

Comparative lahar hazard mapping at Volcan Citlaltépetl, Mexico using SRTM, ASTER and DTED-1 digital topographic data

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Abstract

In this study, we evaluated and compared the utility of spaceborne SRTM and ASTER DEMs with baseline DTED-1 “bald-earth” topography for mapping lahar inundation hazards from volcan Citlaltépetl, Mexico, a volcano which has had a history of producing debris flows of various extents. In particular, we tested the utility of these topographic datasets for resolving ancient valley-filling deposits exposed around the flanks of the volcano, for determining their magnitude using paleohydrologic methods and for forecasting their inundation limits in the future. We also use the three datasets as inputs to a GIS stream inundation flow model, LAHARZ, and compare the results.

In general all three datasets, with spatial resolution of 90 m or better, were capable of resolving debris flow and lahar deposits at least $3 \times 10^6 \text{ m}^3$ in volume or larger. Canopy- and slope-related height errors in the ASTER and SRTM DEMs limit their utility for measuring valley-filling cross-sectional area and deriving flow magnitude for the smallest deposits using a cross-sectional area to volume scaling equation. Height errors in the ASTER and SRTM DEMs also causes problems in resolving stream valley hydrography which controls lahar flow paths and stream valley morphology which controls lahar filling capacity. However, both of the two spaceborne DEM datasets are better than DTED-1 at resolving fine details in stream hydrography and erosional morphologies of volcanoclastics preserved in the valleys around the more humid, eastern flanks of the volcanic range.

The results of LAHARZ flow inundation modeling using all three DEMs as inputs are remarkably similar and co-validate one another. For example, at Citlaltépetl all lahar simulations show that the city of Orizaba is the most vulnerable to flows similar in magnitude to, or larger than, one that occurred in 1920. Many of the other cities and towns illustrated are built higher up on terrace deposits of older debris flows, and are safe from all but the largest flows, which occur less frequently.

Finally, ASTERs 60 km swath width and 8% duty cycle presents a challenge for mapping lahar inundation hazards at E–W oriented stream valleys in low-latitude areas with persistent cloud cover. However, its continued operations enhances its utility as a means for updating the continuous but one-time coverage of SRTM, and for filling voids in the SRTM dataset such as those that occur along steep-sided valleys prone to hazards from future lahars.

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1. Introduction

The December 1999 launch of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) aboard the Terra satellite and subsequent February 2000 Shuttle Radar Topography mapping Mission (SRTM), represent major milestones in remote sensing acquisition of global digital elevation model (DEM) coverage at resolutions < 90 m. High quality DEMs have a multitude of uses such as volcano, landslide and flood hazard mapping. In particular, gravity-driven and/or water-saturated flows from volcanoes can travel for tens of kilometers from their sources, threatening both life and property (Tilling, 1989).

Prior to the launches of ASTER and SRTM, about 20% of the inhabitable land masses of the world with relief greater than 200-m were insufficiently mapped at scales of 1:50,000 or larger (Fig. 1) (Wolf and Wingham, 1992; Bohme, 1993; Welch et al., 1998). More than one-third of the world's inhabitable land

masses do not have pre-launch DEM coverage with 90-m horizontal resolution and ± 30 -m vertical accuracy or better, such as the National Geospatial-Intelligence Agency's (NGA) level-1 DTED product, referred therein as DTED-1 (Fig. 1) (Wolf and Wingham, 1992; NGA, 1996; Welch et al., 1998; Lang and Welch, 1999). Many of these insufficiently mapped or unmapped areas are located in tropical latitudes and/or near geologically active plate boundaries with high earthquake and volcanic activity (Fig. 1). Thus high resolution, vertically accurate DEMs from ASTER and SRTM will allow for better assessments to be made at many potentially hazardous volcanoes around the world, especially those upstream from populated areas at risk.

