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VOLCANIC NATURAL DAMS ASSOCIATED WITH SECTOR COLLAPSES: TEXTURAL AND SEDIMENTOLOGICAL CONSTRAINS ON THEIR STABILITY

L. Capra

Instituto de Geografia, UNAM. Coyoacan, 04510, Mexico D.F., Mexico

INTRODUCTION

The occurrence of sector collapse and debris avalanche at Mount St. Helens in 1980 brought to light the recognition of uniquely hummocky morphology of many analogous avalanches at volcanoes around the world (Francis & Wells, 1988; Siebert, 1984; Siebert *et alii*, 1987; Ui & Glicken, 1986; Vallance *et alii*, 1995). Subsequent studies revealed the occurrence of edifice collapses at several of the better-known volcanoes of the world. Since a debris avalanche is a very rapid gravitational flow, its emplacement generally changes the volcano morphology, e.g. by blocking the river network. The emplacement of the Mount St. Helens debris avalanche produced two main natural dams (Coldwater, Castle Creek) and raised the level of Spirit lakes by 60 m (Figure 1). Artificial stabilization by spillways obviated subsequent rupture. Volcanic debris avalanche deposits are not the only responsible of dam formation in volcanic settings, in fact, if the geomorphologic characteristics of the surrounding area are appropriated, other types of volcanic flows such as pyroclastic flows or no-cohesive debris flows can block the drainage. Generally, in these cases, the resulting dams are smaller in volume and of shorter duration. In this paper a bibliographic recompilation of volcanic natural dams is presented, and based on it, all the parameters controlling dam formation, duration and type of rupture are analyzed and discussed. In particular, ASTER images are used to illustrate the best studied cases, and, where sedimentological data are available, discrimination diagrams are used to illustrate the relation between dam dimension/duration vs. the type of volcaniclastic material involved in its formation. Finally, the best-studied examples are used to illustrate the different aspects of volcanic dam formation, duration and failure.

TERMINOLOGY

A debris avalanche is a rapidly moving, incoherent, and unsorted mass of rock and soil mobilized by gravity (Schuster & Crandell, 1984). Two end member facies define the deposit texture (Glicken, 1991): block facies and mixed (or matrix) facies. The block facies is composed mainly of debris avalanche blocks (unconsolidated pieces of the old mountain transported to their place of deposition) with practically no matrix. The mixed facies is a mixture

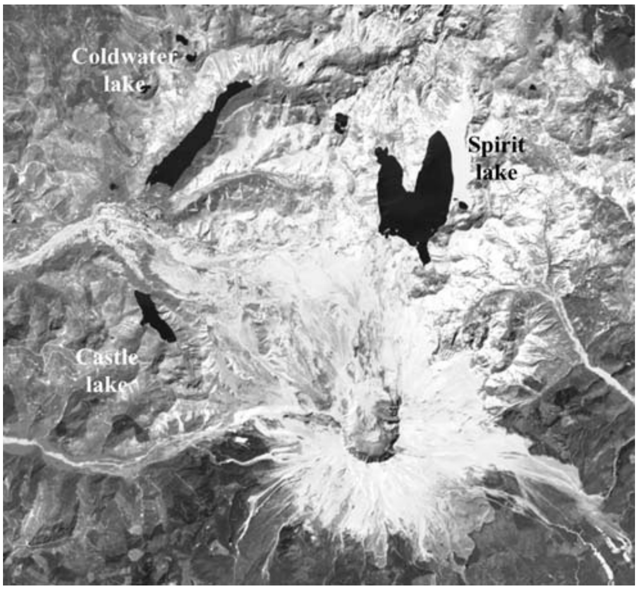

Figure 1 - ASTER image of the Mount St. Helens showing the two new lakes (Coldwater and Castle) formed by the emplacement of the debris avalanche deposit during the May 18, 1980, eruption. The pre-existing Spirit lake underwent an increase in level of approximately 60 m

of clast and interclast matrix and may contain clasts of all rock types and sizes from millimeters to meters. This differentiation is fundamental because these facies control the stability of a natural dam.

