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Overview of the 1997–2000 activity of Volcán de Colima, México

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Abstract

This overview of the 1997–2000 activity of Volcán de Colima is designed to serve as an introduction to the Special Issue and a summary of the detailed studies that follow. New andesitic block lava was first sighted from a helicopter on the morning of 20 November 1998, forming a rapidly growing dome in the summit crater. Numerous antecedents to the appearance of the dome were recognized, starting more than a year in advance, including: (1) pronounced increases in S/Cl and δD values at summit fumaroles in mid-1997; (2) five earthquake swarms between November–December 1997 and October–November 1998, with hypocenters that ranged down to 8 km beneath the summit and became shallower as the eruption approached; (3) steady inflation of the volcano reflected in shortening of geodetic survey line lengths beginning in November–December 1997 and continuing until the start of the eruption; (4) air-borne correlation spectrometer measurements of SO_2 that increased from the background values of <30 tons/day recorded since 1995 to reach 400 tons/day on 30 October 1998 and 1600 tons/day on 18 November 1998; and (5) small ash emissions detected by satellite-borne sensors beginning on 22 November 1997. The seismic and other trends were the basis of a short-term forecast of an eruption, announced on 13 November 1998, with a forecast window of 16–18 November. Although the lava dome actually appeared on 20 November, this forecast is considered to have been a major success, and the first of its kind at Volcán de Colima. Based in part on this forecast, orderly evacuations of Yerbabuena, Juan Barragan, and other small proximal communities took place on 18 November. The lava dome grew rapidly ($\sim$4.4 m^3/s) on 20 November, and was spilling over the SW rim of the crater by the morning of 21 November to feed block-and-ash flows (pyroclastic flows) ahead of an advancing lobe of andesitic block lava. The pyroclastic flows were initially generated at intervals of 3–5 min, reached speeds of 80–90 km/h, and extended out to 4.5 km from the crater. The block lava flow was already $\sim$150 m long by the afternoon of 21 November. It ultimately

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split into three lobes that flowed down the three branches of Barranca el Cordobán on the SSW flank of Volcán de Colima; the lava advanced atop previously emplaced pyroclastic-flow deposits from the same eruptive event, whose total volume is estimated as 24×10^5 m^3. The three lava lobes ultimately reached 2.8–3.8 km from the crater, had flow fronts ~30 m high, and an estimated total volume of 39×10^6 m^3. By early February 1999 the lava flows were no longer being fed from the summit crater, but the flow fronts continued their slow advance driven by gravitational draining of their partially molten interiors. The 1998–1999 andesites continued a compositional trend toward relatively higher SiO_2 and lower MgO that began with the 1991 lava eruption, completing the reversal of an excursion to more mafic compositions (lower SiO_2 and higher MgO) that occurred during 1976–1982. Accordingly, the 1998–1999 andesites show no signs of a transition toward the more mafic magmas that have characterized the major explosive eruptions of Volcán de Colima, such as those of 1818 and 1913. A large explosion on 10 February 1999 blasted a crater through the 1998–1999 lava dome and marked the beginning of a new explosive stage of activity at Volcán de Colima. Incandescent blocks showered the flanks out to 5 km distance, forming impact craters and triggering numerous forest fires. Similar large explosions occurred on 10 May and 17 July 1999, interspersed with numerous smaller explosions of white steam or darker ash-bearing steam. Intermittent minor explosive activity continued through the year 2000, and another large explosion took place on 22 February, 2001.

Keywords: Volcán de Colima; Mexico; lava flows; pyroclastic flows; monitoring; eruption

1. Introduction

Volcán de Colima, an andesitic stratovolcano that rises to 3860 m above sea level, is situated in the western portion of the Trans-Mexican Volcanic Belt (Fig. 1). The volcano marks the intersection of two large local tectonic structures, the N–S-trending Colima Rift Zone (CRZ; Allan et al., 1991) and NE–SW-trending Tamazula Fault (TF) proposed by Garduño-Monroy et al. (1998). Volcán de Colima was one of the 16 Decade Volcanoes selected for special investigation during the last decade of the 20th century by the Commission on Mitigation of Volcanic Disasters, of the International Association for Volcanology and Chemistry of the Earth's Interior. Historically, Volcán de Colima has been the most active volcano in Mexico (Medina Martínez, 1983; Luhr and Carmichael, 1990; De la Cruz-Reyna, 1993; Bretón et al., 2002).

Volcán de Colima's most recent lava eruption began on 20 November 1998 and ended about 80 days later in early February 1999, an interval that was both preceded and followed by numerous geophysical, geochemical, and geological phenomena during the years 1997–2000. This paper introduces the Special Issue devoted to this period of activity in the life of Volcán de Colima and presents an overview of the main results described in the following papers and other publications.

We distinguish three stages during the 1997–2000 activity:

(1) Pre-lava stage (28 November 1997 to 20 November 1998).

(2) Stage of lava eruption (20 November 1998 to 10 February 1999).

(3) Stage of intermittent explosive eruptions (from 10 February 1999).

The third stage of activity was continuing up to the time that this report was being prepared in late 2001, although our emphasis is on the 1997–2000 period. We provide a sequential description of all phenomena and monitoring efforts.

2. Pre-lava stage (28 November 1997 to 20 November 1998)

The volcano-tectonic unrest began with a swarm of earthquakes on 28 November 1997, nearly 1 yr prior to the appearance of the new lava dome. A variety of geophysical, geochemical and geological monitoring systems were in operation during that time, and the data obtained from these systems allowed both a successful long-term forecast and a successful short-term

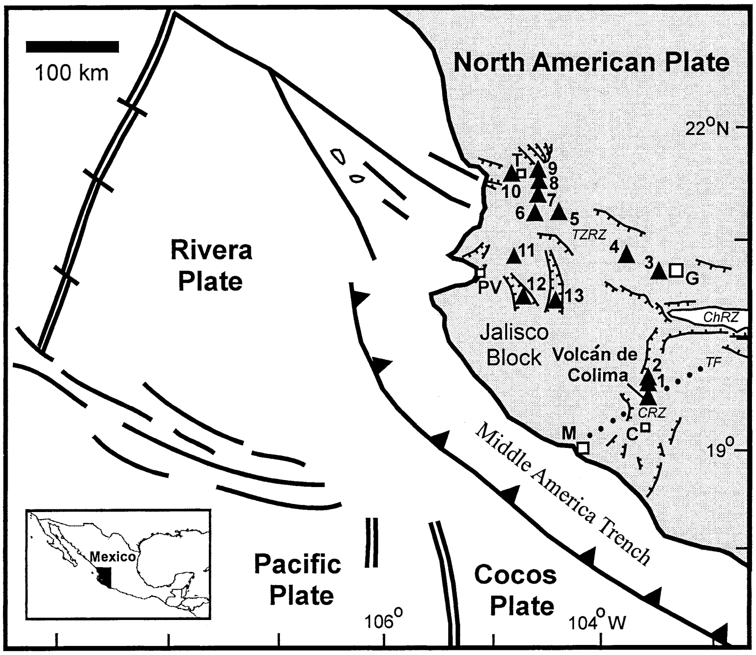

Fig. 1. Generalized map showing the location of Volcán de Colima in southwestern México. On-land faults are adapted from Johnson and Harrison (1990), Allan et al. (1991), Carmichael et al. (1996), and Ferrari and Rosas-Elguera (2000). These faults outline three major rift zones: CRZ, Colima Rift Zone; ChRZ, Chapala Rift Zone; and TZRZ, Tepic-Zacoalco Rift Zone. The dotted line running through Volcán de Colima is the proposed TF zone (Garduño-Monroy et al., 1998). Other major volcanic centers from the western Mexican Volcanic Belt are shown as triangles: 1, Nevado de Colima; 2, Volcán Cántaro; 3, Sierra la Primavera; 4, Volcán Tequila; 5, Volcán Ceboruco; 6, Volcán San Pedro; 7, Volcán Tepetiltic; 8, Volcán Sangangüey; 9, Volcán las Navajas; 10, Volcán San Juan; 11, San Sebastian Volcanic Field; 12, Mascota Volcanic Field; 13, Los Volcanes Volcanic Field. Open squares show major cities: G, Guadalajara; C, Colima; M, Manzanillo; PV, Puerto Vallarta; and T, Tepic. Offshore plate-boundary features were mainly taken from DeMets and Stein (1990) and Bourgois and Michaud (1991).

forecast of the eruption. The latter, in large part, led to a timely and orderly evacuation of inhabitants from the nearest villages. The monitoring networks are shown in Fig. 2, and the schedules of their operation are presented in Table 1.

