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Dynamic relief development and geological risks of the San Cristobal and Casita Volcanic Groups, Nicaragua

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ABSTRACT

The volcanic San Cristobal group represents above all two stratovolcanoes that formed in the La Pelona caldera and a number of minor volcanoes and volcanic centers. This Group lies on the SW margin of the Nicaraguan depression. The San Cristobal volcano has been active until present. The Casita volcano is not considered to be active, there is, nevertheless, an intensive hydrothermal alteration of lava flows and agglomerates that form it. The surface of the volcano is made up of up to several tens of meters thick polygenetic slope deposits, which become unstable on the clayey weathered underground. In 1998, as a consequence of hurricane Mitch, a catastrophic flash flood annihilated two villages. The area is known not only for its exodynamic hazard but also volcanic and seismic hazards. The development of the San Cristobal Volcanic group is polycyclic and its age is thought to be Plio-Pleistocene up to recent.

Key words: volcanic relief, block flow, flash flood, geological risk

1. Introduction

Part of the project "Geological study of vulnerability of the rock environment, the Chinandega – Leon area, Cordillera De Los Marabios" (Hradecký et al. 1999) was an analysis of dynamic development of the relief. The objective of the analysis was to prepare a basis for compiling a map of the geological risks in this area. The result of the analysis was the compilation of a map of the dynamic relief development at 1:50 000 scale. The results of the geological investigation, data from older literature, interpretation of aerial photographs and this author's field observations have been used for the compilation.

2. Geographical setting

The studied area of the volcanic group San Cristobal and of which the Casita volcano forms part (Fig. 1), is situated in the Pacific rim of Nicaragua. It is a part of Nicaragua's volcanic chain which is called in its NW portion Cordillera De Los Maribios.

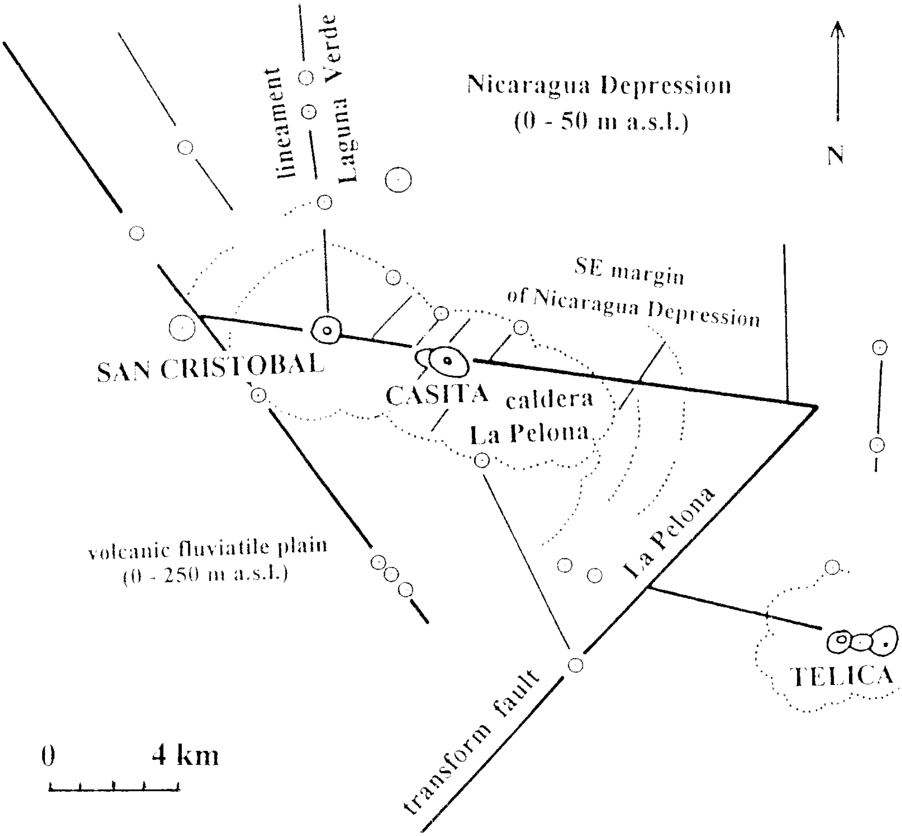

Fig.1: Tectonic sketch – volcanic group of San Cristobal, Nicaragua.

The highest volcano of the group and in Nicaragua, San Cristobal (1745 m a.s.l.) forms a typical cone-shaped stratovolcano (Photo 1). The volcano was covered by forest which was destroyed during great volcanic activity in 1971 and since that year the slope of the volcano has been covered by a bushy grass. The lava flows that cover the eastern slopes probably date back to 1685 as is mentioned by historical sources. The last major activity of the volcano was in 1997 and it has been producing lesser amounts of volcanic ash and volcanic gases since. At the foot of the volcano, there is a series of subsidiary non-active volcanoes – El Chonco (1105 m), Moyatepe (917 m), Acastepe (320 m) and of many minor volcanic centers. The highest slopes of the volcano are not economically exploited. The slopes at the foothills are used as pastureland and to a lesser degree also as coffee-plantations.

Casita (1405 m), sometimes also called Apastepe or Chichigalpa volcano (el Volcán De Chichigalpa) rises in the La Pelona caldera. It is thought to be non-active. A formidable blocky flash flood that annihilated two villages El Porvenir and Rolando Rodriguez, in which over 1600 inhabitants perished, slid on 30th October 1998 at about

11.00 a. m. down the southern slope of Casita. The slopes of the volcano are used as coffee-plantations or pastureland. Telecommunication aerials have been built on its top which is accessible by field cars.

The regions surrounding the San Cristobal Volcanic Group belong to two climatic zones – on-shore plains and the plains in the Nicaraguan depression which belong to the tropical dry zone, which is marked by six months of dry weather and six months of rainy weather. Average annual temperatures range between 25 and 30 °C, according to altitude. Annual rainfall is 700 mm in the most arid regions, and over 1500 mm in the most rainy regions. In the studied area, the Chinandega meteorological station mentions an annual rainfall rate of 1883.4 mm, León 1487.2 mm and Corinto 1842 mm measured over a time span of 1971–1995.