In proximal areas, the surface of volcanic debris avalanche deposits generally is made of mounds (hummocks or cerrillos) consisting of single debris avalanche blocks; in distal areas the surfaces are generally flat, with fewer mounds but with lateral levees and an abrupt front. A debris flow is a flowing mixture of debris and water with a sediment concentration between 70 and 90% by weight (Pierson & Costa, 1987). When the content of clay fraction is >3-5% by weight, they are defined as cohesive debris flows (Scott *et alii*, 2002). A lahar is a general term for rapidly flowing water-saturated mixture of rock debris and water from a volcano, which emplaces different types of debris-flow deposits (Smith & Fritz, 1989).

ORIGIN OF VOLCANO INSTABILITY

The instability of a volcanic edifice is dependant on many factors directly related to volcanic activity as well as exogenous processes such as weathering. The volcanic factors include direct magmatic intrusion into the edifice (Bezymianny-type activity, GORSHKOV, 1962) or subvolcanic crust (DAY, 1996; ELSWORTH & VOIGHT, 1996), deposition form voluminous pyroclastic deposits on steeps slopes (MCGUIRE, 1996), hydromagmatic processes (DZURISIN, 1998), and phreatomagmatic activity (Bandai-type activity, MORIYA, 1980).

The structural setting of the volcano may influence the direction of collapse and, in some cases, faulting may trigger collapse (LAGMAY *et alii*, 2000; MCGUIRE, 1996; SIEBERT, 1984). In addition, the volcano mass may induce isostatic flexure, compactation and deformation that can lead directly to collapse (BORGIA, 1994; VAN WYK VRIES & BORGIA, 1996; VAN WYK VRIES *et alii*, 2001).

Although simple gravitational failure may occur in response to progressive weakening of an edifice, discrete triggering mechanisms are commonly independent of the processes producing edifice instability. KEEFER (1984) established that numerous large landslides during historic times were triggered by earthquakes. SCHUSTER & CRANDELL (1984) determined that approximately 35% of landslides causing natural dams were seismogenic. The most recent example of a catastrophic seismogenic flow from volcanic terrain occurred in 1994 at Nevado del Huila volcano (Colombia) in response to an earthquake of 6.4 M (SCOTT *et alii*, 2002). Here saturated by recent rainfall, more than 3000 shallow failures coalesced with flank collapses to produce a single wave of cohesive debris flow that traveled over 100 km and caused as many as 1000 fatalities. Other triggering mechanisms include phreatic explosions and precipitation. A hurricaneinduced rainfall triggered flank collapse at Casita volcano in Nicaragua in 1998 killed 2500 people (SHERIDAN *et alii*, 1999; SCOTT *et alii*, 2004).

Progressive weakening of a volcanic edifice by hydrothermal alteration is an indirect factor leading to collapse (CAPRA, 2000; CARRASCO-NUNEZ, 1993; FRANK, 1983; VALLANCE & SCOTT, 1997); e.g. cohesive debris flows directly mobilize from flank collapses of saturated, highly altered and clay-rich material (CROWLEY & ZIMBELMAN, 1997; SCOTT, 1985; VALLANCE & SCOTT, 1997). In general, cohesive debris flows may also originate in other ways, such as: 1) transformation during transport of the distal portion of a water-saturated debris avalanche (PALMER & NEALL, 1989), 2) post-depositional remobilization of water-saturated portions of a debris avalanche (GLICKEN, 1991), and 3) rupture of natural dams produced by debris avalanches (CAPRA & MACIAS, 2002; COSTA, 1988; COSTA & SCHUSTER, 1988). This last case is very important because dam rupture associated with cohesive-debris flows may be more devastating than the initial debris avalanche that caused the river-blockage.