2.1. *Seismic monitoring (Domínguez et al., 2001; Zobin et al., 2002; Reyes-Dávila and De la Cruz-Reyna, 2002)*

The volcano-tectonic earthquake swarm that began on 28 November 1997 continued into December, and was followed by other similar swarms in March, May, June–July, and October–November of 1998, the latter leading into the emergence of the lava dome (Fig. 3C). The foci of microearthquakes (the majority of which had magnitudes less than 0.5) were distributed within and below the volcanic edifice at depths from the surface down to 12 km (Fig. 4B). During the final pre-lava swarm in October–November of 1998, the focal depths were the shallowest (Zobin et al., 2002).

2.2. *Deformation monitoring (Ramírez Ruiz et al., 2002; Murray and Ramírez Ruiz, 2002)*

Measurements of distance changes from the summit of Volcán de Colima to benchmarks situated on the lower slopes of the volcano revealed abrupt shortenings during the interval 27 November to 31 December, 1997. The shortening was greatest (up to 46 cm) for the line between summit reflector PT4 and the Fresnal station on the

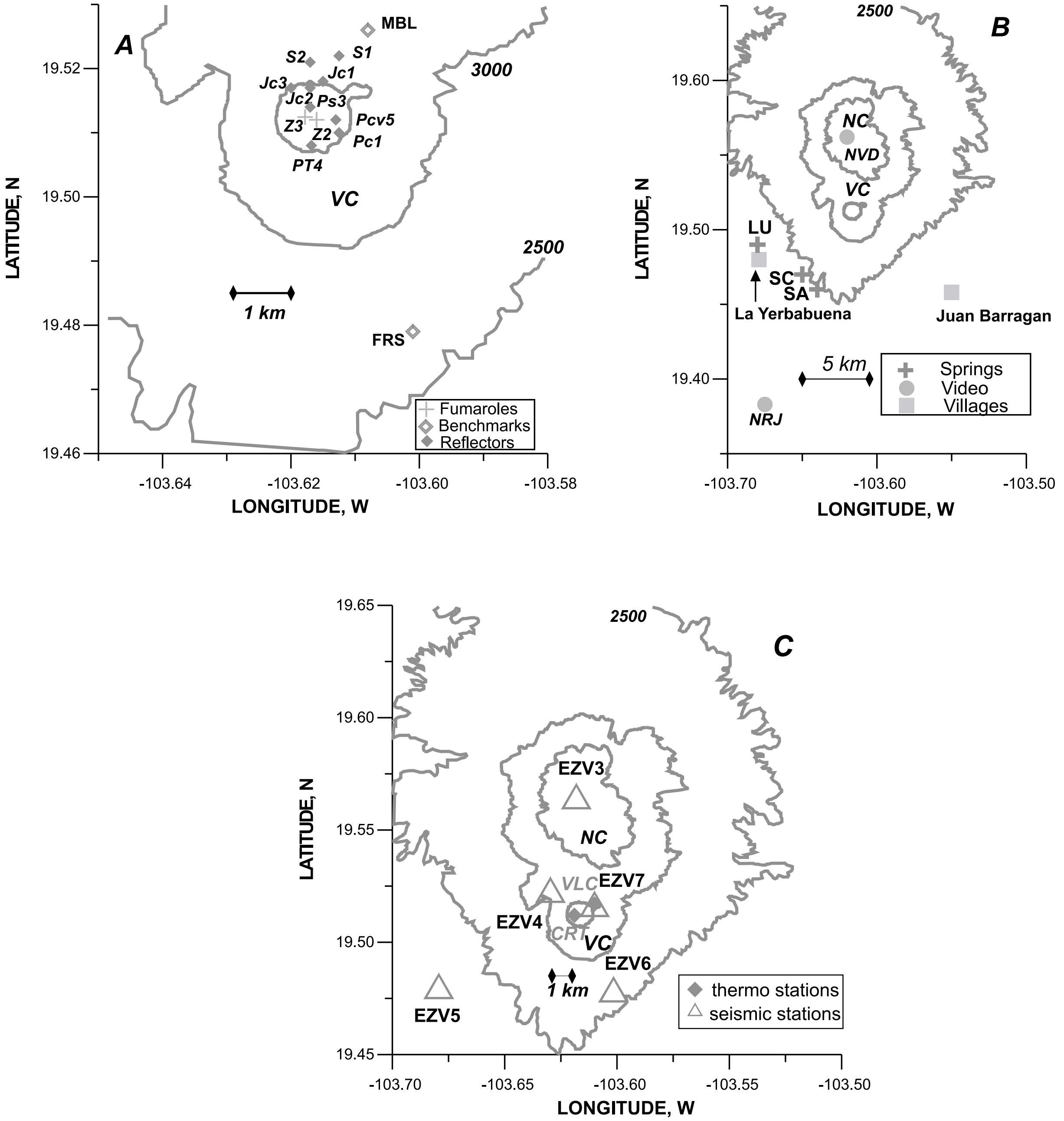

Fig. 2. System of monitoring stations at Volcán de Colima (VC). Latitude and longitude are in decimal degrees. Nevado de Colima summit shown as NC. Codes for station names are listed in Table 1. (A) Fumaroles, benchmarks, and geodetic reflectors, (B) springs, video stations, and villages, (C) thermal and seismological stations.

southeast flank (Figs. 2A and 3B). A line from summit reflector JC1 to the northeastern benchmark Membrillera also revealed shortening, but of lesser amplitude. The shortening of these geodetic lines continued gradually up to the beginning of the eruption (Fig. 3B), probably reflecting inflation of the volcanic edifice due to magma intrusion.

Table 1
Schedule of deployment for various monitoring systems at Volcán de Colima

Name	Code	Start of operation	End of operation	Comment
(1) *Seismological monitoring*				
Nevado	EZV3	04.1990		Alt. 3957 m
Somma	EZV4	04.1990		Alt. 2962 m
Fresnal	EZV5	22.06.1989		Alt. 2173 m
Yerbabuena	EZV6	13.12.1989		Alt. 1697 m
Volcancito	EZV7	15.08.1998	17.07.1999	Alt. 3500 m; destroyed by explosion
(2) *Deformation monitoring*				
(A) Benchmarks				
Membrillera	MBL	13.12.1996		Alt. 3100 m
Nevado	N1	23.04.1997		Alt. 4000 m
Fresnal	FRS	13.07.1997	04.02.1998	Alt. 1800 m
(B) Reflectors				
	Pc1	23.04.1997	22.04.1998	Alt. 3800 m
	PcV5	24.05.1997	10.02.1999	Alt. 3780 m
	Ps3	01.11.1997	03.12.1998	Alt. 3860 m
	Pt4	22.04.1997	22.04.1998	Alt. 3860 m
	Jc1	26.05.1998	17.07.1999	Alt. 3300 m;
		19.04.2000		destroyed by explosion
	Jc2	26.05.1998		Alt. 3300 m
	Jc3	26.05.1998	10.05.1999	Alt. 3300 m;
		19.04.2000		destroyed by explosion
	S1	13.12.1996		Alt. 3100 m
	S2	13.12.1996		Alt. 3100 m
(3) *Video monitoring*				
Naranjal	NRJ	08.07.1998		Alt. 1220 m
Nevado	NVD	03.01.2000		Alt. 4000 m
(4) *Thermal monitoring*				
Crater (AVHRR data)	CRT	1996		Alt. 3855 m
Volcancito (meteorological station data)	VLC	1996		Alt. 3500 m
(5) *Springs*				
Santa Cruz	SC	1996		hot spring, 32°C
San Antonio	SA	1996		hot spring, 24°C
La Lumbre	LU	1996		cold spring, 14°C
(6) *Fumaroles*				
Zone 2 of fumaroles	Z2	1995		400°C
Zone 3 of fumaroles	Z3	1995		800°C

2.3. Remote-sensing advanced very high resolution radiometer (AVHRR) monitoring (Galindo and Domínguez, 2002)

AVHRR satellite data were used to monitor ash emissions and the thermal state of the volcanic summit. Thermal anomalies were calculated as the difference between the AVHRR-derived temperature measurements for the summit crater area (CRT) and the continuous ambient temperature measurements recorded at the meteorological station Volcancito (VLC), located 1.3 km NE of the summit crater (Fig. 2C). Fig. 5 shows variations in this temperature difference during 1997–