The area above 500 m a.s.l. and below 1500 m a.s.l. belongs to the transitional subtropical zone, which is marked by a protracted rainy season lasting 7–8 months. The average annual temperature is 22–27 °C and the annual rainfall is between 1500 and 2500 mm. The area is often covered by clouds. Only the top of the San Cristobal volcano (1745 m) can be placed in the pre-montane zone, which is considered to lie above 1500 m a.s.l. Average annual temperature is around 20 °C and average rainfall rate is above 2000 mm.

Isolated peaks of the high volcanoes have a specific diurnal climatic regime marked by large-scale oscillations of temperature and by a converging rise of warm air during the day up the slopes of the volcanoes and by a sinking of cold air down the slopes in the morning and towards the evening.

Tropical storms and hurricanes that strike the area from time to time are usually rich in rainfall. The following values were measured by the stations during the hurricane Mitch at the end of October 1998:

Day	Chinandega	León	Corinto
28. 10. 1998	310 mm	165 mm	61 mm
29. 10. 1998	422 mm	280 mm	223 mm
30. 10. 1998	485 mm	290 mm	258 mm
31. 10. 1998	203 mm	144 mm	182 mm
During October 1998	1985 mm	1349 mm	1156 mm

During the hurricane Mitch in October 98 in the environs of the Chinandega town, the rainfall exceeded the annual rates. The foothill slopes of the volcanic groups and the near-shore plateaus and those of the Nicaraguan depression are mostly used as crop fields and pastureland. The landscape is predominantly deforested. Except for the Pan-American Highway which connects León and Chinandega and continues further to Somotillo, most of the roads are unpaved and not upgraded. The streams are not canalized. Settlement on the southern side of the volcanic groups is relatively dense. It is thin on the northern side.

3. Morphostructural units

The studied area can be subdivided as to their morphostructural predisposition into the following units.

3.1. Structural slopes of the San Cristobal volcano

The San Cristobal stratovolcano (1745) is the highest volcanic cone in all Nicaragua. Its ground plan covers an area of approximately 45 km^2 (Photo 1). The foot of the volcano lies at an altitude of about 150 m. The volcano is considered to be active. Its structural slopes are in a constant process of formation and are therefore very loose and unstable. On the eastern side, the structural slope of the volcano is formed on the eastern side by lava flows that partially cover pyroclastic fallout material. Since they are very young, no soil or vegetation cover have formed on their surface, except for grass and herbal assemblages. These lava flows are thought to be only several centuries old, they actually date back to historical times. The lava flows run round an older volcanic structure Moyatepe (917 m) and fill several maar and collapse structures on the Lago Verde lineament. They are therefore younger than these structures. The basalt lavas were very viscous and have filled every depression and the fronts of their flows extended over 9 km away from the crater. The western slopes of the volcano are covered by more or less thick layers of volcanic slag and pyroclastic flow deposits. The slags are deposited in the prevailing wind direction which is from the NE. The slags are very loose and therefore subject to intensive erosion in the form of barancos. They slid down the western slope to form a triangular planar landslide. A series of lava flows can be observed at the foot of the volcano which have a larger extent than the youngest flows and thus they have not been entirely covered by them. The thickness of the older flows is several meters and they are already covered by soils that have been able to develop on them. There are another two levels of older lava flows observed even in erosional valleys under several meters thick volcano-fluviatile deposits or under alluvial-fan deposits. The fronts of lava flows prograde up to 16 km away from the crater or 10 km away from the foothills. Several parasitic cones of volcanic slag or dacite domes occur on the slopes of the volcano.

Volcanic deposits of San Cristobal presumably cover also a part of the lower older Casita volcano which is sunken into the La Pelona caldera. The relation of San Cristobal and Casita is not entirely clear, but supposedly, San Cristobal was generated at the western margin of the La Pelona caldera on a newly formed volcanic vent and took over the main activity. The tectonic system of the Lago Verde line may also play a major role since it actually crosses the main direction of the Nicaraguan volcanic chain at the site of the San Cristobal crater.

3.2. Structural slopes of the Casita volcano

The Casita stratovolcano reaches an altitude of 1405 m and fills approximately the central part of the La Pelona caldera. It belongs to the oldest volcanos in the Nicaraguan volcanic chain. Its age is estimated to be Middle to Lower Pleistocene. At present, the

Photo 1: San Cristobal volcano. Crater Ollada on the top of Casita volcano in the foreground. (Photo 1 – 4 J. Šebesta)

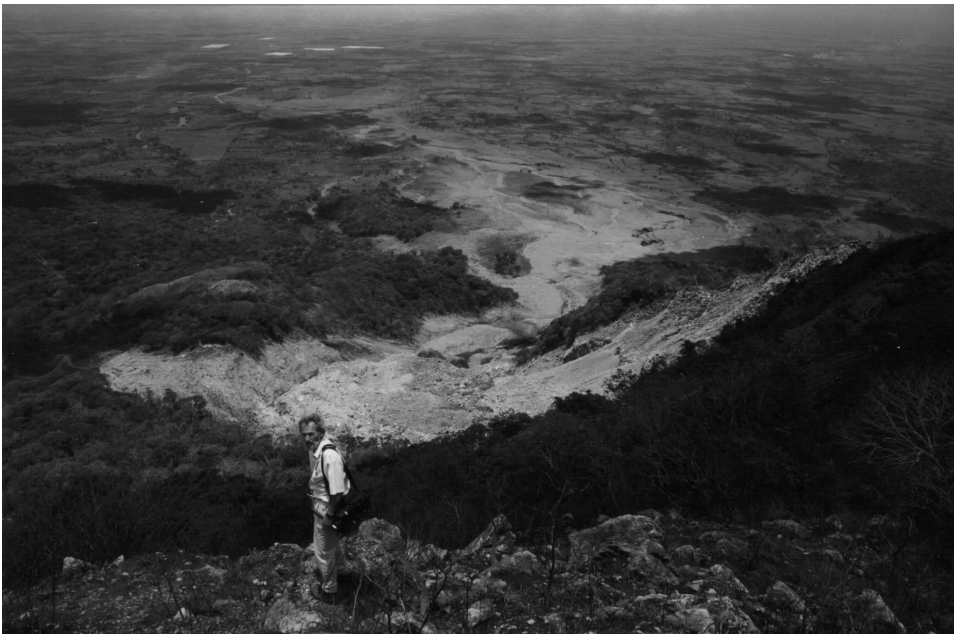

Photo 2: Overall view of the earthflow formed on October 10, 1998 on the southern slope of Casita.