Numerous computer flow algorithms and GIS-enabled software packages have been developed for either predicting the path and extent of volcanic flows or visualizing their effects and potential impacts to infrastructure for mitigation or planning purposes (e.g. Malin and Sheridan, 1982; Wadge, 1988; Kover and Sheridan, 1993;

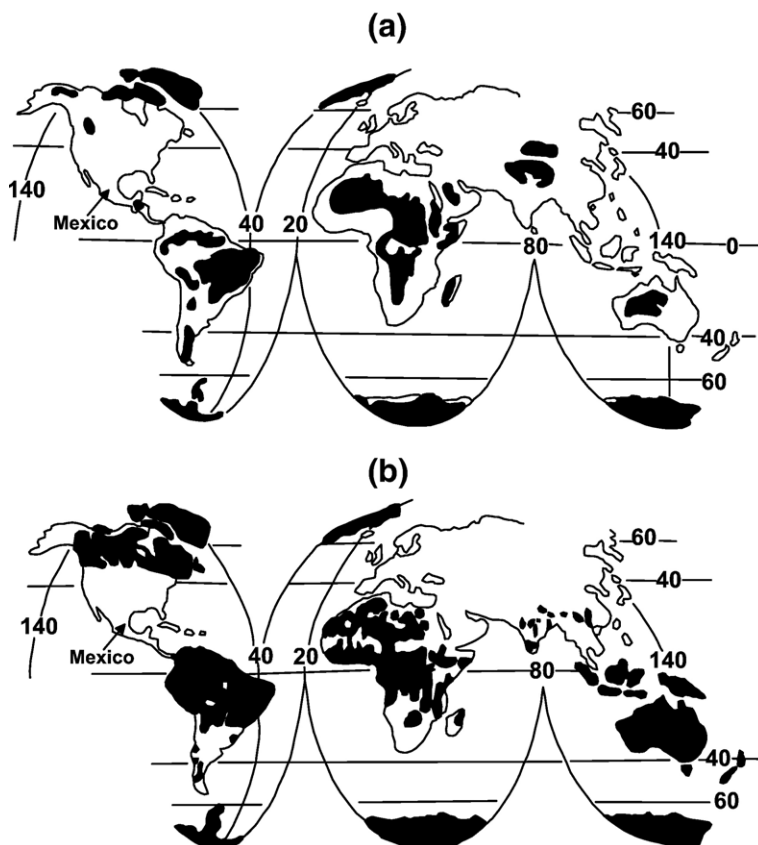


Fig. 1. (a) Areas of the world (shown in black) with topographic relief > 200 m mapped inadequately at 1:50,000 scale prior to the launch of SRTM and ASTER. (b) Areas of the world (shown in black) not covered by ~ 90 m resolution DTED-1 DEMs prior to the launch of SRTM and ASTER. Note that much of Mexico has been mapped at 1:50,000 scale or less by INEGI, and has full DTED-1 DEM coverage prior to SRTM and ASTER. After Welch et al. (1998) and Lang and Welch (1999).

Schilling, 1998; Sheridan et al., 2005 to mention a few). Each of these computer programs and GIS models shares the requirement of high quality DEMs. One particular GIS code, LAHARZ, was written in ARC/INFO *aml* at the United States Geological Survey (USGS) for objective mapping of lahar inundation zones, using only a DEM and user-specified debris volumes as model inputs (Schilling, 1998; Iverson et al., 1998).

Using DEMs derived from digitized 1:50,000 scale topographic maps of Ruapehu and Taranaki volcanoes, New Zealand, and a 10-m resolution TOPSAR DEM of Ruapehu used to simulate SRTM data, Stevens et al. (2002) evaluated the effects of height and morphology errors in their DEMs on the lahar inundation mapping results generated using LAHARZ. Stevens et al. (2004) showed that ASTER stereo-derived DEMs better resolve stream channel hydrography and morphology than DEMs digitized from topographic maps. They also suggest that multi-temporal stereo coverage from ASTER would be useful for updating SRTM data rendered obsolete by topographic changes both at the summit (e.g. Popocatepetl, Mexico — Macias and Siebe, 2005), and within constantly inundated rivers valleys (e.g. Pinatubo, Philippines — Torres et al., 2004). Unfortunately, ASTER and SRTM data were not simultaneously available at the time of writing for direct comparison by Stevens et al. (2002, 2004).