VOLCANIC NATURAL DAMS

The emplacement of a debris avalanche generally modifies the topography of the area around the volcanic edifice and provokes the interruption of the drainage. Therefore, the formation of natural impoundments by blocking the river network system and their subsequent rupture should be a common process in volcanic terrains. SCHUSTER & CRANDELL (1984) determined that, of all the known cases of natural dams, 9% of the causalities were associated with volcanic collapse. A resume table of all known cases of volcanic natural dams associated to volcanic collapse is here reported (Table 1). In the literature it is possible to found other examples not directly associated with a volcano collapse, including: 1) the 1982 eruption of the Chichon volcano (Mexico) where block-and-ash flow deposits blocked the Magdalena river forming a $26x10^6$ m^3 dam which failed after approximately two months (MACIAS *et alii*, 1984); 2) the 1992 Pinatubo eruption, where several post-eruption lahars obstructed the Mapanuepe river (UMBAL & RODOLFO, 1996); 3) the 1980 rainininduced Polallie Creek landslide that formed a dam on the east Fork Hood River which broke after just 12 minutes (GALLINO & PIERSON, 1985). All of these cases demonstrate that different types of volcaniclastic deposits can produce natural dams and, depending on the type of material and deposition rate, the duration of the dam and the characteristics of secondary flows associated with its failure will change.

Valley morphology is fundamental in determining the formation of natural dams. As noted by COSTA & SCHUSTER (1988) volcanic natural dams correspond to type III of SWANSON *et alii* (1986) where the dam fills the valley from side to side and move considerable distances upvalley and downvalley blocking other tributary rivers to the main valley.

SCHUSTER *et alii* (1986) showed that the duration of a natural dam depends on: 1) volume of the dyke; 2) type of material; and 3) inflow rate. This author presents an analysis of the duration time and he found that the 90% of the dams failed during the first year. This scenario is not probably appropriated for volcanic natural dams since they generally resist longer. In fact, the volume of the mass produced by the volcanic collapse is generally higher than 1 km^3 and produces a dyke thicker than 100 m. In addition, because of the greater cohesive strength of the volcanic material, it can resist to fail over the load of the water-lake. In the best studied cases of this type (i.e. Volcan de Colima, CORTES, 2002; Nevado de Colima (Mexico), CAPRA & MACIAS, 2002 and Nevado del Huila (Colombia), PULGARIN *et alii*, 2001) 10-20 m thick lacustrine sequences found in the infilling area indicate a longer duration for the dam.

Natural dams generated by volcanic collapses are one of the most voluminous examples, with a reservoir capacity ranging from $30x10^6$ m^3 to 1.5 km^3, and their rupture generates very large debris flows. The obstruction generally occurs in the proximal zone, at the base of the volcanic edifice, where the debris avalanche may consist of the block facies only (with no matrix). In particular, it appears that these types of dams resist longer than other types by reaching equilibrium in their hydrological balance. For example, debris avalanches at Parinacota (Chile) and Iriga (Japan) volcanoes produced natural lakes that have lasted since the Late Holocene and the Nineteen century, respectively (Figures 2 and 3). This may be explained by the rel-

Table 1. Summary of all known cases of volcanic natural dams associated with volcano collapse.