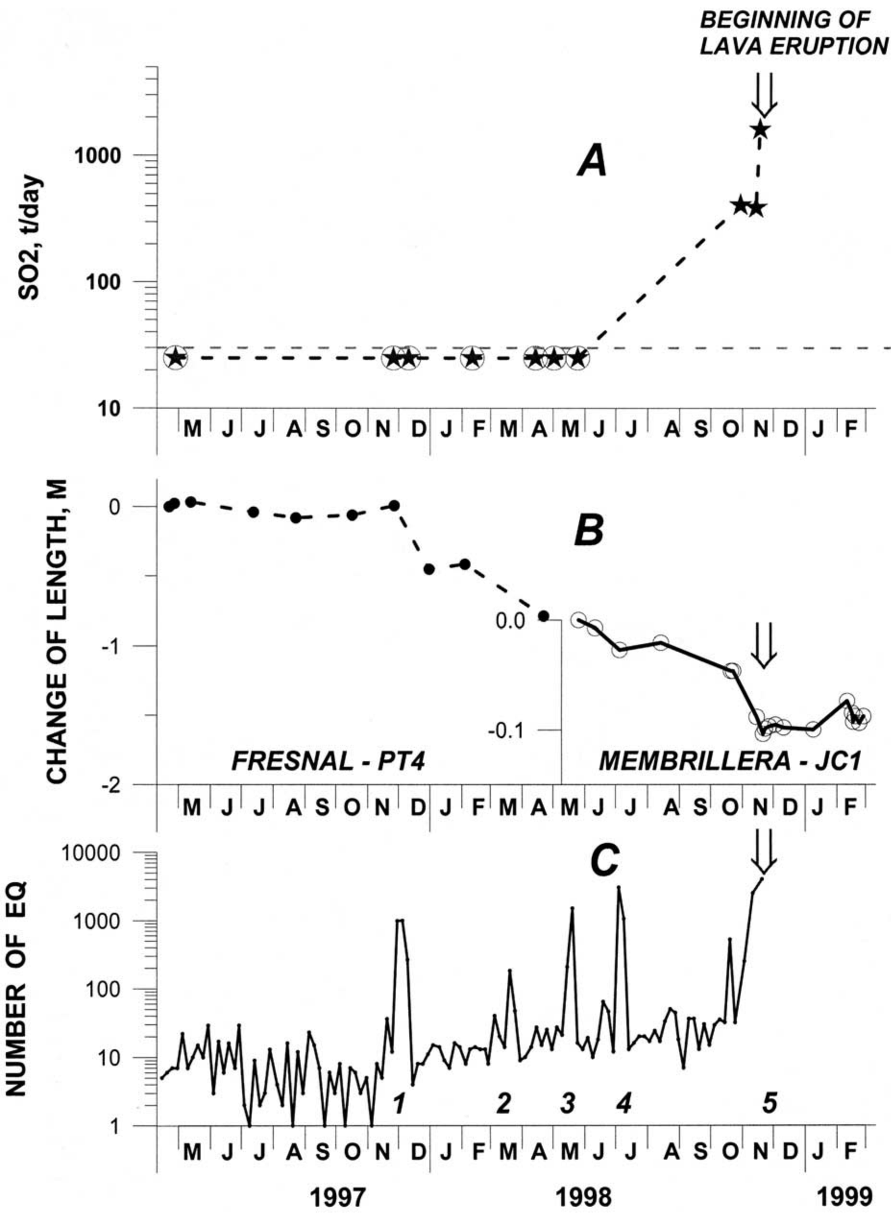

Fig. 3. Changes in geochemical, geodetic, and seismological monitoring parameters from April 1997 through the beginning of the block-lava eruption on 20 November 1998. (A) Variations in SO_2 emission rates (COSPEC measurements by J.C.G.). The measurements before October 1998 indicated SO_2 emission rates lower than the detection limit of the instrument (30 tons/day: shown by the light horizontal dashed line). (B) Geodetic line-length changes for stations Fresnal - PT4 (April 1997 to May 1998) and Membrillera - JC1 (May 1998 to February 1999). Note the scale change in May 1998. Locations for reflectors PT4 and JC1 are shown on Fig. 2A. Reflector PT4 was destroyed in July 1998. Data are from Ramírez-Ruiz et al. (2002). (C) Earthquake counts in 5-day intervals recorded by at least four of the five stations on Volcán de Colima, adapted from Zobin et al. (2002). The numbers 1–5 mark the seismic swarms recorded prior to the 20 November 1998 eruption start. The geodetic and seismological monitoring parameters clearly show the beginning of the volcanic unrest in early November 1997, 1 yr prior to the appearance of the lava dome on 20 November 1998.

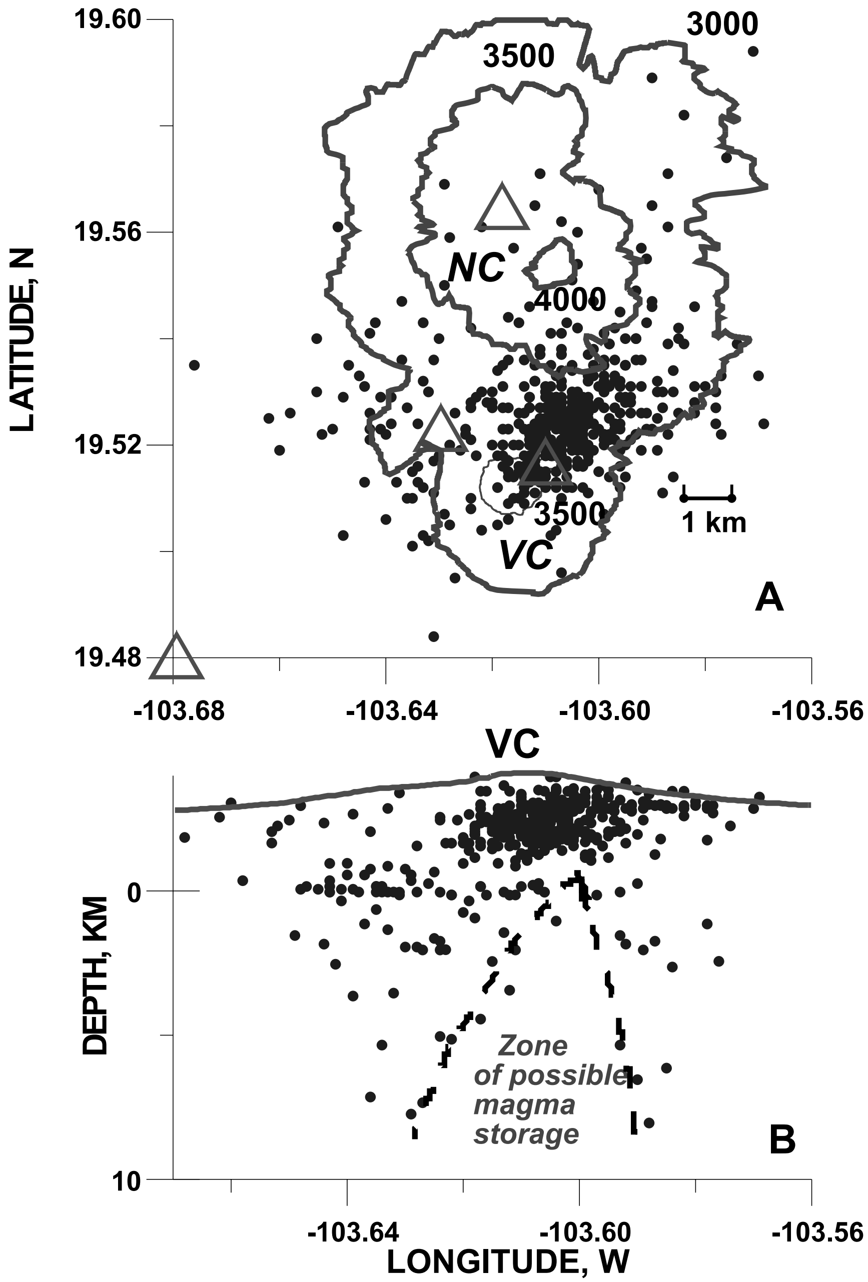

Fig. 4. Earthquake locations for events during the seismic crisis of 1997–1998 at Volcán de Colima. (A) Earthquake epicenters in map view. The contour lines of 3000, 3500, and 4000 m reflect the relief of the Colima Volcanic Complex. VC marks the summit of Volcán de Colima; NC marks the summit of Nevado de Colima. Large triangles show seismic stations (Fig. 2C). Latitude and longitude are in decimal degrees. (B) Earthquake hypocenters (foci) for the same events shown in (A), but plotted as longitude versus depth. The area absent of seismic foci below the Colima Volcanic Complex is shown as a zone of possible magma storage.