Photo 3: An earthflow has changed drainage from one catchment area into another using this newly formed streambed.

Photo 4: Lava blocks several meters in size were transported over a distance of up to 6 km.

body of the stratovolcano is in a state of intensive denudation expressed mainly by erosion and slope movements.

Casita is situated at the junction of two tectonic systems – on the SE trending lineament of the Nicaraguan volcanic chain and a NNE trending transform fault system. At present, an active and extensive fumarole field lies on this junction and brings about an intensive alteration of the surrounding volcanic rocks.

A system of retreating craters with the last crater La Ollada, which is approximately 1200 m wide and more than 200 m deep, lies on the top of the volcano. The crater is not active. There is only a fumarole field in its northern portion. The top of the volcano in the vicinity of the crater is formed by disintegrated dacite lava flows. The slopes of the volcano are formed by highly altered andesite lava flows and agglomerates covered by thick slope deposits, particularly between the slope of the volcano and the rising rim of the La Pelona caldera. The thickness of these disintegrated accumulations is estimated to reach 100 m. The slopes are deeply eroded. The northeastern slopes of the volcano are covered by the youngest basalt flows and presumably, the young lavas cover the above described slope. Another fumarole field, elongated in a NW direction (the strike of the Nicaragua volcanic chain) lies near the former source of the lava flows.

The Casita and San Cristobal volcanoes were formed in the youngest caldera of the whole system – La Pelona. It is, however, older than San Cristobal. It is marked by intensively hydrothermally altered lava flows and agglomerates that provide a favorable environment for the formation of various slope movements. Slope movements of many generations produce thick accumulations of loose slope deposits which are the source of block flows, landslides and mudflows. The last major series of mudflows occurred here in 1998, during the hurricane Mitch which was marked by heavy rainfall.

The disintegrated and clayey lava flows and agglomerates that form thick layers on the slopes of the stratovolcano are an environment prone to giving birth to slope movements, and along with the heavy rainfall, they were undoubtedly the main cause for the catastrophic mudflow in October 1998 during the hurricane Mitch. The character of the slope deposits suggests that the October mudflow (Photo 2) was not the first case of this kind. These processes here have a polycyclic development that has continued since the birth of the Casita stratovolcano until today and has not finished yet. Accumulations after fossil mudflows have been registered at several localities in the volcanoclastic sediments on the southern slope of the volcano between the villages of Apastepe and Santa Narcisa.

The mechanism of formation of the catastrophic mudflow from October 30, 1998 may be reconstructed in the following manner:

The southern slope of Casita, known for the occurrence of initial slope movements, is covered by very unstable and highly altered lava flows and agglomerates that were formed near the large fumarole field lying below the top of the volcano and described above. These altered layers are covered by heaps of older block flows, small landslides, slope deposits and mudflows. Their thickness increases down the slope and reaches more than 100 m near the margin of the La Pelona caldera. A by-road that leads to the aerials at Casita's top cuts at several places mounds of block flows that are very recent and are not stabilized at all. The altered and clayey rocks form a very favorable environment for the formation and movement of block flows here. Their movement depends on atmospheric conditions. During normal rainfall they may move at a rate of 1 cm or more per day and in dry seasons their movement is brought to a standstill. During excessive rainfalls new blocks of altered rocks are broken off and the surficial loose slope accumulations are saturated with water. Their movement speeds up and may become an earthflow.

The heavy rainfall during hurricane Mitch caused saturation of the whole formidable body of foothill block-flow accumulations and additional new minor block flows from the slope of Casita disturbed the balance giving rise to a large earthflow. Similar dangerous conditions exist in the Los Maribios area and elsewhere in Nicaragua.

3.3. Structural slopes of pre-Casita

A former volcano that covered the area of the whole volcanic group of San Cristobal, Casita and La Pelona caldera is called pre-Casita. Its explosion gave rise to the explosive La Pelona caldera, whose minor part is not yet covered by new volcanoes and is located in the eastern portion of this structure, where the structural slopes of this volcano have been preserved. The slopes consist of layers of basalt and andesite lava flows, often highly altered, of volcanic ash and tuff deposits and of thick pyroclastic flows and waves. The structural flows are covered by thick layers of pumice that came from the La Pelona caldera. At present, the thickest pumice layers are found at the foot of the structural slope as cuestas. The original pumice layers are deeply eroded leaving only smaller relicts on the slopes. Indications of another two caldera-like sunken depressions can be observed on the slopes.

Several volcanic centers occur at the caldera's margin that gave rise either to lava flows – near La Concepción, Rolando Rodriguez, Argentina and SW of Colonia Santa Cruz or to small cones and flows of slag deposits (near La Concepción).

The rest of the caldera's depression is not drained by surface streams thus forming a confined aquifer. Saturation of this aquifer by the rainfall of hurricane Mitch probably caused the catastrophic "deslave" on the southern side of Casita. The bottom of the caldera depression lies at 570 m a.s.l. The foothill plains lie at 120–170 m a.s.l. therefore there is a difference in altitude of over 400 m.

The structural slopes of pre-Casita are deeply eroded, and numerous slope movements, particularly block flows and even planar landslides are not an exception. The largest planar landslide is on the northern side of the structure, west of the village of El Higueral. The landslide can be considered as fossil.

3.4. Structural slopes of the Chonco volcano

The Chonco volcano (1105 m) is situated about 5 km west of the crater San Cristobal. On its top only part of the crater has been preserved, opened northwards. A steep dacite dome Teta (660 m), around 800 m in diameter is located 1 km west of the crater on the slope of the volcano. Another dacite dome Loma Caparra (540 m) is situated 2 km NNE of the crater, it is not so steep as Teta and is smaller. Still smaller is the nearby Loma La Bruja dome which may be part of the Loma Caparra dacite dome. The steep slopes of the

Chonco volcano have their foot at around 400 m a.s.l., less steep slopes continue then down to an altitude of 200 m. The structural slopes of Chonco are built up by pyroclastic flows, waves and slags which form thick non-cohesive horizons on the present-day surface. The slags of Chonco partly cover even the structural slopes of the neighbouring San Cristobal and therefore it may be suggested that this slag is younger than the underlying pyroclastic flows and slags of San Cristobal. The slags build up mainly the steep part of the cone of the volcano. Pyroclastic flows predominate on less inclined slopes. No lava flows have been observed either on the structural slopes of Chonco or in their vicinity.