One of the purposes of this study is to compare the utility of actual SRTM and ASTER DEM data for mapping debris flow inundation limits using the LAHARZ program. In the process, we evaluate the sensitivity of LAHARZ to elevation height errors and mistakes in cross-sectional valley morphology inherent in both datasets. We also present analytical GIS methods for locating ancient valley-filling debris deposits, assessing their magnitude and frequency, and determining inundation risk and vulnerability to populated areas at volcanoes worldwide.

The two main sources of height and morphology errors that we consider are the obscuring effects on the “bald-earth” topography by canopy (ASTER — Eckert et al., 2005; SRTM — Sun et al., 2003; Kelndorfer et al., 2004), and the slope and aspect of the terrain relative to the optical geometries of the two spaceborne sensors (ASTER — Toutin, 2002; Eckert et al., 2005; SRTM — Rabus et al., 2003). We do this by first identifying the source of height and morphology errors in the ASTER and SRTM datasets relative to the “bald-earth,” corrected DTED-1 dataset. We then demonstrate how these vertical accuracy limitations constrain our ability to resolve the extent and magnitudes of ancient valley-filling debris deposits using the DEM datasets derived from three different sources, standard paleohydrologic

methods (e.g. Scott and Vallance, 1995) and by ground truth checking cross-sectional valley profiles in the field.

Finally we simulate the inundation limits of possible future lahars using LAHARZ, volumes spanning several orders of magnitude representative of those that have occurred in the past, and the three input DEMs (ASTER, SRTM and DTED-1). The results are then compared by extracting cross-valley profiles near major population centers to illustrate the potential impacts and floodwave heights predicted by LAHARZ using topography generated from the three DEM data sources.

2. Study area

Citlaltépetl volcano (Pico de Orizaba) is a historically active and the youngest volcano of a nearly north–south trending range consisting of (Fig. 2, from north to south): Cofre de Perote, La Gloria Volcanic Complex (Cerro Tecomales and Desconocido), Las Cumbres, Citlaltépetl and Sierra Negra. At 5675 masl, Citlaltépetl is the highest peak of Mexico and the highest volcano in North America. The basement underlying the volcanic massif consists of folded and faulted Cretaceous-age limestones and shales. Steeply dipping, uplifted blocks of these rocks form important topographic barriers to volcanoclastic flows from Citlaltépetl (Sheridan et al., 2004a). A hazard map was published for Citlaltépetl (Sheridan et al., 2002), in which the lahar hazard boundaries were based on LAHARZ simulations using the DTED-1 DEM as topographic base (Sheridan et al., 2004b). The volcano has been dormant for more than 300 years (Crausaz, 1993; Hoskuldsson and Robin, 1993), although minor activity was reported in 1867 (De la Cruz-Reyna and Carrasco-Núñez, 2002).

The climate on the eastern side of the volcanic range is sub-tropical to tropical. Because this side of the range receives the most rainfall, perennial rivers and streams form V-shaped valleys and canyons, which have high filling capacity for small debris flows, pyroclastic flows and other volcanoclastic sediments (Carrasco-Núñez and Gomez-Tuena, 1997). The eastern side of the range is also the most heavily populated and intensively cultivated. De la Cruz-Reyna and Carrasco-Núñez (2002) estimate that about 750,000 people live within 40 km east of the summit of Pico, about half of whom live in the two sprawling industrial cities of Cordoba and Orizaba (Fig. 2). The total number of people likely to be affected by future debris flow and flood-related hazards increases to about 2 million people if the metropolitan city of Veracruz is considered (Fig. 2).