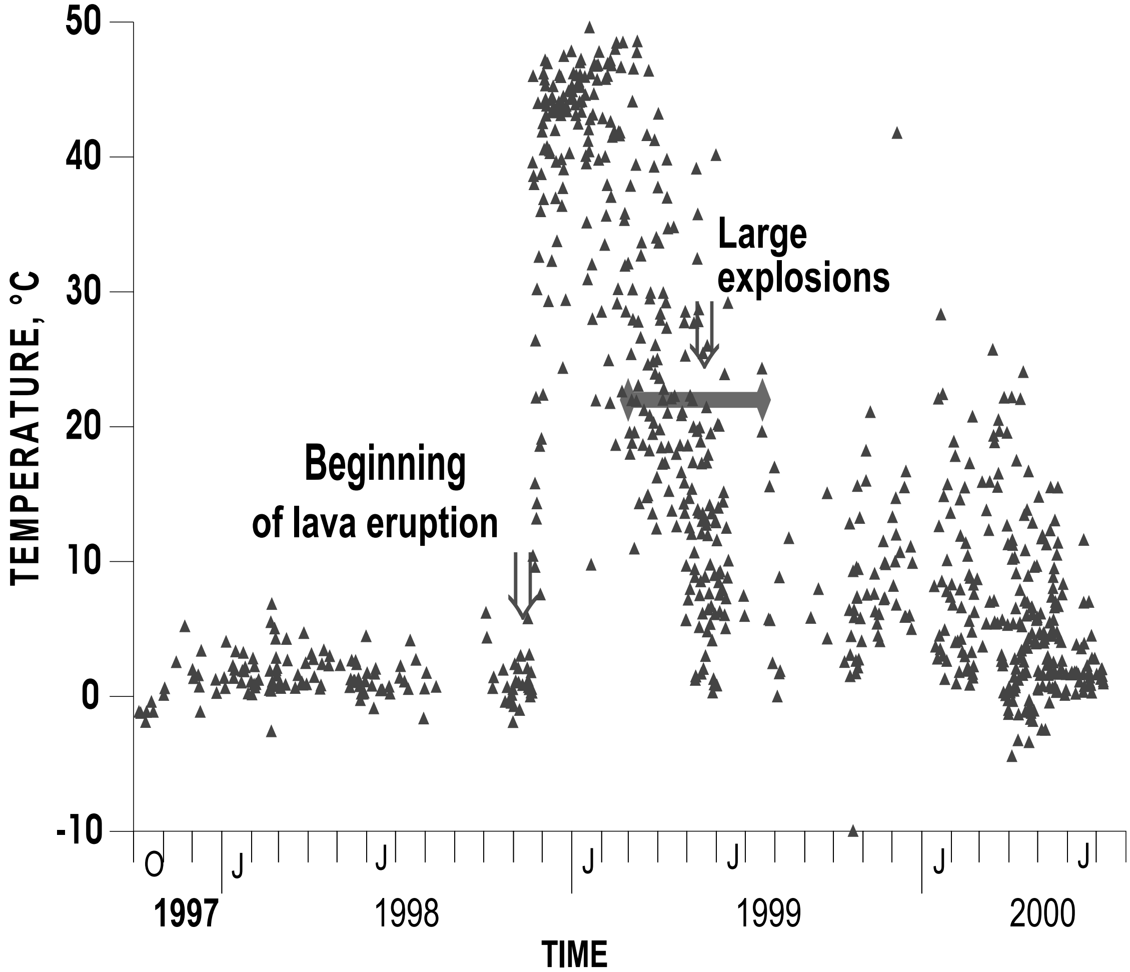

Fig. 5. Variations in temperature differences during October 1997 to July 2000 between values at the summit of Volcán de Colima determined by AVHRR, and those recorded by thermometer at the Volcancito Meteorological station (see text for details; slightly modified from Galindo and Domínguez, 2002). These data provide an excellent marker for the beginning of the 1998 lava eruption and its aftermath.

2000. The pre-lava stage of October 1997–November 1998 was characterized by stable small summit temperature anomalies of −3° to 5°C.

Ash emissions to the atmosphere were first detected by AVHRR data on 22 November 1997 at a height of about 6 km above sea level over an area of about 20 km^2 above the volcano. A larger ash signal covering an area of about 85 km^2 was detected on 28 November, when the seismic swarm began. Smaller ash emissions were detected up to the beginning of the lava eruption, but without obvious correlations to seismic activity.

2.4. *Fracturing of the dome (Gavilanes-Ruiz and Cortés-Cortés, 2000)*

Three ascents to the summit of Volcán de Colima were made on 27 November 1997, 18 March 1998, and 5 May 1998 in order to map its features and measure fractures (Fig. 6). The 31 measured fractures had lengths from 5 to 170 m. The main directions of fracturing were N20–30°E for the fractures of length less than 50 m (Fig. 6B) and about N60°E for the fractures of length more than 50 m (Fig. 6C). The latter is close to the

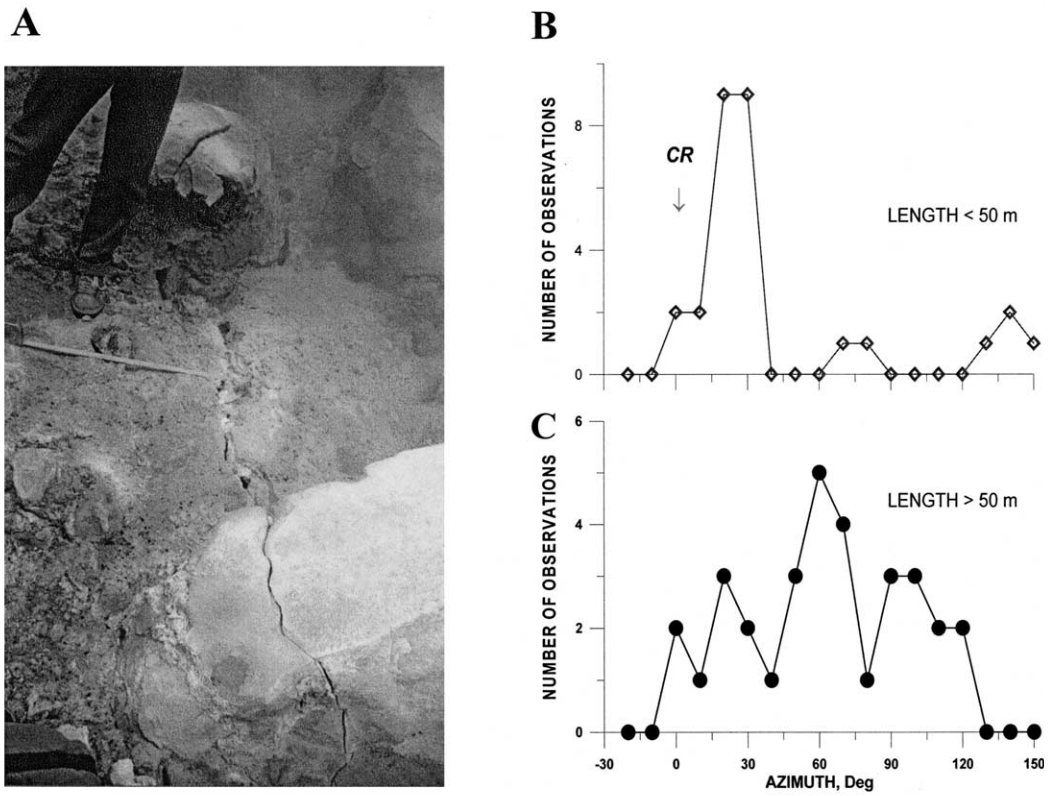

Fig. 6. Fractures at the summit crater of Volcán de Colima, measured during 1997–1998. (A) A typical fracture, with legs for scale. Photo by J.C. Gavilanes, 5 May 1998. (B) Histogram of fracture azimuth using data for 14 fractures with lengths <50 m measured by A. Cortés and J.C. Gavilanes in 1997–1998; data were smoothed in 10° steps. The N–S orientation of the CRZ is indicated. (C) Histogram of fracture azimuth using data for 17 fractures with lengths >50 m also measured by A. Cortés and J.C. Gavilanes in 1997–1998; data were smoothed in 10° steps.

orientation of the parasitic vent Volcancito with respect to the summit crater, presumably reflecting a dike joining the two vents in the subsurface. This is also the orientation of the TF (Fig. 1). Relatively few summit fractures follow the N–S orientation of the CRZ (Fig. 1).

2.5. Geochemical monitoring (Taran et al., 2000; 2002-this volume)

The fluid- and gas-phase response of the volcanic system during 1996–1999, including the recent eruptive activity, was monitored by analysis of fumarolic gases from the summit crater, spring waters from the southern flank, and SO_2 flux from the summit crater measured by an aircraft-based correlation spectrometer (COSPEC).

The chemical and isotopic compositions of gases collected from two summit fumaroles (Z2 and Z3: Fig. 2A) approximately every 3 months showed variations that are best explained by reactivation of the volcano's magmatic system. Increases in S/Cl and δD began approximately 1 yr before the November 1998 eruption.

Water chemistry (Taran et al., 2000) was monitored from three mineral springs on the SW flank of the volcano (La Lumbre, Santa Cruz and San Antonio: Fig. 2B), with samples collected approximately each month. The water chemistry was dominated by seasonal variations; other significant variations included smooth increases with time in Mg/Cl and dissolved CO_2 for La Lumbre spring and a peak in boron concentrations for all three springs about half a year before the November 1998 eruption. The Mg/Cl and CO_2 trends are consistent with slight acidification of shallow groundwaters from volcanic gases released during formation of new fractures. The peak of boron is more difficult to explain, because it was not accompanied by similar increases in sulfur or chlorine concentrations.