The Chonco volcano is presumed to be situated on a junction of two tectonic systems, the NW trending and the ubiquitous NE trending one, the latter having here the character of a transform fault system. It may also be estimated that it is situated at the margin of one of the La Pelona calderas. The volcano is younger than San Cristobal. Regarding the position of the two nearby dacite domes it may be suggested that theses domes are still younger.

Structural slopes made up of the non-cohesive slags are deeply eroded. The drainage pattern is relatively dense and has the form of deep erosional furrows or even smaller canyons. At the mouth of erosional furrows the water logged slags are aggraded into large and relatively thin alluvial fans. This indicates a very dynamic development of the relief.

3.5. Structural slopes of the Moyatepe volcano

The volcano of Moyatepe (917 m) lies at the foot of San Cristobal, approximately 6 km north of the crater. No crater or volcanic-cone structure has been preserved on Moyatepe. Structural slopes are built up by highly baked slags, lava flows and slag flows. The slopes here are very steep and “non-traditional”. Particularly steep and short slopes alternate with less steep and much longer ones. The structure of the volcano is sharply confined towards its surroundings. The volcano is supposed to be in a state of caldera-like irregular downwarping. The bow-like short slopes represent planes along which this downward movement takes place (a similar structure, but not so deeply sunken, can be observed in another Nicaraguan volcano, Asososca, in the vicinity of Puerto Momotombo). At present, the volcano is rimmed on two thirds of its perimeter by the youngest basalt lava flows from San Cristobal. The viscous lavas make use of a depression situated near the caldera fault. A smaller lava flow erupted from a lateral center on the northern side of the volcano.

Since the volcanic rocks that build up the structural slopes are intensively baked and permeable, almost no erosion occurs on the steep slopes and they have been preserved in their original structural forms.

3.6. Relicts of tectonic relief

Tectonic blocks probably form the basement of the whole volcano-fluviatile plain and of the volcanic area proper. In the studied area they are only exposed near the Pacific coast, 7–10 km SE of the town of Chichigalpa and NW of the village of Tonala near the Fonseca bay. These blocks consist of dacites and andesites of the Tamarindo formation of

Miocene–Pliocene age. The relief here is moderately wavy. Moderately rising hills are formed by relatively little weathered cores of the tectonic blocks. Dacites in particular weather here into big ball-shaped or oval blocks. The original blocks were confined by cracks that served as nucleii for the weathering processes.

Intensive weathering and subsequent denudation progressed also along the faults. At present, the depressions between the single blocks are filled by the Leon formation, often overlain by volcano-fluviatile deposits or by the youngest alluvial deposits.

3.7. Volcano-fluviatile plain

Polycyclic volcano-fluviatile deposits form a relatively flat and mildly inclined relief round the groups of volcanos. The slopes dip away from the foot of the volcanos towards the SSW, towards the Pacific Ocean, westwards and northwards to the Fonseca bay and towards the Estero Real depression. The surface of the volcano-fluviatile deposits lies at an altitude from 0 m to 250–300 m on the Pacific side and from 0 m to 50–100 m on the northern side, towards the Nicaragua depression. The drainage pattern on the surface of these deposits is similar to that on the flat alluvial fans. In places, the streams aggrade and form flat alluvial fans, elsewhere they are deeply incised forming canyon-like erosion furrows. The volcano-fluviatile deposits are mainly loose with frequent inhomogeneities in their lithological composition. They contain, above all, distal portions with more or less lithified wind-deposited or water logged ash, slag layers, pumice, pyroclastic waves and flows, trough interbeds with sandy or gravelly fill, fossil flash floods and block flows and many other deposits of transitional character. Interbeds of fine-grained lacustrine sediments consisting of water logged ash have also been observed. Resistent buried lava flows also occur in some places.

The ratio between erosion and aggradation must have changed constantly, as is shown by the case from Las Mercedes at the foot of Casita. Old Indian engravings, previously covered by 1.5 m thick water logged deposits, have been exposed in the bed of a nameless stream. The age of most of the deposits is estimated to be Plio-Pleistocene, as is the age of the volcanic group which acted as the source. The polycyclic volcano-fluviatile deposits level up the complicated buried tectonic relief, formed by tectonic blocks of the Miocene Tamarindo formation.

3.8. Independent volcanic structures and centers

The main stratovolcanoes are accompanied by a number of minor volcanic centers of various origin. They are usually situated on tectonic lines or at margins of the calderas. Maars predominate in the San Cristobal and Casita area. Smaller slag cones, a tuff cone, dacite domes and sources of parasite lava and slag flows are also present.

The “Laguna Verde” fault line is significant. It strikes NNW and the main crater of San Cristobal is situated on it. On the slope of the stratovolcano there is a minor slag cone which lies on a probable junction of the “Laguna Verde” line with the La Pelona caldera. The line continues then along lined-up maars. The maars are rimmed by small erupted mounds. At present, two maars are filled by basalt lava flows. In Laguna Verde the maar is flooded by a lake.

The tuff cone Acastepe (320 m a. s. l.), which is approximately 1.5 km in diameter and 160 m in height, is an exceptional structure. There are several groups of maars on the southern margin of the San Cristobal and Casita volcanic groups. Lugar La Hoyada consists of three maars lined-up in NW direction. The largest maar is approximately 800 m wide and up to 140 m deep. The maars are periodically flooded. Lugar El Arenal is another group of three maars. The largest maar is over 1 km wide. At present, these maars are eroded. There are two maars at La Joya, they are drainless and are around 800 m in diameter and 70 m deep. All maar lines are oriented towards NW.