In contrast, the western side of the range is mostly a semi-arid desert that slopes into a closed sedimentary basin,

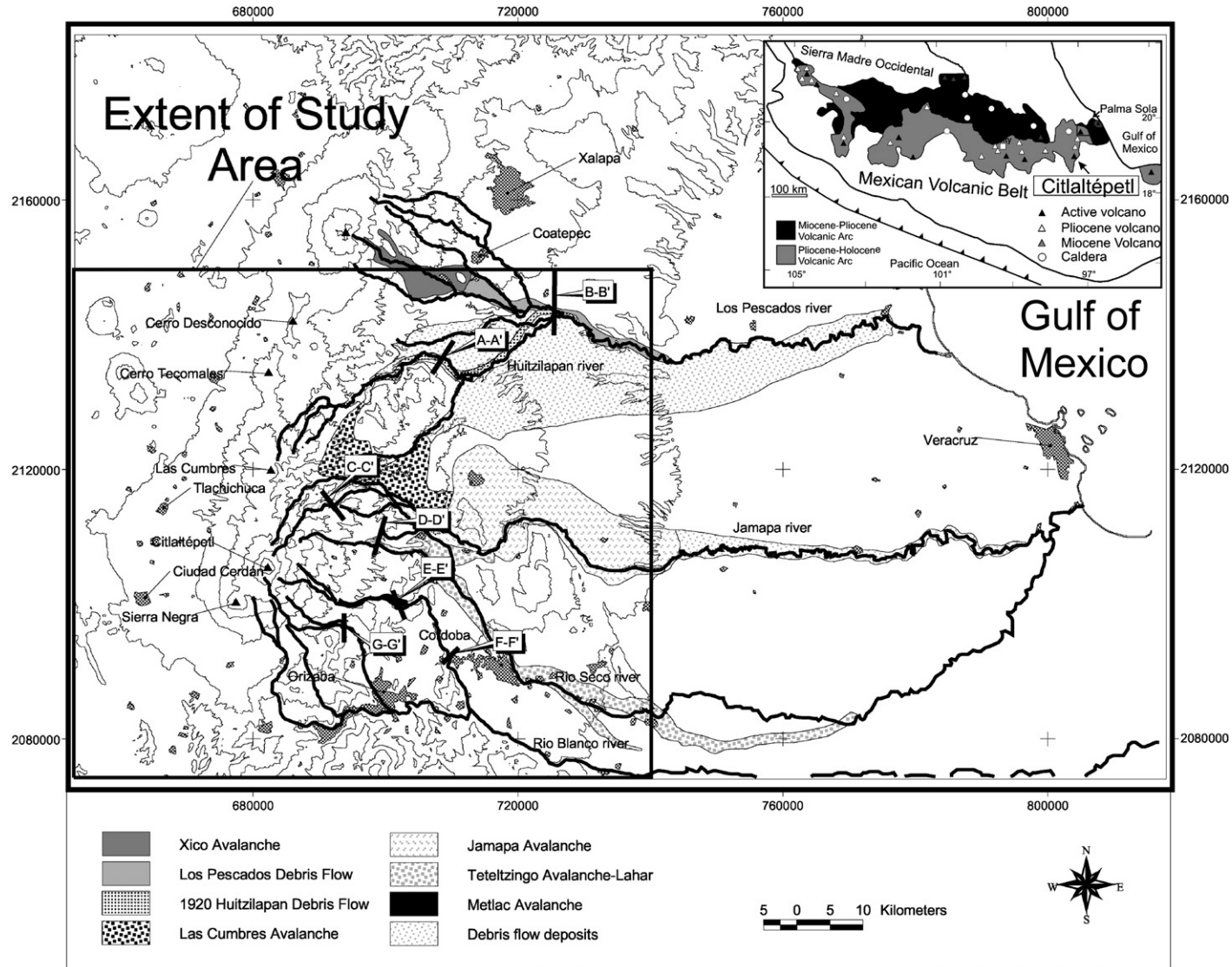


Fig. 2. Location map showing the extent of our study area and associated remote sensing and GIS coverages shown in later figures. Also shown are the mapped extents of large debris flow deposits with runouts towards the Gulf of Mexico coast of Veracruz, and locations of cross-valley profile transects shown in Figs. 7–9. Modified after Carrasco-Núñez et al. (in press).

