First compressive phase: subaerial volcano grows up and diapiric deformation occurs all around the cone. Clastic sediments build up in the western area (*shaded layer*). Magma collects in a shallow chamber and evolves toward silicic compositions. **C** Destructive phase: Tierra Blanca dacite pumice eruptions cover the diapiric rises and a caldera perhaps formed. **D** After re-growth, Concepción reaches sufficient mass to break the volcanolcastic layers deposited to the west. Thrusting begins, while elsewhere diapiric deformation continues. Magmas are erupted with greater ease than during **B** and range from high-alumina basalt to silicic andesite. **E** Intrusive complex begins to spread, a thrust develops on a dêcollement at the top of the Tertiary flysch. The spreading leads to increased central extension and greater ease of eruption for magmas. (*T* Tertiary flysch, *D* detrital sediments, *L* mudstones)

Rivas anticline formed a structural boundary in the distal southwest sector of the volcano that inhibited radial propagation of deformation in this direction. The sharp density contrast between the Tertiary flysh (of the Rivas anticline) and the overlying Quaternary lacustrine sediments also formed a preferential site for magma intrusion and accumulation.

Onset of volcanism (Quebrada Grande) (Fig. 16A)

At the beginning of this period, magma intruded the crust and erupted undifferentiated basaltic rocks at the surface. The eruptions were mainly hydromagmatic and emplaced the Snowball Surge and the water-lain tephra layers immediately above. We imagine that the earliest magma probably also intruded at the base of the lacustrine and detrital sediments, beginning the formation of a shallow reservoir. Subsequent eruptions tapped the differentiating shallow reservoir. The lava flows sank in the unconsolidated lacustrine sediments, becoming rootless and disaggregated. Soft-sediment deformation characterised the lacustrine layers below pyroclastic deposits. The end of this period is then marked by a major unconformity.

First building phase: compressive phase (up to Tierra Blanca) (Fig. 16B)

Following the onset of volcanism, the eruptions built the first subaerial volcanic edifice. Accordingly, the sedimentary sequence became coarser with a larger volcanoclastic component. During this phase, the tephra apron and the lava domes remained little deformed. In contrast, the lava flows, emplaced on the soft mudstones on the distal reaches of the volcano, continued to be partly disaggregated after deposition. Tephra evolved to dacitic compositions, reflecting the entrapment of magma below the volcano. The building of the first edifice had two important effects on the volcanic environment: firstly, the load of the new edifice started the compressive phase (Borgia 1994) within the volcano and immediate substratum, causing magma to collect and differentiate at the base of the lacustrine sediments. Secondly, there was a new input of clastic material, which, due to the trade winds and currents, formed volcanoclastic sandstones downwind (west) of the volcano, while mudstones remained in the east. This dichotomy in the lithology and rheology of the substratum was subsequently reflected in the style of deformation of the cone.

Destructive phase (Tierra Blanca) (Fig. 16C)

The compressive phase ended with the climatic plinian eruptions that, originating in the shallow reservoir, erupted magma with a significant compositional range. This eruption could have perhaps formed a small caldera, reducing the volcanic load, and inhibiting further gravitational deformation of the system. This structure, if it does exist, is now buried.

Second building phase: thrusting and diapiring phase (El Mogote to Recent) (Fig. 16D)

As the shallow reservoir became replenished again from the deep one with new magma (which was now a high-alumina basalt) the eruptions built up a new cone, which was now set onto a substratum that was generally more brittle, particularly toward the west. Tephra layers formed an unbroken stratigraphy until the edifice reached a significant mass and height, which caused the beginning of spreading on the sedimentary substratum (Merle and Borgia 1996; Borgia et al. 2000b). As a result of spreading, the stresses around the shallow reservoir could not build up sufficiently to confine the magma. Thus, the magma could not differentiate beyond andesitic compositions before it was erupted. To the west of the cone, the deformation style was characterised by the initiation of the thrust-anticlines at Moyogalpa. To the east, the lava flows were uplifted over the mudstone diapirs, while still continuing to sink into them. The isthmus between Maderas and Concepción volcanoes (Fig. 3) probably formed during this time. The two uplifting sides of the cone are divided by a zone of subsidence and rifting, accompanied by extension and magma intrusion.

Plutonic spreading phase (Fig. 16E)

The cumulitic complex, formed at the base of the lacustrine sediments, will eventually begin to spread (Borgia 1994; Merle and Vendeville 1995). The pure east-west extension observed today on the fault that cuts the summit could also be a sign of this incipient creeping. This extension of the system may eventually allow stress relaxation of the crust and allow less evolved magma to again reach the surface.