There is a line of four maars north of the Telica volcanic group near the village of El Portón. These maars are partially filled with volcano-fluviatile deposits and only parts of the mounds have been preserved. Their diameter are about 1 km. The maars are rimmed by more or less extensive mounds.

4. Dynamic relief development

4.1. Stages of terrigenous development of the relief

The volcanoes of the San Cristobal group are presumed to be of Pliocene-Pleistocene age. The San Cristobal volcano is constantly active. The Cordillera De Maribios to which this group belongs, is approximately 70 km long and begins with the Momotombo volcano in the south. The volcanic group forms its northernmost closure, approximately 20 km long. The line of volcanoes lie at a distance of 25 km from the Pacific coast. The foothills of the volcanic chain have a difference in altitude of about 150–200 m on the southern and northern sides respectively. This is caused by the fact that the northern margin lies in the tectonically sunken Nicaraguan depression. In the studied area the Nicaraguan depression is about 30 km wide.

The group lies at the SW margin of the Nicaraguan depression, which is tectonically and volcanically most active. The SW margin of the Nicaraguan depression does not show a simple and continuous course. It is relatively often dismembered by transversal transform faults or pull aparts and shaped in addition by tectonic phenomena related to volcanic activity (Wyk de Vries 2000). A large number of minor subsidiary volcanoes and volcanic centers occur in the San Cristobal volcanic group – slag and tuff cones, calderas, maars and collapse structures.

Approximately 15 km NE of the line of volcanos, there is the lowest part of the Nicaragua depression, the Fonseca bay that gradually passes over into a very shallow depression drained by the Estero Real river. The depression is filled with thick volcano-fluviatile polycyclic deposits. The coast of the Pacific Ocean, distant approximately 25 km from the depression, is to the SW. The tectonic blocks of the Miocene-Pliocene volcanic Tamarindo formation also occur here. The blocks consist of thick dacite and andesite lava flows and ignimbrites. South of the town of Leon, 200 to 300 m high tectonically predisposed mesas formed. Pyroclastic flows and waves of the Leon formation were later deposited in the depressions that had formed between the single tectonic blocks. It is estimated to be of Pliocene age. Towards the north this formation is again covered by polycyclic and polygenetic volcano-fluviatile deposits. The plains covered by these deposits form a considerable part of the foothills of the volcanic group.

Table 1: Stages of terrigenous development of the relief

Miocene and Pliocene: Beginning of development of the Nicaraguan depression and formation of relief of the coastal Pacific zone.
Lower Pleistocene: Deposition of pyroclastic flows and pyroclastic waves of León formation on the tectonic relief and beginning of formation of a polycyclic and polygenetic volcano-fluviatile plain. Genesis and development of pre-Casita volcano and continuation of development of volcano-fluviatile deposits.
Middle Pleistocene: Beginning of stage-wise development of La Pelona caldera with deposition of several layers of pumice and rise of dacite domes of Loma San Lucas, Loma Ojo De Agua and Lama San Isidro.
Middle to Upper Pleistocene: Effusions of lowermost lava flows and beginning of formation of inner caldera volcanoes Casita and San Cristobal.
Upper Pleistocene: Genesis of Loma Acastepe tuff cone; beginning of formation of volcanos Chonco (phase of pyroclastic flows) and Moyatepe (phase of lava flows and slag flows); lava flows (lower) from San Cristobal and Casita.
Holocene to historic times: Genesis of maars on Lago Verde lineament and of a maar SE of Colonia Hermanos Garcia, maars Lugar La Hoyada, Lugar El Arenal, maars near La Joya on south slope of pre-Casita.
Historic times: Lava flows (upper) from San Cristobal, Casita and Moyatepe, pyroclastic flows and slags from San Cristobal. Slag-dominated phase of Chonco. Dacite domes of Loma La Teta, Loma Caparra, Loma La Bruja.

4.2. Tectonic predisposition of relief development

The Nicaraguan depression, with the San Cristobal volcanic group at its SW margin, has probably been spreading since the Upper Miocene and it is its SW margin that has mainly been active. Because the spreading is not regular, partial dismembering of the SW flank of the depression takes place along transform faults or even pull-aparts (e.g. the Managua pull-apart, Frishbutter 1997) accompanied by the formation of calderas and tectonic movements linked with volcanic activity.

In the studied area the volcanism shows a lined-up structure but always only within the individual groups. The volcanic line of the San Cristobal group strikes ENE but it is not connected with the volcanic line of the Telica group, which has a similar strike, but is shifted 8 km southwards. Provided that the volcanic activity is related to the margin of the Nicaraguan depression, an important transform fault between both volcanic groups can be presumed. The transform fault line probably runs between Posoltega and the village of Mocoron (Comarca Las Marias) and is called La Pelona fault (Wyk de Vries 1993).

Major volcanoes form usually on the junction of several fault systems. The San Cristobal volcano lies on the junction of the line of the Nicaraguan depression, of a NE striking fault system and of the important almost N – S striking Laguna Verde fault line, which is, however, visible only in the Nicaraguan depression but does not appear on the SW flank of the depression.

The Casita volcano lies on the marginal fault of the Nicaraguan depression, where it crosses a NW trending fault and faults running in NE and N – S directions. Unlike in the San Cristobal case, the N – S trending faults are recorded here only on the external margin of the depression.

The main volcanic centers are situated along the faults corresponding to the theoretical margin of the Nicaraguan depression and along the faults that accompany them. The area around Casita is affected by intensive hydrothermal alteration of surrounding volcanic rocks caused by fumaroles.

The resulting tectonic segments confined by deep transform faults and by marginal faults of the Nicaraguan depression are separated into minor tectonic blocks. These blocks are limited by NE trending faults running perpendicularly to the theoretical SW direction of the margin of the Nicaraguan depression. The density of these NE trending faults is relatively high. We suppose that they are rather closely packed fracture zones being mostly used by selective hydrothermal alteration and by fumaroles. They subsequently influence the development of drainage or they act as root areas for landslides and other slope movements.

The parallel SW trending faults on the SW flank of the Nicaraguan depression with the youngest volcanic centers (maars, effusions of young lavas etc.) are considered to be the youngest faults. They may represent another stage of the spreading of the Nicaraguan depression.