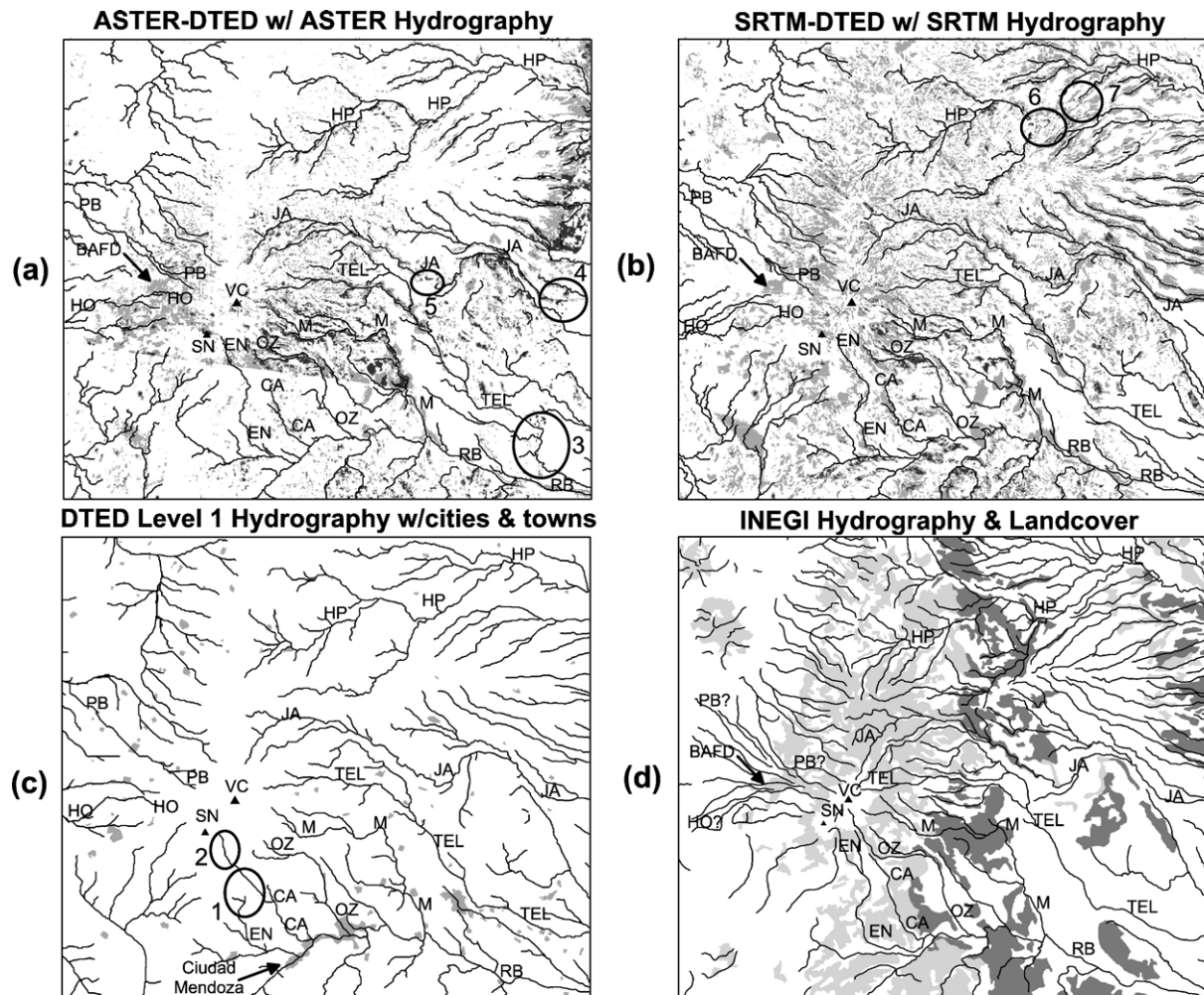


Fig. 3. (a) Height error difference image for ASTER minus DTED-1, with superimposed stream drainage hydrography derived from ASTER. Light gray areas show the distribution of cells with height errors between 35–70 m (which matches the extent of pine tree covered BAFD deposit shown in Fig. 5), while dark gray areas have height errors between 70–500 m. (b) Height error difference image for SRTM minus DTED-1, with superimposed stream drainage hydrography derived from SRTM. Light gray areas show the distribution of cells with height errors between 15–70 m (which matches the extent of pine tree covered BAFD deposit shown in Fig. 5), while dark gray areas have height errors between 70–500 m. (c) DTED-1 stream hydrography with cities and towns shown in gray transparent shading. (d) Spatial distribution of closed canopy types shown in dark gray, and open canopy types shown in light gray, based on a 1983 INEGI 1:250,000 scale vegetation landcover map. Canopy types are summarized in Table 2. Circled areas show hydrographic errors in the ASTER (a), SRTM (b) and DTED-1 (c) datasets as discussed in detail in the text. Labels abbreviated for clarity purposes are as follows: VC = volcan Citlaltépetl, SN = Sierra Negra volcano, HP = Huitzilapan–Pescados rivers, JA = Jamapa river, TEL = Tliapa-El Seco rivers, M = Metlac river, OZ = Orizaba river, CA = Carbonera river, EN = Encino river, RB = Rio Blanco river, PB = Barranca Paso Buey, HO = Barranca Honda, and BAFD = Holocene western block-and-ash fan deposit. Circled hydrographic errors are numbered by the order in which they are discussed in the text.

Serdan-Oriental, forming a high plateau (~2200 masl) that contains alluvial sediments, salt flats, maar lakebeds and isolated volcanic centers. Many of the streams are ephemeral and originate on U-shaped glacial valleys and cirques on the western side of the volcanic range (see Fig. 3d) and emerge onto flat, unconfined floodplains, which have poorly developed channels. As a result, debris flows originating on the western side of the vol-

cano are more likely to overbank and spread laterally to form debris “fans” than on the eastern side (e.g. Siebe et al., 1993).

Although debris avalanche and debris flows involve different physical processes with particular characteristics (cf. Pierson and Costa, 1987; Vallance, 2000), here we envisage that they are part of a flow continuum because we observe that lateral transformations from