Time of visco-elastic relaxation versus time of spreading

Van Wyk de Vries and Borgia (1996) suggested that the relaxation time of the Concepción system was very short, due to the low viscosity of the substrata and the thin brittle layer. Therefore the deformation of the basement of the volcano may rapidly follow periods of cone building. To calculate the time of relaxation of the basement we observe that the Maxwell relaxation time may be written as:

$$\tau = \frac{\mu}{\lambda} \tag{1}$$

where τ is the time for relaxation, μ is the viscosity of the ductile layers, and $\lambda=10^8$ Pa is the Young's Modulus (the elasticity of soft sediments). The characteristic time for the occurrence of spreading T is given by (Borgia et al. 2000b):

$$T = \frac{3\mu L_v^2}{\rho g H_v H_d^2} \tag{2}$$

where L_v=7,000 m is the radius of the volcano of density ρ=2,500 kg m^{-3} and height H_v=1,600 m; g=9.8 m s^{-2} is the acceleration of gravity; and H_d=1,000 m is the thickness of the ductile lacustrine sediments. Solving Eq. (2) for the viscosity and substituting into Eq. (1) leads to:

$$\tau = \frac{\rho g H_v H_d^2 T}{3\lambda L_v^2} \tag{3}$$

Evaluating Eq. (3) gives $\tau << T$, indicating that the time for the relaxation of the elastic stress created by the emplacement of volcanic products is much smaller than the time needed for the occurrence of spreading. Thus, it appears that thrusting and diapirism are in the short-term episodic and directly associated with the new load imposed during eruptive periods. This could be easily tested by continuous GPS during the next eruptive period.

Discussion and conclusions

In this paper, we describe to a first-order approximation the growth and evolution of Concepción volcano, which was born into a sedimentary basin previously unaffected by volcanism. We observe that this volcano appears to be significantly more complex in geology stratigraphy, structure, sedimentology, petrology and geodynamics than just a vent surrounded by its deposits, as the definition of volcano indicates (Bates and Jackson 1987). Indeed, Concepción is characterised by complex interactions among all kinds of geologic phenomena. The trade winds control the rheology of the substrata, which rules the style of volcanic deformation. In turn, the deformation appears to influence the residence time and degree of differentiation of magma in the shallow reservoir. Magma intrusions and the load of volcanic products added to the edifice forces it to spread on the underlying sediments. Finally, the newly emplaced products are rapidly eroded to form lahars and volcanoclastic sediments that are an important structural component of the lower part of the volcanic pile.

Role of substrata

Of paramount importance in the development of spreading is the type of substrata present below Concepción. First, the Rivas anticline, found below the lake sediments, limits the deformation to the west of the volcano, while to the east the deformation may propagate freely away from it.

Since the beginning of the volcanic activity, the trade winds have accumulated, on the western side of the volcano, a relatively thick sequence of sand, laharic and tephra layers above the clayey sediments of Lake Nicaragua. These clayey sediments still form the majority of the stratigraphic sequence on the eastern side of the volcano. Because of these lithologic differences, volcanic spreading generates thrust-related folds on the western side, producing about 200 m of uplift, 8 km west of the summit. Instead, mud diapirs are characteristic around the eastern base, rising to about 100 m above the lake through the lower part of the cone, only 4 km from the summit. We recall that at the very beginning of the volcanic activity, when the volcanoclastic layers had not yet been laid down, the deformation was also diapiric in the west, as shown by the deformation under the Quebrada Grande unconformity (Figs. 4, 6).

Control of deformation on magmatic evolution

At Concepción we chart an initial magmatic cycle of direct ascent and eruption of basic parental magma followed by three successive episodes in which magma has differentiated at both lower and upper crustal levels. We attribute this change to the building of the Concepción edifice that imposed a significant load onto the crust (in the order of 5×10^7 Pa), triggering the compressive phase and facilitating the residence and differentiation of magma probably at the density contrast between the Tertiary flysch and the lake sediments. As shown by the geology, the compressive phase came to an end with the Tierra Blanca eruption, when the volcano became sufficiently large to start the thrusting/diapiring phase. This phase, which still continues today, brought the core of the volcanic edifice into extension (forming the north-trending alignment of faults and cones on the surface) and decreased the pressure on the shallow magma reservoir. In turn, the pressure decrease allowed the eruption of basic magma again (the high-alumina basalts of El Mogote, Papaturro and Alta Gracia) that bypassed the shallow reservoir. Each of the magmatic episodes appears to be triggered by the arrival in the shallow reservoir of new high-alumina basalts that are first erupted at the base of the edifice. These basalts are always followed by the eruptions of more heterogeneous batches of lava and tephra that have differentiated in the shallow reservoir to a composition that ranges from basalt to silicic-andesite. Notably there is no progression to dacitic compositions, characteristic of the end of the first magmatic cycle and of the compressive phase.