A gradual shifting of active craters from the east to the west can be observed in both the San Cristobal and the Telica volcanic groups. This may be caused by overall trend in the subduction of lithospheric plates.

4.3. Assessment of the dynamic relief devolopment

Development of the relief of the San Cristobal volcanic group is mostly influenced by volcanic activity as a consequence of tectonic unrest on the subduction zone of the Mid-American trench, where the oceanic Cocos plate descends beneath the Caribbean plate. The Pacific zone of Nicaragua is marked by high Mioene-Pliocene, Pleistocene and recent tectonic activity in the formation and spreading of the Nicaragua depression. Tectonic development on the SW margin of the depression is accompanied by intensive volcanic activity which leads to the formation of the Nicaraguan volcanic chain with the San Cristobal volcanic group as one part. Mainly stratovolcanoes as well as smaller slag cones and tuff cones, maars, collapses etc. form in the Nicaragua volcanic chain. Development of the relief is mostly influenced by volcanic activity. Above all, positive surficial volcanic forms and volcano-tectonic structures (mainly calderas) are generated.

The Nicaraguan depression develops in this part as a very shallow sea bay, Fonseca, which continues inland as broader depressions Estero Real, Olomega and Tecomapa. Its altitude is minimal, 1–20 m. Here, the sinking of the Nicaraguan depression is not so prominent, but it is evident that the northern foot of the volcanic group is situated lower than its southern foot by 150–200 m.

The young relief shaped by endogenic activity is exposed to intensive exogenic processes linked with the warm humid climate, which results in the high dynamism of relief development. The newly generated volcanic forms are then shaped by exogenic processes, particularly by erosion and other processes such as mass wasting, processes of mass movements, transitional accumulation in the form of aggradation in alluvial fans and by weathering.

The age of the relief of the San Cristobal volcanic group is thought to be Pliocene-Pleistocene. The basement of the volcanic groups is most probably formed by tectonic blocks of the Coyol and Tamarido formations, which are of Miocene-Pliocene age. The Pliocene ignimbrites, developed in great thicknesses in the environs of Managua and Granada, have not been observed in this area.

Volcanoes of the San Cristobal group have a polygenetic and polycyclic character. The system of La Pelona caldera gave rise to the stratovolcanoes San Cristobal, Casita and probably also to the volcanoes Chonco and Moyatepe. Obviously the most conspicuous is the youngest margin of La Pelona caldera, but there are two or three older stages of the caldera, a fact indicated by pumice fall out. San Cristobal and Casita were formed as new volcanoes in La Pelona caldera. The San Cristobal stratovolcano has covered the original extent of the caldera, Casita only its part.

An important phenomenon in this area is the development of extensive polycyclic and polygenetic volcano-fluviatile deposits. Their lithology corresponds to that of similar deposits in the surroundings of the Fuego volcano in Guatemala described by Vessell, Davis (1978). These deposits are devoloped in the southern part of the Nicaragua volcanic chain only locally or not at all.

Formation of the volcanic groups probably took place in phases. Criteria for assignment into the individual phases are the mutual relations of single volcanic centers and their products, degree of weathering and denudation of the surface, or of the whole volcanic structure in relation to their geomorphological position and to the areas of accumulation.

5. Exposure to geological risks

5.1. Types of geological risks

The studied region comprises areas that are actually or potentially exposed to high-degree geological risks. These risks are of either endogenic or exogenic character. The most recent case is the devastation of the area by the hurricane Mitch in October 1998.

The extremely high rainfall that accompanied the hurricane resulted in a natural catastrophe caused in this case by exogenic processes. These extreme climatic conditions lasted only less than a week. The list of damages is already widely known. The objective of this study is to elucidate the processes that occurred and which may occur in the future.

Table 2: Geological risks

Endogenic risks Renewal of volcanic acitivity: fall-out of ashes and slags, effusions of lava flows, devastating pyroclastic flows and lahars, formation of monogenetic volcanic centers (maars, slag cones, tuff cones, lava effusions etc.), intensive hydrothermal alterations of volcanic rocks.
Seismic activity: accompanying volcanic activity, re-shaping of calderas (active margins of calderas), movements on transform faults, movements on marginal fault of the Nicaragua depression (induced by movements on subduction zone of the Mid-American trench).
Exogenic risks Extreme rainfall causes: intensive areal erosion of soil, intensive vertical erosion, lateral erosion of stream banks and widening of stream beds, enormous transport of alluvial materials and their deposition in the form of superficial accumulations in alluvial fans or in flash floods, genesis of enormous slope movements as effects of intensive (subterranean) erosion, large-scale oscillation of ground-water level (hydrostatic pressure).

5.2. Volcanic risk

An active volcanic region is a potential focus of volcanic activity even though a number of volcanic centers lack any historical eruption record. In the world there are, nevertheless, cases of a sudden renewal of volcanic activity in volcanoes known for being extinct – the geographically nearest cases are the volcanos of El Chichón and Arenal.

The only actually active volcano is San Cristóbal, which erupted several times in the historical record. The main products of its eruptions are phreatic ashes or effusions of basalt lavas. The ashes can cover not only the body of the volcano and its foothills but they may also endanger the town of Chinandega owing to the prevailing winds of SW direction. The fall-out of basaltic ash may not only endanger the town and the surrounding villages but it may also destroy agricultural land, contaminate water and cause respiration deseases of the population.

An much greater risk may be represented by possible strong pyroclastic eruptions which were described in geological records in the past. Pyroclastic flows and the lahars derived from them seem to be the most devastating.

The main risk which may be caused by the San Cristobal volcano is a hypothetical extrusion of an acid and gaseous magma into a near-surface chamber and subsequent explosions of a Plinian type.

Rejuvenation of volcanic activity of the Casita volcano represents a relatively lower risk. However, opening of lateral volcanic centers on its slopes, particularly in the case of magma ascension along active faults or joint systems cannot be excluded. Another risk on Casita is the existence of deeply altered zones on fossil or present-day fumaroles. The rise of entirely new, small volcanic centers (slag cones) which may produce slags, ashes or lava flows at limited distances must also be considered. This situation was recorded in August 1999 when three volcanic centers suddenly formed near the foot of the

Nicaraguan volcano Cerro Negro and were active for a week. These centers are located on a fault line near the active volcano.