debris avalanche to debris flow to hyperconcentrated (or lahar runout) flows and even to streamflows are a common occurrence on the studied deposits (Fig. 2). Tetelztingo is a typical example of a cohesive lahar (>3% clay in the matrix) that formed as a debris avalanche that rapidly transformed and behaved as a lahar. While debris avalanches are rapid, highly energetic masses of incoherent, unsorted and unsaturated rock and soil mobilized in response to gravity, debris flows are coherent, water-saturated mixture of fragmented rock debris and water controlled by gravity; and lahars are simply volcanic debris flows (Pierson and Costa, 1987; Vallance, 2000 and references therein).

For this study, we focus on potential lahar inundation along the major drainages on the eastern side of Citlaltépetl such as (from north to south — Figs. 2 and 3d): Jamapa, Tliapa-El Seco, Metlac-, Orizaba-, Carbonera- and Encino-Rio Blanco tributary systems. However, we do use the record and magnitude of debris avalanche/flow events that have occurred throughout the Citlaltépetl–Cofre de Perote Volcanic Range (referred therein as CCPVR — Carrasco-Núñez et al., in press) (Fig. 2 and Table 3) in the past to forecast possible debris flow and lahar hazards at Citlaltépetl.

3. Data sources and methods of study

3.1. DTED-1, SRTM and ASTER

3.1.1. DTED-1

Prior to ASTER and SRTM, NGA's (formerly National Intelligence Mapping Agency - NIMA) digital terrain elevation dataset level-1 (DTED-1) was established by NASA's Earth Observing System (EOS) program as a baseline pre-launch dataset for global DEM coverage, with the goal of at least matching its 3 arc second (~90-m) spatial resolution, 130-m horizontal accuracy and ±30-m vertical accuracy (NGA, 1996). DTED is acquired from a variety of topographic map sources, including national cartographic datasets generated by many countries at scales between 1:24,000 and 1:250,000 (e.g. Bohme, 1993), and standard bilinear interpolation algorithms to yield levels 0 (GTOPO30-30 arc second, or ~900-m postings), 1 (3 arc second, or ~90-m postings), and 2 (1 arc second, or ~30-m postings) DEMs (NGA, 1996). For example, Instituto Nacional de Estadística Geografía e Informática (INEGI) produces topographic coverage of Mexico at a minimum scale of 1:50,000 using stereo air photography and standard photogrammetric contour plotting methods (Lillesand and Kiefer, 2004 — chapter 4; INEGI, 2005). Fig. 4a shows the INEGI 1:50,000 quadrangle boundaries