Between 1995 and September 1998, SO_2 emission rates were mostly less than 100 tons/day, and commonly below the COSPEC detection limit (30 tons/day). On 30 October 1998 a value of 400 tons/day was measured, and on 18 November 1998, 2 days before the lava dome appeared, a value of 1600 tons/day was recorded, then a record for Volcán de Colima. This jump in SO_2 emission proved, if only in hindsight, to have been a reliable precursor to the eruption (Fig. 3A).

3. Activity of the Scientific Advisory Committee (SAC), eruption forecasts, and the first evacuation

The monitoring of Volcán de Colima was coordinated by the SAC (formally known as the Comité Científico Asesor para el Volcán de Colima), which was organized by Colima University from the very beginning of this volcanic unrest and later authorized by the Colima State Government on 18 November 1998. The SAC consisted of scientists from Colima University, UNAM, CENAPRED, and Guadalajara University, as well as state civil protection authorities, military officers, and foreign specialists, and served to advise the Colima State Government with regard to volcanic-hazard mitigation. The SAC had meetings practically every week beginning in the spring of

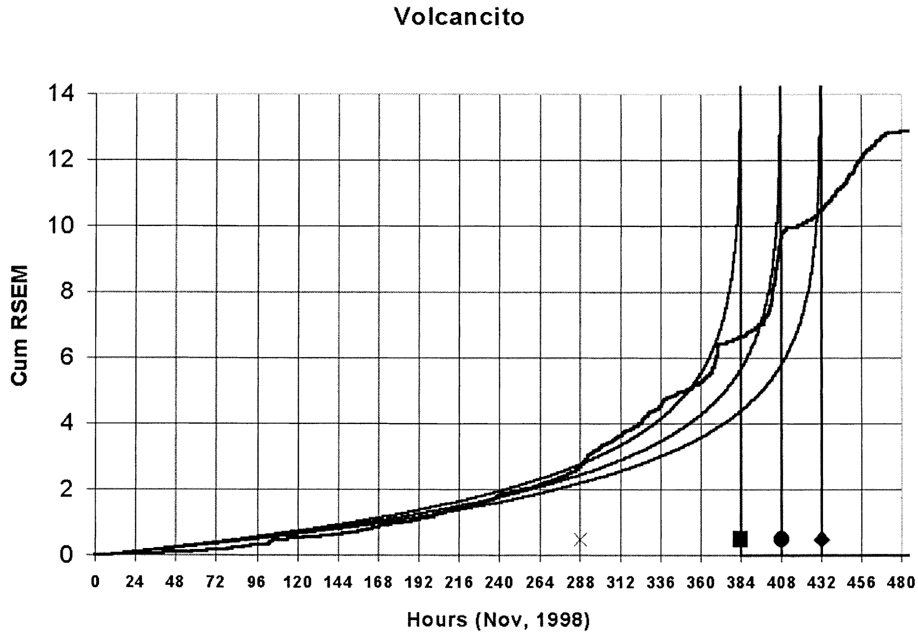

Fig. 7. The three material-failure models used to support the forecast of an eruption at Volcán de Colima for the period 16–18 November 1998. The figure was taken from De la Cruz-Reyna and Reyes-Dávila (2001), and Reyes-Dávila and De la Cruz-Reyna (2002). The thick irregular line represents cumulative 2-min averages of real-time seismic energy measurements (RSEM: expressed as the square of the seismic signal amplitude $\times 10^{-7}$) obtained during the first 20 days (480 h) of November 1998 from Volcancito station (EZV7, see Fig. 2C), the nearest to the crater. This is not to be confused with real-time seismic amplitude measurements (RSAM: Murray and Endo, 1989). The initial forecast, using the viscoelastic model, was issued late on 12 November 1998 (marked by 'X'). Based on these 288 h of data, three sets of model parameters were used to define a forecast range for the failure time (times marked with a square, a circle, and a diamond). Around hour 371 (midday on 16 November), the strain accumulation rate decreased for about 1 day, and then resumed its increase. The regime of strain release changed again after hour 408 (late on 17 November). A new lava dome was first seen growing in the summit crater at 07.30 h on 20 November (hour 463).

1998; three of the meetings were held with the Governor of Colima State. The SAC was directed by the Head of Scientific Investigations of Colima University, and by the Technical Secretary of the Civil Protection of Colima State. At each meeting the SAC discussed the development of volcanic activity and prepared a report for public dissemination. The Bulletins of the SAC were published regularly on the website of the Colima Volcano Observatory (CVO).

During 1998, two groups of SAC members saw indications in monitoring data for a future eruption of Volcán de Colima, and expressed those concerns first in a long-term forecast, and later in a short-term forecast. The long-term forecast was based on observed increases of S/Cl and δD in gases from two summit fumaroles beginning in late 1997. Calling attention to those trends at the January 1998 session of the SAC, Y.A.T. and J.C.G. forecast an effusive eruption "sometime in the nearest future, maybe this year". On 13 November 1998, during the 5th seismic swarm (Fig. 3C), the SAC received a Memorandum prepared by two other members, S.D.L.C.-R. and G.A.R., in which they announced a high probability of a new eruption at Volcán de Colima during the interval 16–18 November. Their short-term forecast was based mainly on seismic data and on a model related to the material-failure method of Cornelius and Voight (1995). The forecast range of dates was estimated from three sets of model parameters (Fig. 7). In their Memorandum to the SAC, the authors of the forecast proposed three scenarios for the eruption, with the most probable scenario involving formation of a new dome in the summit crater followed by lava flows and pyroclastic flows.

This Memorandum received the support of the SAC members, and on this basis recommendations for the State Government were elaborated. In response, on the morning of 18 November the Government of Colima State evacuated the ∼180 inhabitants of Yerbabuena, a village located 8 km SW from the crater of the volcano, and moved them to pre-arranged shelters (Fig. 8). That same day, Jalisco State evacuated the ∼120 residents of Juan Barragan, located 10 km SE of the crater. The inhabitants of Yerbabuena, Juan Barragan, and other proximal communities had been prepared for this action during many previous interactions with the Social Response Group of the CVO (Gavilanes-Ruiz, 2000). These scientists had many discussions with the villagers during 1997–1998 about the hazards associated with future eruptions of Volcán de Colima, prepared a booklet about volcanic hazards, and publicized the evacuation route (Fig. 8A). As a result, the evacuation of 18–19 November took place without complications. The lava eruption began during the night of 19–20 November.

4. Stage of lava eruption (20 November 1998–10 February 1999)

4.1. *Lava-dome growth and lava-flow emplacement (Navarro-Ochoa et al., 2002)*

The first confirmation of the eruption's start, sighted during a helicopter overflight at 07.30 h on 20 November 1998, was a new circular dome of dark andesitic block lava that was actively filling a crater formed by an explosion through the summit dome in July 1994. CVO scientists were surprised by the high dome-extrusion rate, estimated at ∼4.4 m^3/s, which was ∼50 times faster than dome growth at the start of the otherwise similar eruption of 1991. A helicopter overflight on the following morning of 21 November revealed that the 1994 crater was full and that new lava was already spilling over the SW rim to form block-and-ash flows (pyroclastic flows) at average intervals of 3–5 min. These pyroclastic flows moved at speeds of 80–90 km/h and extended out to 4.5 km horizontal distance from the crater (Fig. 9A). They mostly descended the eastern branch of Barranca El Cordobán, and marked the advance of a tongue of block lava, which was already ∼180 m long by the afternoon of 21 November. The block-lava front initially advanced at high velocities up to 36 m/h on steep upper slope angles up to 40° (Fig. 9B). The block-lava flow eventually split into the three separate branches of Barranca El Cordobán (Fig. 9C). Lava-front flow rates diminished to 0.2–1.0 m/day in early February 1999, by which time the