Volcano	Age of the event Type of activity	Type and dimensions of the dam	Time to fill	Lake dimensions	Dam "life" MECHANISM OF RUPTURE	ref
Bandai Japan	July 15, 1888 phreatic	? V: 1.5 km^3	Several month	Five lakes 1.5 km^2	Partial overflowing - Still existing	31
Mt. St. Helens USA	May 18, 1980 Criptodome intrusion (Bezymianny type)	Block facies Andesite lava	Spirit lake 3.7 yrs Coldwater and Castle lakes 1.7 yrs	Spirit Lake: A: 1,4 km^2, D: 69 m, V: 618 10^6 m^3 Coldwater lake: A: 0.4 km^2, D: 71 m, V: 140 106 m^3 Castle lake: A: 0.1 km^2, D: 37 m, V: 30 106 m^3	Three main dams are controlled by artificial spillway. Estimated peak flow discharge 16240 m^3/s	31
Mt Spurr Alaska	10 000-3 800 yr B.P.	Block facies 17 km x 150 m	ND	1.2x10^9 m^3	Overflowing associated with erosion of the downstream end of the dam face during knick point retreat.	39
Iriga Philipine	1628 tectonic-induced	Block facies 1.5 km^3	ND	ND	Still existing	22
Nevado del Huila Colombia	46 000 -200 000 yr BP tectonic-induced	Mixed facies 1.5 km^3	3 days	0.5 km^3	Overflowing	29
Nevado de Colima México	18 500 yr B.P. Bezymianny type	Mixed facies 1.5 km^3	9 days – 1 yr	1 km^3	Overflowing	2
Volcán de Colima México	3 600 yr B.P. Bezymianny type	Mixed facies 1 km^3	11 days	0.4 km^3	Overflowing	7
Parinacota Chile-Boliva	8 000 yr B.P. tectonic-induced	Block facies, andesite lava V 6 km^3	ND	15 km^2	Still existing	6

Abbreviations are: V, volume; A: area; D: depth. ND: no determined.

Table 1 - Summary of all known cases of volcanic natural dams associated with volcano collapse

atively high permeability of the mass rock due to the absence of matrix, which avoided overflowing and the low internal and/or superficial erosion because the fragments that constitute the deposit are too large (10-100 m in diameter) to be removed by water. This hypothesis has important implications because debris avalanche deposits that consist only of the block facies (with no matrix) are probably exclusive of a tectonic-induced collapse, without a magmatic component. In contrast, sector collapse due to an explosive activity will emplace debris avalanche deposits with an important proportion of matrix (CAPRA, 2000), and the associated dam will have a high probability of failure.

In most observed cases, debris avalanche deposits responsible for damming rivers onsist of the mixed facies, c and therefore the dyke contains clasts and megaclasts (that can be more that 10 m in diameter) with a muddy-cohesive matrix filling all voids. This sedimentological "architecture" produces a low permeability for the dyke that is only removable by superficial erosion, when dam overtflowing occurs. Similarly, SCOTT (1985) stated that cohesive volcanic debris flows may form stable dams that last for thousands of years.

SEDIMENTOLOGY OF VOLCANIC DAMS

Very few papers report detailed data at the site were the natural dams fo a distribution of a volcanic or volcaniclastic deposit is highly variable, one cannot use data of samples collected from other site downstream. This limits the data to the few cases reported in the diagrams below, nevertheless they appear to give a good approximation of the phenomena. By analyzing the sedimentological characteristics of different volcaniclastic deposits that formed natural dams, and by considering their duration, it results that low sorting and coarse grain-size (but significant clay content) equate with a longer duration for a natural dam. In particular, by plotting mean grainsize (Md)

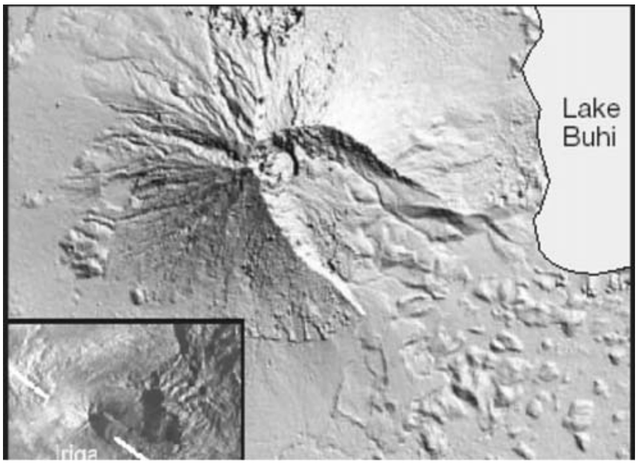

Figure 2 - Digital elevation model of Iriga volcano. Note the hummocky morphology on the SE sector, where the Lake Buhi formed. The inset shows the presence of a fault crossing the edifice, suggesting that the collapse was structurally controlled LAGMAY et alii, 2000)