5.3. Seismic risk

Most of the studied area is exposed to seismic risk. The zoning of degrees of seismic risk has been compiled on the basis of the present state of knowledge of the dynamic tectono-volcanic development of the area.

The highest degree of seismic risk may be expected to occur within the caldera area of both volcanic groups and in the surroundings of active volcanoes. The sinking of the La Pelona and Telica calderas is not completed and it may therefore be expected that this downward movement accompanied by earthquakes will continue.

Another source of earthquakes is situated on the SW margin of the Nicaragua depression and on NNE trending tranform faults and on accompanying faults (e. g. the Laguna Verde lineament).

All the described areas are not densely populated and are not the subject of any important economic activity. However, these areas must be respected in the case of any future land-use planning. Agricultural use of these areas is also considerably limited.

At present, there are monitoring stations of INETER located near all active volcanos, including San Cristobal and the measured data are transmitted to Managua.

5.4. Exogenically derived risks

Extreme rainfall which causes a number of exogenic processes with a high degree of risk is the most important exogenic element. The higher the rainfall the greater the risk. A young and constantly changing relief is exposed to exogenic processes which shape it rapidly. Erosion is very intensive. During heavy rains the eroded material is transported in large quantities into tectonically derived depressions, where it accumulates in the form of alluvial fans.

Intensive flood-sheet erosion occurs during heavy rains on loose volcanic ashes, slags, maar ejecta etc. Erosion is mostly active at the frontal parts of the drainage system and is very often combined with slope movements and with subterranean erosion (processes of “mass wasting”). In the studied area an intensive sheet erosion affected particularly the structural slopes of the Chonco volcano, the western slopes of San Cristobal, and the slopes of Casita and the La Pelona caldera. Sheet erosion on the slopes of Cerro Montoso, Cerro Aguerra and Telica was very intensive.

Intensive vertical erosion. Some stream beds are deepened during the floods at a rate of tens of centimeters or even meters. Since the relief is young, the erosion curve is rapidly levelled (Photo 3). Vertical erosion is particularly high in the upper courses of streams or on alluvial fans that reached maximum rate of aggradation. Vertical erosion strikes selectively forming benches on the streams, particularly on more resistent lava flows.

Lateral erosion of streambeds and their broadening progresses rapidly during floods in particular in the stream bends or at any place with an obstacle in the stream. The obstacle may be a fallen tree trunk or a new accumulation of gravel. Intensive lateral erosion occurred at many places during hurricane Mitch. Lateral erosion damaged built-up areas near the town of Posoltega.

Transport of floating material and its accumulation. Erosion produces large quantities of material. This material is later accumulated in alluvial fans or is transported on the surface during sheet floods (Photo 4). Formation of alluvial fans is related to levelling of the erosion curve on a young relief. In the studied area the largest accumulations occurred in the environs of Comarca Las Marias and at several places north of the road Villa 15 Julio – El Higueral, near the mouth of the rivers Olomega and Estero Real. A large quantity of slag was accumulated at the feet of the volcanoes Telica and Cerro Montoso near Colonia Cristo Rey and at the western foot of San Cristobal and Chonco during hurricane Mitch.

Slope movements are widespread mainly on the structural slopes of the volcanoes. They are predisposed by the slope configuration, by high rainfall, non-cohesive volcanic deposits, by hydrothermal alteration of lava flows and agglomerates and by specific hydrogeological conditions.

Hurricane Mitch generated a catastrophic flash flood and a series of other slope movements. Study of the newly exposed sections in volcano-fluviatile deposits has confirmed that these floods occurred on several occasions in the recent geological history. The flash-flood deposits form part of the volcano-fluviatile sequence.

Several types of slope movements have been observed in the studied area: block flows, planar landslides, polygenetic landslides, rock collapse and particularly flash floods. The Casita volcano and the structural slopes of the caldera are mostly affected, with numerous relicts of block flows, various polygenetic landslides, collapses and flash floods being preserved on their slopes. A relatively extensive planar landslide has been observed on the western slope of the San Cristobal volcano. Minor, but numerous polygenetic landslides and block flows occur on the slopes of the Cerro Montoso and Cerro Aguera volcanos in the Telica volcanic group.

Subterranean erosion is an unconspicuous agent which, neverthelesss, causes intensive denudation of surface and accelerates sheet erosion and deep erosion. Subterranean erosion is mainly active in highly permeable rocks suchas slag, volcanic ashes, tuffs, low-baked pyroclastic flows and waves. Large quantities of soaked-in water dissolve soluble minerals and remove the finest fractions. Thus, the water-logged rock becomes even more non-cohesive and is rapidly eroded.

Ground-water circulation is very vivid in this area. The rocks are very permeable here and are able to take up enormous volumes of water. They are also easily dewatered. The climatic cycle and changes of weather also influence the ground-water level. The frequent and great oscillation of ground-water level causes, besides flushing of the fine fraction and soluble minerals, also changes in hydrostatic pressure which bring about an intensive decomposition of inhomogeneous rocks.

Exogenically derived risks can be summarized as follows:

a) Streambeds are places of high, deep-incised erosion and it may happen that a newly built pier is laid bare and the static balance disturbed. The pier may crumble down or may be entirely washed away.

b) Intensive lateral erosion is active in canyon-like valleys of the streams during inundations and may erode the surroundings of a pier and cause its destruction.

c) In areas with volcanic and volcano-fluviatile deposits rapid ground-water circulation related to climate may cause great changes of hydrostatic pressure that may affect the foundations of a building and bring about its vertical movement. If the hydrostatic pressure is higher than the resistance of the building, the building may be subject to periodical movements and may crack. These phenomena can also occur on causeways. The movement may reach a rate of 10 cm or more. The pier may collapse.

d) In young loose rocks an intensive compaction takes place. It does not reach the same speed in every single rock. It is different in gravels or in volcanic ashes. It is therefore necessary that the buildings be founded in possibly one rock type, where the compaction is homogeneous. Differences in the compaction rate beneath different parts of the buildings may cause their cracking and crumbling. To prevent these effects, it is necessary to use better foundation technologies, which, indeed, are very costly.

e) Intensive compaction or subterranean erosion of artificially dumped material takes place also on access causeways of bridges that must be reinforced and protected from excessive soaking in of rain water.

f) Access dirt roads must be protected from erosion. It has been verified by practice that steeper sections of a road must be equipped with frequent oblique runnels leading into the nearest drainage, whereas the less steep sections need not. If the road is not equipped with anti-erosion runnels it often happens that the road becomes a new drainage course and it even taps up the original drainage pattern. Thus, the man-made drainage stops working and the road takes over its role. Heavier rainfall may then cause unforeseeable inundations in places where they have not been expected.

g) Deforestation is a very dangerous agent, accelerating soil erosion and outflow of rain water. Deforestation is one of the causes of catastrophic effects of heavy rainfall. Landscape-development projects should rely on aforestation, mainly where the woodland fulfils its anti-erosion role in soil and prevents rapid inundations.