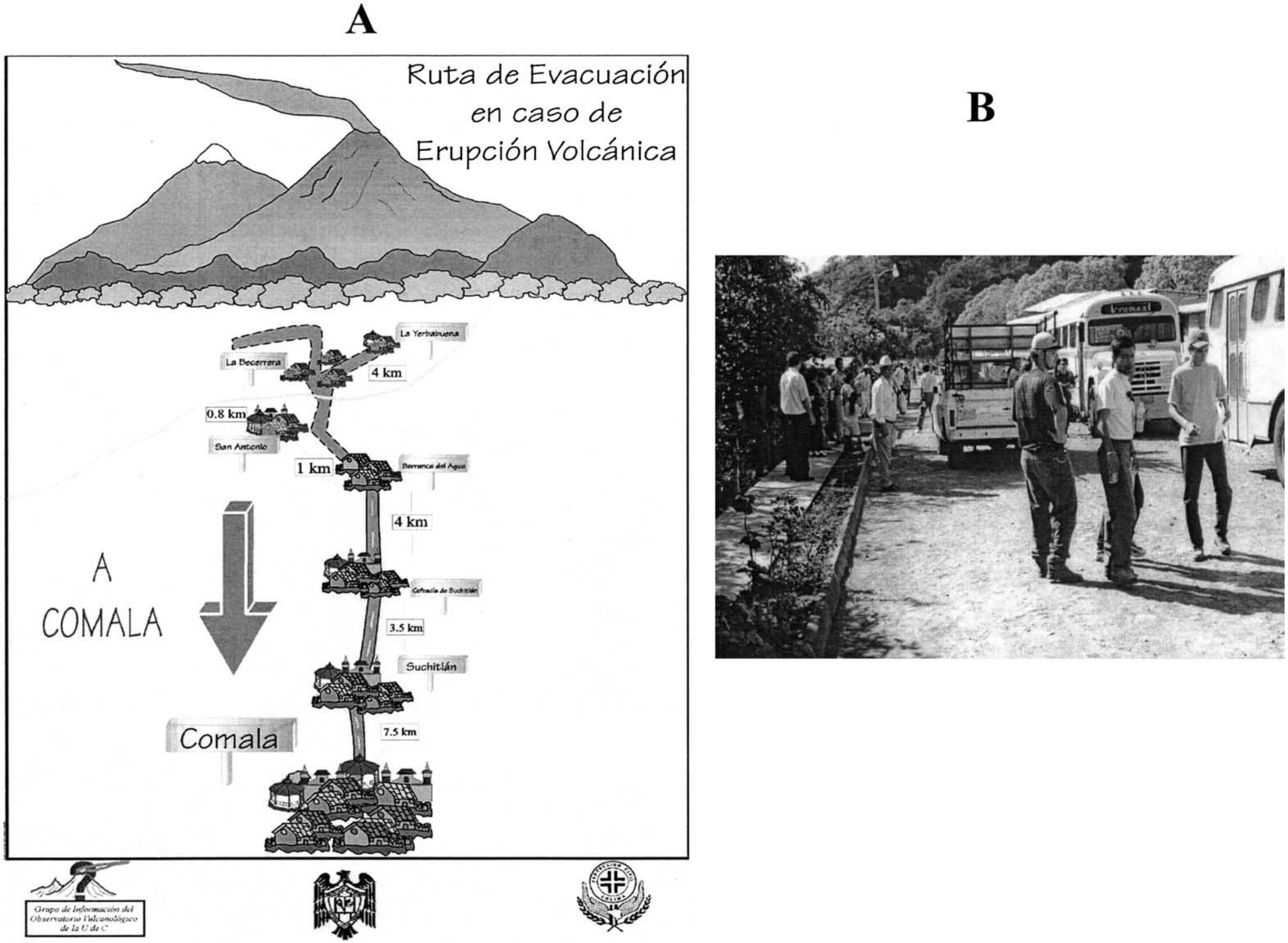

Fig. 8. Evacuation of the village Yerbabuena. (A) The planned evacuation route for Yerbabuena residents taken from a poster prepared by J.C. Gavilanes and the members of the Group of Social Response of CVO. (B) The Yerbabuena evacuation in progress on 18 November 1998; photo by Alicia Cuevas.

block-lava flows were no longer fed from the summit crater, but were moving by gravitational draining of the partially molten flow interiors. At the end of the eruption the three block lava flows had horizontal lengths of 2.8 km (eastern lobe) to 3.8 km (central lobe), as shown on the map of Fig. 10. The flow fronts were ~30 m high (Fig. 9D). Assuming an average lava flow thickness of 20 m, the total erupted lava volume is estimated as 39×10^6 m^3.

4.2. Emplacement of pyroclastic flows (Saucedo et al., 2002)

As mentioned above, hot blocks collapsing from the front of the new lava flow repeatedly sent pyroclastic flows down the SW flank of Volcán de Colima ahead of the advancing lava flow (Fig. 9A). Over much of its course, excepting perhaps the steep uppermost slopes, the lava moved over a bed of these recently emplaced pyroclastic-

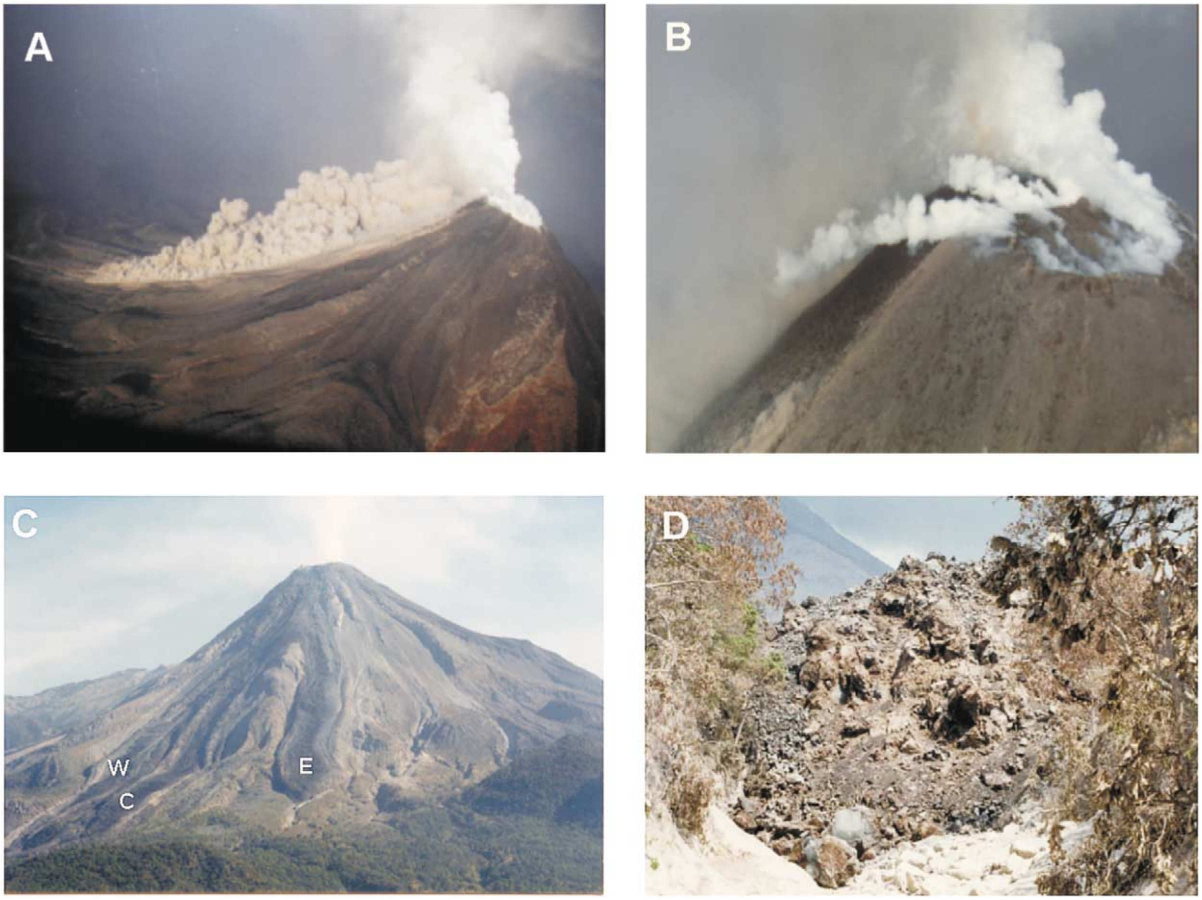

Fig. 9. (A) An oblique, wide-angle aerial photo from the ESE taken with the camera somewhat tilted to the left showing a pyroclastic flow descending Barranca el Cordobán at 08.30 h on 22 November 1998. The resultant block-and-ash flow deposits extended out to 4.5 km from the summit. Photo by Abel Cortés. (B) New lava flow emerging from the crater onto the steep upper SSW slope on 24 November 1998. View from the ESE. Photo by Mauricio Bretón. (C) Aerial view from the south on 16 March 1999 showing the three 1998–1999 lava flows in the western (W), central (C), and eastern (E) branches of Barranca del Cordobán at their final positions. Photo by Mauricio Bretón. (D) Near-final position of the lava flow front in the western branch of Barranca el Cordobán on 7 February 1999. For scale, the two large lava blocks at the base of the flow front are ~4 m in diameter. The flow front is ~30 m high. Photo by Mauricio Bretón.