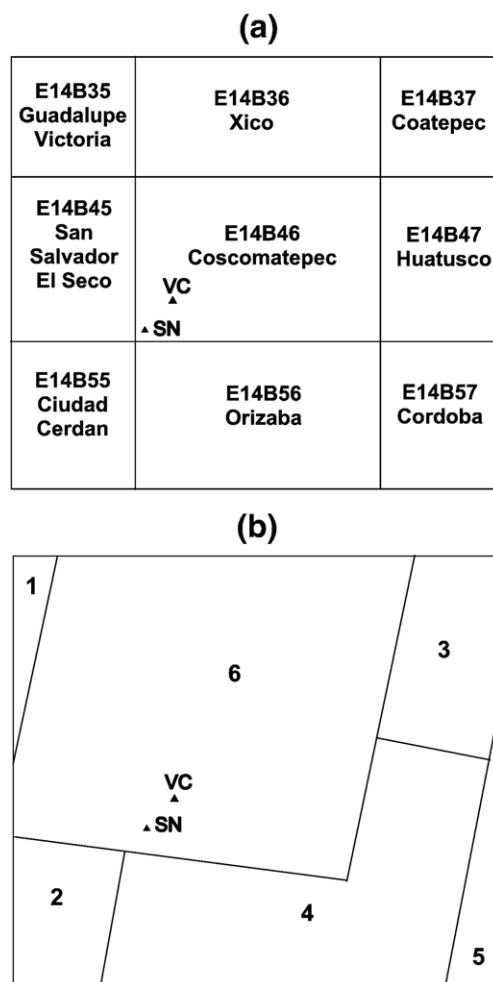


Fig. 4. (a) Index map of 1:50,000 INEGI topographic map quads used in generating ~90 m resolution DTED-1 coverage. (b) Index map of six ASTER DEM subsets mosaicked together to form continuous coverage of our study area. Subsets 1–5 are absolute DEMs and 6 is a relative DEM obtained from EDC, as summarized in Table 1. VC = volcan Citlaltépetl and SN = Sierra Negra. Coverage extent for both index maps “a” and “b” is also shown as boxed outline in Fig. 2.

for our study area as outlined in Fig. 2. Shaded relief models derived from our DTED-1 data show subtle edge-matching artifacts, or mosaic seams, which preserves the boundaries of INEGI topo quads B45, B46, B55 and B56 (Fig. 4a; arrow — Fig. 5c). Similar to level 1 (lowest quality, highest RMSe) USGS DEMs which are also interpolated from manually derived stereo plotted hypsography (USGS, 1986), “bald-earth” surfaces are interpreted directly from the airphotos (INEGI, 2005), even through canopy and man-made constructions (Maune, 1996). For this study, we use the DTED-1 dataset as a reference surface for “bald-earth” topography, although small but notable RMSe can exist in dense or closed