6. Recommendations and conclusions

To minimize the destructive effects of natural catastrophies, particularly floods, we recommend simple amendments in streambeds and on roads.

1. We recommend the cleaning of streambeds by removing the drift consisting of trees, roots and branches deposited there during the hurricane Mitch. This drift may form obstacles during the subsequent inundations, the water may form dams in the streambeds, the streams may form a new bed and inundate fields and villages in the surroundings or erode soil.

Organic drift may also be trapped on new bridges, form dams and the water in seeking new streambeds may erode the piers of bridges, erode access causeways or the roads themselves in areas located farther away from the bridge.

2. It is important to remove large blocks of rocks and coarse gravel that were deposited in the streambeds during the hurricane Mitch. These coarse deposits have the same effects

as tree-trunks, roots or branches. We recommend removal of the gravel with bulldozers towards the stoss-sides of the streams to minimize lateral erosion during floods, to reinforce the banks and to streamline future floods.

3. It is necessary to remove unstable trees and bushes growing on streambanks that might be torn away during future floods and might cause damming of the streambeds and overflowing of the areas surrounding the streams.

4. We recommend the planting of a protective belt of deep-rooted trees along streams at a distance of at least 10 m from the banks. The root system will reinforce the banks and prevent their possible erosion. The distance of 10 m from the banks is necessary to prevent erosion of the trees and their removal by flood.

5. To prevent a gradual broadening of streambeds or their displacement, it is important to tear down sharp edges of the canyon-like valleys. The vertical valley banks are constantly eroded and they collapse. An ideal solution is to shovel the gravel infil of the streambeds towards the banks and cover it by the material from the canyon edges. Thus the bank will become gradually milder and be covered by vegetation which will prevent its destruction by erosion.

6. Foundations of bridges and buildings in the vicinity of streams must be made at least down to a depth of 10 m. There are several reasons, the intensive vertical erosion being one of them, another is the intensive compaction of young loose rocks. Constant changes in hydrostatic pressure due to oscillating ground-water level throughout the year has a negative impact on building foundation. Piers must be constructed possibly several meters away from the stream proper to keep them from the reach of lateral erosion.

Three main regions have been proposed as to the degree of their geological risks. Risks of endogenic and exogenic character, which are usually combined with each other, have been taken into consideration.

The region with **high-degree geological risk** encompasses the area of major volcanoes and their vicinity – San Cristobal, Casita and Telica. The risk consists above all in a possible renewal of volcanic activity, particularly in the form of ash-dominated eruptions and emissions of gas. Although the probability of a strong (phreatomagmatic) eruption is relatively low, possible pathways of distribution of the most devastating volcanic products – pyroclastic flows and lahars have been suggested. The region involves caldera systems around the above mentioned volcanos and the Laguna Verde tectonic line on which seismic activity and possible volcanic activity on minor, monogenetic volcanic centers is expected. The slopes of the volcanoes are exposed to intensive erosion in incohesive slags and other fall-out material. Slope movements, in particular on the slopes of Casita, are a great risk here.

The region of **medium-degree geological risk** involves particularly the feet of the largest volcanoes. This area is within the reach of presumed distal volcanic manifestations or of volcanic activities at minor volcanic centers. Intensive erosion, but also possible accumulation of clastic material on foothill slopes, occur here. Seismic activity can be expected to occur mainly along the major faults.

The region of **low-degree geological risk** is situated mainly on the volcano-fluviatile plains. These areas are also marked by minor erosion as well as accumulation. The region is situated outside possible effects of volcanic risk.

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DYNAMICKÝ VÝVOJ RELIÉFU A GEOLOGICKÁ RIZIKA VULKANICKÝCH SKUPIN SAN CRISTOBAL A CASITA V NICARAGUI

Résumé

Vulkanickou skupinu San Cristobal představují především dva stratovulkány, které vznikly v kaldeře La Perona a řada dalších menších sopek a vulkanických center. Tato vulkanická skupina se rozkládá na JZ okraji nicaraguyské deprese a její polycyklický vývoj probíhá od pliocénu až do současnosti. San Cristobal je aktivní, zatímco sopka Casita je pokládána v současné době za neaktivní. Nápadné jsou však intenzivní hydrotermální alterace jejích lávových proudů a dalšího vulkanického materiálu. Povrch těchto vulkánů je tvořen několik desítek metrů mocnými polygenetickými svahovými sutěmi, které jsou na jílovitě zvětralém podloží nestabilní. Po hurikánu Mitch v roce 1998 zničil katastrofický bahnitý proud dvě vesnice.

Studovaná oblast vulkanické skupiny San Cristobal je známá vysokým stupněm exodynamického, vulkanického a seismického ohrožení. Byla stanovena území tří hlavních stupňů geologických rizik s kombinacemi těchto přírodních ohrožení. Region s vysokým stupněm geologického rizika zahrnuje hlavní vulkány San Cristobal, Casita a Telica a jejich okolí. Riziko spočívá především v možném obnovení aktivity vulkánů, v seismicitě tektonické zóny Laguna Verde a ve svahových pohybech a intenzivní erozi na svazích sopek. Region středního stupně geologického rizika představují zejména úpatí největších vulkánů a region s nízkým geologickým rizikem je na vulkanicko-fluviálních plošinách, a to mimo dosah přímého vlivu vulkanického ohrožení.