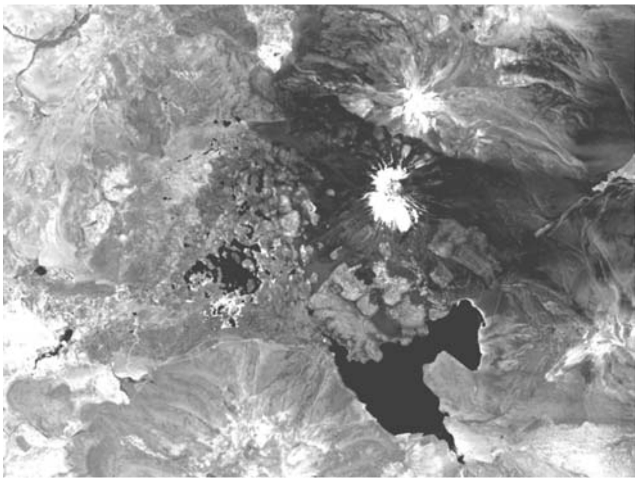

Figure 3 - ASTER image of the Parinacota volcano (Chile) showing the lake formed by the emplacement of the ~8.000 yr BP debris avalanche. Based on the stratigraphic study of the debris avalanche deposit (CLAVERO et alii, 2002) the dam consists of the block facies

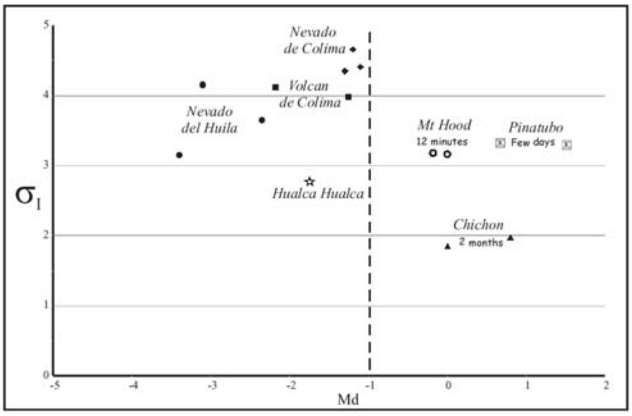

Figure 4 - Mean grain size Md vs. sorting σ_I diagrams. Note that the value of -1 phi separates debris avalanche-dam other dams formed by other types of volcanic and volcaniclastic deposits

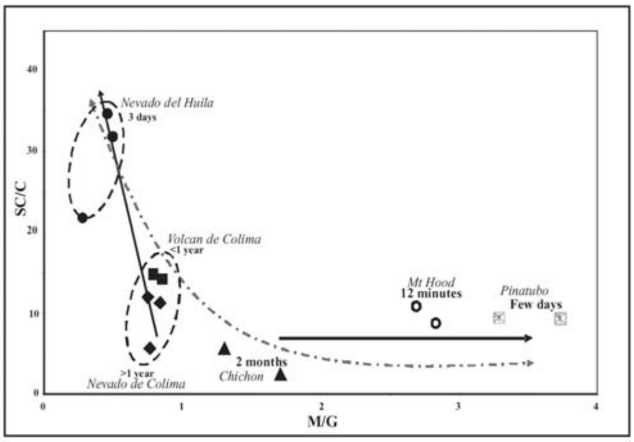

Figure 5 - Matrix/Gravel (M/G) vs. Silt+Clay/Clay (SC/C) diagram showing the relation between the dam grain-size and duration of the impoundment