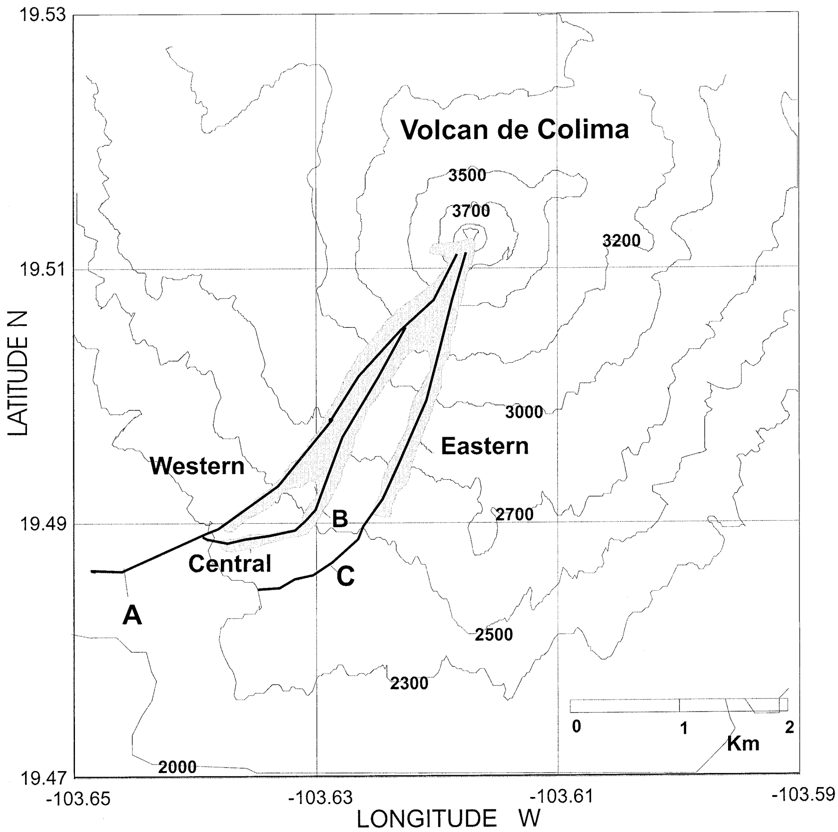

Fig. 10. Map showing the extent of 1998–1999 pyroclastic-flow deposits and lava flows. The final positions of the tongues of block lava (western, central, and eastern) are shown in gray. The maximum extent of pyroclastic flows along the three branches of Barranca el Cordobán are shown by solid lines, recorded on 25 November 1998 for the western and central branches, and on 24 November 1998 for the eastern branch. The areal extent of the pyroclastic-flow deposits is not depicted.

flow deposits. A similar pattern occurred during Colima's eruptions in 1975–1976 (Thorpe et al., 1977), 1981–1982 (Smithsonian Institution, 1982 and 1991 (Rodríguez-Elizarrarás et al., 1991), indicating that pyroclastic flows typically accompany movement of block lava flows at Volcán de Colima. The striking contrast between the advancing front of the dark 1999 block lava flow and the fine-grained, light-gray ash of the underlying pyroclastic-flow deposit is illustrated in Fig. 9D. The final extent of the 1998–1999 pyroclastic-flow deposits is shown in Fig. 10. The total volume of unconsolidated pyroclastic-flow deposits associated with the lava eruption is estimated as 24×10^5 m^3 (Saucedo et al., 2002).

Following cessation of the lava eruption, pyroclastic flows were also generated by a different mechanism, column collapse, during the explosive eruptions of 10 February, 10 May, and especially 17 July 1999 (Saucedo et al., 2002). Regardless of the mechanism by which the pyroclastic flows are generated, each segregates into a basal avalanche that moves by granular flow, and an upper cloud in which particles are in dilute turbulent suspension. The basal avalanche loses velocity in contact with the ground surface and eventually comes to rest, at which time the upper dilute cloud can separate from it to form a pyroclastic surge capable of scorching, toppling, and sandblasting vegetation and other objects. When the pyroclastic surge finally comes to rest, suspended particles can rise to form a cloud from which a fine ash-fall layer is deposited.

4.3. Petrology and geochemistry of the 1998–1999 lavas (Luhr, 2002; Mora et al., 2002)

The block lavas erupted in 1998–1999 are andesites with 59.5–61.3 wt% SiO_2 and 2.6–3.8 wt% MgO (normalized anhydrous with all Fe as FeO). They have minor amounts (< 0.5 vol%) of brown hornblende with reaction rims accompanying the dominant minerals plagioclase, orthopyroxene, clinopyroxene and Fe–Ti oxides (mostly titanomagnetite), surrounded by a microcrystalline to glassy groundmass. Also present are rare rounded quartz xenocrysts and olivine xenocrysts with Cr–Mg–Al-rich spinel inclusions. Pyroxene rim compositions were used to estimate eruption quench temperatures of ~975–1045°C based on the algorithm of Wells (1977).

It is useful to evaluate data for the 1998–1999 lavas in the light of mineralogical and whole-rock compositional changes since the lava eruption of 1869, the earliest eruption at Volcán de Colima whose products can be identified with confidence in the field. Luhr and Carmichael (1990) and Luhr (this volume) discussed the historical activity of Volcán de Colima with regard to eruptive cycles whose limits are marked on roughly 100-yr intervals by major explosive eruptions, as occurred in 1818 and 1913 (see De la Cruz-Reyna, 1993, for an alternative interpretation). Most lava eruptions from Volcán de Colima involve andesites with 61 wt% SiO_2, but andesitic scoriae are typically more mafic with ~58% SiO_2, as was the case for the most recent large explosive eruption in 1913. The first block-lava flows to leave the summit crater of Volcán de Colima following the cycle-ending 1913 eruption, those issued in 1961–1962 and 1975–1976, were fairly homogeneous at ~61 wt% SiO_2. Beginning with the last lobe of lava erupted in 1976 and continuing through the 1981–82 lava flow, compositions became decidedly more mafic, with SiO_2 reaching ~58.8%. This trend appeared to indicate a shift toward mafic magma compositions similar to that erupted explosively in 1913. Since then, however, andesitic lavas became progressively richer in SiO_2 during the 1991 eruption and the 1998–99 eruption, although Mora et al. (2002) argued for mixing of hotter mafic andesitic magma as a trigger to the 1998–1999 eruption.

Compared with andesites of similar overall composition erupted in 1869–1913 (last cycle), those erupted in 1961–1999 (current cycle) are richer in plagioclase and the elements Y, Nb, Tb, Ho, Er, Yb and Ta, and poorer in the water-bearing mineral hornblende and the elements Ba and Sr. These observations are all consistent with the interpretation that the magmas of 1961–1999 had significantly lower water contents compared to those erupted in 1869–1913. Accordingly, the explosive eruption of 1913 is probably a worst-case scenario for the termination of the current eruptive cycle. Complicating this interpretation is a relatively poor understanding of transition between block-lava eruptions and explosive eruptions at Volcán de Colima, a transition that must depend critically on magma viscosity, ascent rate, and degassing. The relatively higher viscosities of andesitic magmas with ~61% SiO_2 likely lead to relatively slower ascent rates and more thorough degassing prior to their emergence in the summit crater as block lava. In contrast, the lower viscosities of more mafic andesitic magmas with ~58% SiO_2 generally result in faster ascent and greater retention of volatiles until they erupt explosively from the summit crater.

4.4. Seismic activity

Seismic activity, primarily in the form of volcano-tectonic earthquakes, sharply decreased just after the start of lava extrusion, but was replaced on the seismograms by noisy signals related to numerous block-and-ash flows moving down the SW flank (Fig. 11A). The stable strong seismic background continued up to the end of December 1998, when block-and-ash flow activity decreased significantly. Discrete, very small earthquakes with magnitudes near zero were rare during this stage.

4.5. Deformation

Deformation of the volcanic edifice continued (Ramírez Ruiz et al., 2002; Murray and Ramírez Ruiz, 2002), but changes became very small and