Control of intrusive complex on spreading

During the life of Concepción, the shallow magma reservoir must have already differentiated a substantial cumulitic complex (gabbroic xenoliths are already present in the Tierra Blanca products). Like at Kilauea (Borgia 1994; Clague and Denlinger 1994) or Etna (Borgia et al. 1992; 2000), this complex should be spreading slowly and propagating the extension into the volcanic edifice. In the future, it may become one of the dominant components of the volcanic deformation inducing a plutonic spreading phase.

Generalisation: hazard implications

Knowledge of the magmatic and spreading histories at Concepción allows us to make tentative predictions about the future style of eruptive activity, sector collapses and lahars.

Eruptions

The stratigraphic record shows that, during the ongoing thrusting phase, eruptions have emplaced relatively small amounts of tephra and lava ranging in composition from basalt to silicic-andesite. No dacite magma has been erupted. Thus, in the short term, similar activity can be expected. This limits, for example, the maximum thickness of tephra likely to fall on the town of Moyogalpa to about 50 cm, as no scoria layer in the stratigraphic sequence is thicker than this in the town.

The exact periodicity of eruptive episodes appears to be in the order of a few hundred years, although it cannot be defined better until further dating of the volcanic deposits. It appears, however, that the volcano is now towards the end of a magmatic episode. Thus, if the former pattern continues, the next magmatic cycle will start with the eruption of high-alumina basaltic tephra and lava from a vent close to the base of the volcano.

At Concepción, it appears that magma intrusions could set off deformation episodes and that spreading, by reducing the lithostatic pressure, may induce intrusion with a feed-back process. Thus, volcanic activity could be used to predict the occurrence of spreading. In turn, spreading (monitored through deformation and seismic activity) may give advance warning of eruptions.

Sector collapse

Van Wyk de Vries and Borgia (1996) suggested that spreading volcanoes are less likely to suffer sector collapse, as they relax elastic stresses rapidly, reduce slopes and form normal faults which dip inwards, cutting possible slide surfaces (Borgia 1994). We believe that the data here generally support this. However, at two other volcanoes, Mombacho and Socompa, we have identified collapses that have involved spreading-related structures (van Wyk de Vries and Francis 1997; van Wyk de Vries et al. 2001). These have occurred where spreading occurs in a single direction, and since the majority of spreading at Concepción is westwards, there may be a possibility of collapse in this direction. However, we believe that the mudstones are so weak at Concepción that the volcano-loading stresses that drive collapse are too rapidly relaxed to build up to failure levels. Only immediately after large mass additions and possibly intrusive events might the volcano be regarded as dangerously unstable. The GPS deformation network will provide a monitoring tool to detect increased movement which might signal hazardous stress buildup.

Lahars

The stratigraphic record shows that lahars have not occurred with the same intensity throughout the history of the volcano. They appear to become more frequent at the end of magmatic episodes, when cone building occurs with a significantly higher fraction of tephra relative to lava. Thus these periods, including the current one, have in general a higher hazard.

The rising anticlinal ridges at the base of the volcano significantly divert the drainage down the volcano, influencing lahar (and lava flow) hazard. For example, the Moyogalpa hills effectively protect the town from lahars (Fig. 3B). Conversely, where the drainage does break through the hills, the hazard is significantly increased. For this reason the villages to the north (San Marcos, Concepción, La Flor) and south (San Juan del Sur) are often damaged by lahars and floods (van Wyk de Vries 1986). In fact, also south of Moyogalpa the only airstrip on the island was destroyed by a relatively small lahar that followed a drainage through the hills (Fig. 3B). This lahar destabilised a section of the steep, frontal limb of the anticlinal ridge, which added material to the lahar making it very destructive (Navarro 1996). Therefore, the thrust-related basal anticlines may also increase hazards by creating steep, unstable slopes.

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