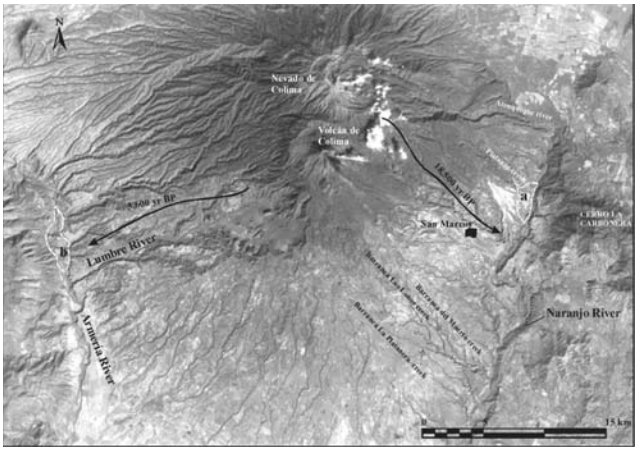

Figure 6 - ASTER image of the Colima Volcanic Complex. Black arrows indicate the path of debris avalanches that produced the obstruction of both the Naranjo river (a) and the Armeria river (b), 18500 yr BP and 3600 yr BP respectively

against sorting (σ_I) (Figure 4), the value of -1 phi for Md represents an important dividing line between volcanic natural dams formed by pyroclastic and/or debris flow deposits that last just few days (Md >-1 phi) from those produced by debris avalanche deposits, that last more that one year or are still existing (Md < -1 phi).

The relation between M/G (M: matrix, G: gravel) and S+C/C (S: silt; C: clay) indicates that for M/G lower than 1, there is an inverse relation between mud content (S+C) and dam duration. But for dams formed exclusively of fine material (phi less than -1, with comparable fine fraction), dam duration decreases as matrix content increase (Figure 5).

IDENTIFICATION OF VOLCANIC NATURAL DAMS

Although natural volcanic dams are common in volcanic terrains, their recognition is more difficult where the dams have breached especially for these of Holocene or older age. The best example of such a phenomenon is represented by the 18500 yr BP collapse of the Nevado de Colima volcano first described by STOOPSE & SHERIDAN (1992) that resulted in the largest debris avalanche deposit in the world, which traveled more than 120 km from the source. On the other hand, CAPRA & MACIAS (2002) reinterpreted the debris avalanche to be a cohesive debris flow originated from the dam breakdown and determined that the edifice collapse generated a debris avalanche flow that traveled just 45 km from the source and obstructed the Naranjo river drainage forming a 1 km^3 natural dam. The deposit interpreted by STOOPES & SHERIDAN (1992) as a debris avalancheis actually.

The main important factors in identification of a natural volcanic dam are: 1) relation between the drainage network and the debris avalanche deposit distribution (this is the most "intuitive" way to determine the possible river blockage); 2) presence of lacustrine deposits in a "no-naturally" lake environmental (in some studied cases lacustrine sediments have been found in elevated areas that correspond with lateral terraces of the river), and 3) the presence of slack-water sediments deposited during maximum inundation of the temporary lake, as observed for the Nevado de Colima case (CAPRA & MACIAS, 2002). The latter is probably the most difficult to recognize because slack-water sediments are generally very thin and poorly preserved, but their presence is prior proof of the existence of a lake.

SECONDARY FLOWS ASSOCIATED TO DAM FORMATION AND BREAKOUT

The formation of a natural dam may lead to the generation of secondary debris-flows, either during the dam formation or after its failure. Thus, during the infilling period, backwater flooding in areas located up-flow of the impoundment occurs. Several debris flows can also originate from the initial assessment of the dam or from lateral drainage filled by the same material which obstructed the main river. When the lake reaches equilibrium, lacustrine sedimentation can take place, with the deposition of fine, muddy layers, possibly interbedded with coarser layers. But, when the dam fails, devastating debris-flows form downstream the main drainage. As stated before, the most common process of failure is overflow of the dyke with its consequent superficial erosion. In this sense, after an initial formation of small debris flows from the over-saturated zones or from the remobilization of the more external portions of the dyke, the main rupture of the dam give place to several debris-flows that can coalesce into a main one. Different types of debris flow can form depending on the material forming the dam. The failure of a dam constituted by pyroclastic flows or no-cohesive debris flow deposits, generally produces non-cohesive debris flows that rapidly transform to more diluted hyperconcentrated debris flows. In contrast, the failure of dam formed by debris avalanche deposit can originate non-cohesive to cohesive debris-flows that, instead to go throughout a process of down-flow dilution, they experiment an increase in volume (bulking process) to up six times the original volume, with a discharge up to 4 millions of m^3/s or even more. Eventually, they can transform to hyperconcentrated debris flow only after more than 100 km from the source.