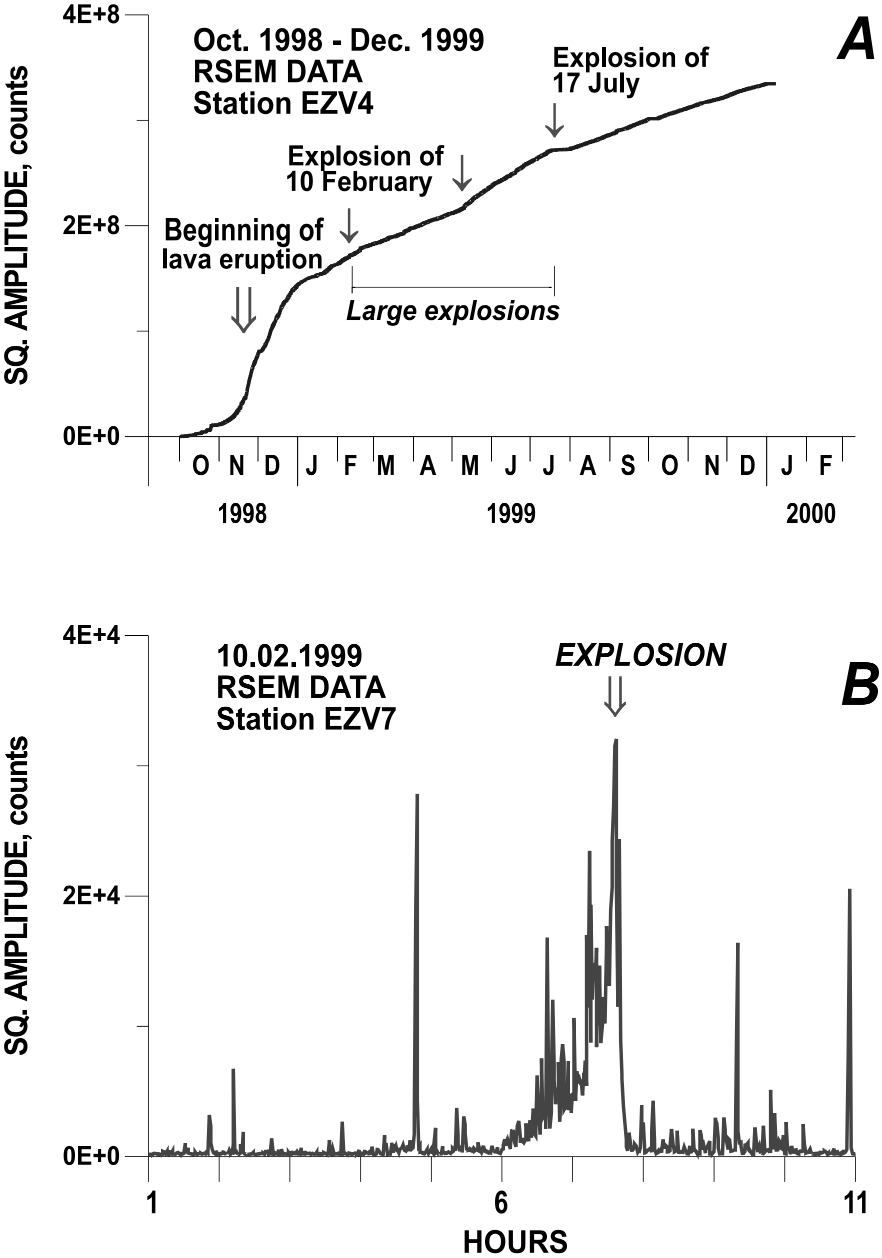

Fig. 11. Seismicity at Volcán de Colima during October 1998 through January 2000. (A) RSEM for station EZV4, located 1.7 km NW of the crater (Fig. 2C). Changes in the slope of the curve reflect changes in the rate of seismic energy release. The highest rate was observed during the initial part of the eruption and was mainly related to seismic noise produced by the movement of block lava flows and pyroclastic flows. With the termination of most pyroclastic-flow activity in mid-January 1999, the seismic energy release sharply decreased and then stayed more or less constant through the stage of explosions. (B) short-term variations in RSEM through the first strong explosion on 10 February 1999.

reversed direction, with line shortening (inflation) replaced by line lengthening (deflation) (see Fig. 3B).

4.6. Geochemical monitoring (Taran et al., 2002)

On 26 November 1998, as block lava was rapidly advancing down the SSW flank of the volcano, SO_2 emission reached the current record level of ~20 000 tons/day. Lower values of 2000 to 5000 tons/day were measured through the eruption and its aftermath until April 1999.

4.7. Remote-sensing AVHRR monitoring (Galindo and Domínguez, 2002)

Time-series measurements by AVHRR showed a sharp increase in differential summit temperature (up to 50°C) on 20 November 1998, coinciding with the start of lava extrusion (Fig. 5). High values persisted throughout the lava eruption and into the following stage of explosive eruptions, trailing off in June 1999 (Fig. 5).

5. Stage of intermittent explosive eruptions (from 10 February 1999)

As the lava flows ceased movement in early February 1999, eruptive activity changed to an intermittent explosive style that was continuing in late 2001 when this report was being written. Many small emissions of light-gray steam or darker gray steam-and-ash have occurred since February 1999. The largest explosive events were on 10 February 1999, which formed a new crater in the 20 November 1998 dome (Smithsonian Institution, 1999a,b), and subsequent blasts on 10 May (Smithsonian Institution, 1999c), and 17 July (Smithsonian Institution, 1999d,e), which enlarged the 10 February crater. These larger explosions launched incandescent ballistic blocks with diameters up to 90 cm out to distances of ~5 km, igniting forest fires on many sides of the volcano. The ballistic trajectories and impact crater geometries following the 10 February eruption were described in Smithsonian Institution (1999b). Aerial inspection of the summit in August 2000 showed the crater to have a diameter of 250 m and a depth of 60–80 m; a large explosive eruption on 22 Feburary 2001 (Smithsonian Institution, 2001) undoubtedly modified the summit morphology further. The daily average of small explosions in 1999–2000 was 2–3. Following each of the large 1999 explosions, Yerbabuena and other proximal villages were evacuated; the evacuations took place during 14 February to 2 March, 10 May to 11 June, and 17–19 July 1999.

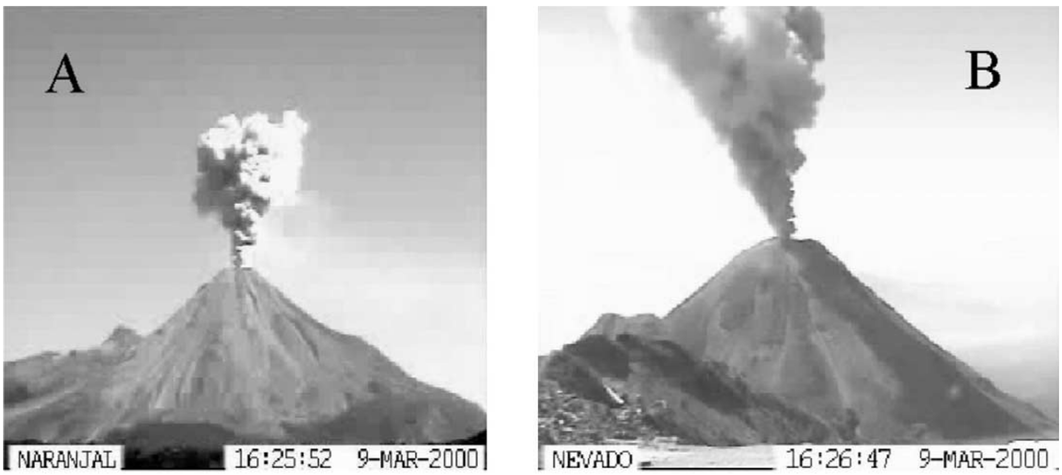

Fig. 12. Examples of the automatic video images for an explosion of Volcán de Colima at ~16.26 h on 9 March 2000. (A) Camera at the Naranjal Observatory (Fig. 2B, NRJ). (B) Camera atop Nevado de Colima (Fig. 2B, NVD).

5.1. Seismic activity

ach of the large explosions was preceded by an increase in seismic activity. This close relationship for the 10 February 1999 explosion is illustrated in Fig. 11B. The increase in number of small earthquakes began 2 h before the explosion and reached its maximum at the moment of the explosion.

5.2. Deformation

Deformation of the volcanic edifice associated with the 1999 explosions was very minor. It was possible to note a weak inflation–deflation mechanism related to the explosion of 10 February 1999, but neither of the explosions in May or July were reflected in the geodetic data, because measurements were made too infrequently to detect such short-term changes (Ramírez-Ruiz et al., 2002).

5.3. Remote-sensing AVHRR monitoring (Galindo and Domínguez, 2002)

Remote-sensing AVHRR monitoring indicated a gradual decrease of summit temperature from April 1999 until background values were reached in June 1999, with considerable scatter during the following year (Fig. 5).

5.4. Video monitoring (Bretón et al., 2000)

Two fixed video cameras were installed for visual and infrared monitoring of Volcán de Colima. One located at the Naranjal Observatory, 15 km S of the active crater (Fig. 2B, NRJ), has operated since 8 July 1998. The other, located near the antennas atop Nevado de Colima, 5.5 km N of the active crater (Fig. 2B, NVD), was installed on 3 January 2000. These cameras allow real-time, continuous visual and infrared observations of the volcano, so that its eruptive behavior can be correlated with other instrumental monitoring data. Near real-time images from these two cameras are available on the website of the CVO. As an example of the utility of this video system, two views of a small explosion on 9 March 2000 are shown in Fig. 12.

6. Conclusions

The andesitic block-lava eruption that began at Volcán de Colima on 20 November 1998 was notable for several reasons: (1) no previous eruption of Volcán de Colima had been so comprehensively studied; a broad array of monitoring techniques was employed to collect both pre-eruption baseline data as well as deviations related to volcanic unrest. (2) For the first time in the history of the volcano, the start of the eruption was forecast a week before it began, with the forecast range falling just 2 days short of the actual start date. (3) Orderly evacuations of nearby communities were conducted 2 days before the eruption start.

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