Figure 7 shows the difference between sedimentological characteristics of the well-sorted, coarse sandy hyperconcentrated debris flow originated from the failure of the dam formed by block-and-ash flow deposit at el Chichon volcano during the 1982 eruption, from the coarser, poor sorted, cohesive debris flow deposits originated fro the failure of dam constituted by debris avalanche deposit from the Colima Volcanic Complex (Mexico) and the Nevado del Huila volcano (Colombia) (CAPRA & MACIAS, 2002; CORTES, 2002, PULGARIN *et alii*, 2001).

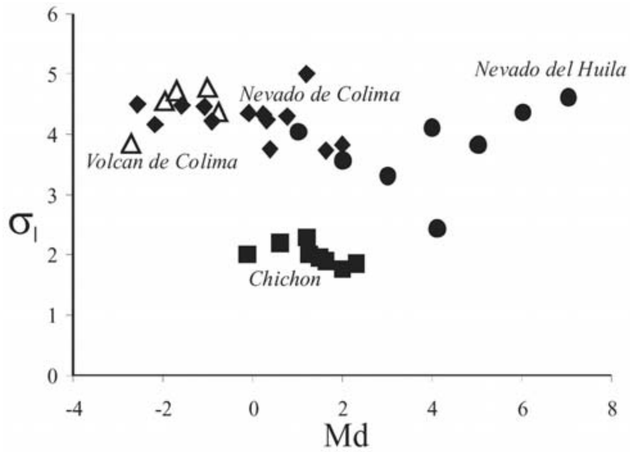

Figure 7 - Difference between sedimentological characteristics of debris flow originated from the failure of the dam formed by block-and-ash flow deposit at el Chichon volcano and the failure of dam constituted by debris avalanche deposit from the Colima Volcanic Complex (Mexico) and the Nevado del Huila volcano (Colombia)

CONCLUSIONS

The collapse of a volcanic edifice may result in several secondary effects, including the formation of one or more natural dams. The duration of the dam depends in first case on the volume of the obstructing mass and on its textural characteristics. A block facies of a debris avalanche produces durable dams, while mixed facies is easily eroded after overflowing. Unsorted, coarse material with an important clay fraction appears to be the most resistant, whereas well-sorted, fine material may experiment internal erosion by piping and accelerating the dam failure. However the most devastating effect is related to the generation of secondary debris flow, in general cohesive debris flows, which can originate from the dam failure. These secondary flows are generally more voluminous and extensive than the primary debris-avalanche deposit. It is very important to evaluate the potential interaction between the emplacement of gravity-driven flows and the morphology of the surrounding area as these secondary effects can threaten areas a long way from the volcano. Recent experiences, such as the 1980 Mount Saint Helens eruption, have demonstrated that engineering work can mitigate such secondary effects, but they can still represent a hazard in these volcanic areas where this phenomenon it is not yet well understood. If it is not feasible to prevent the dam failure, and if the volume of past flows is known or the flow discharge is calculated using a dam-break model (i.e. DAMBRK of National Weather Service NOAA) (MANVILLE *et alii*, 1999; WAYTHOMAS *et alii*, 1996), the limit of the inundation area of secondary debris-flows can be delineate by using a GIS-based model (i.e. LAHARZ, IVERSON *et alii*, 1998), to prepare a hazard map for the local authorities.

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