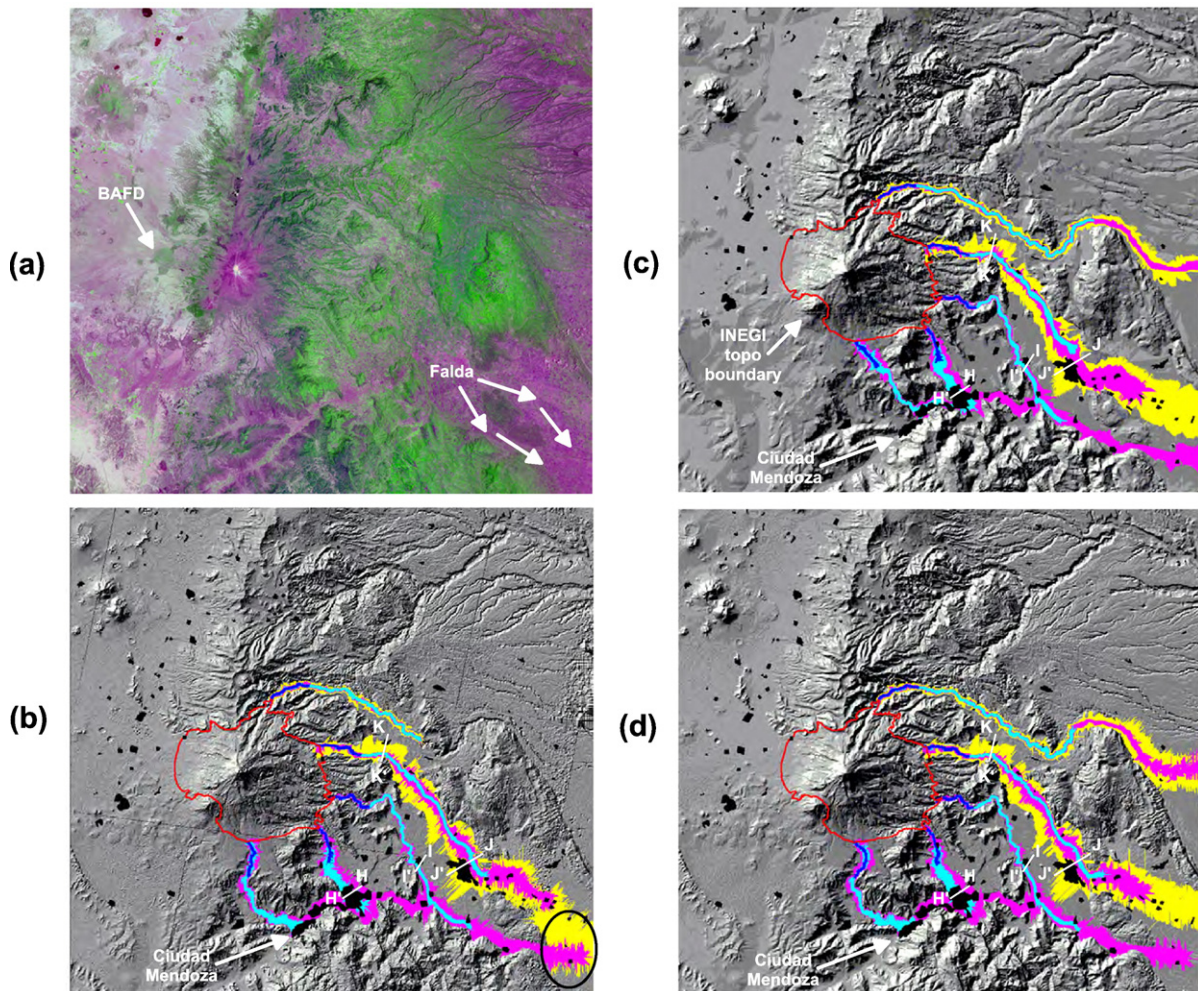


Fig. 5. (a) Color composite of 15 m resolution ASTER VNIR bands 1, 2, and 3 displayed as red, blue, and green, respectively in order to illustrate the location, distribution and seasonal variations in canopy vegetation throughout the study area. BAFD shows the location of the pine-tree covered 4-ka block-and-ash and lahar fan shown also in Fig. 3 and discussed in various places throughout the text. (b) Shaded relief rendition of the ASTER DEM mosaic showing the results of LAHARZ simulations. Note the visible seams between subsets. (c) Shaded relief rendition of the DTED-1 DEM showing the results of LAHARZ simulations. Arrow shows the barely visible seam between the 1:50,000 scale INEGI Coscomatepec and Orizaba quads (Fig. 4a). (d) Shaded relief rendition of the SRTM DEM, with continuous coverage and no seams or related artifacts caused by preparation. Also shown is the location of the suburban city of Ciudad Mendoza upstream of Orizaba, for which flows are correctly routed on the ASTER (b) and SRTM (d) DEMs, but incorrectly on the DTED-1 DEM (c). Transects H–H' across the city of Orizaba, I–I' across the town of Fortin, J–J' across the city of Cordoba, and K–K' across the town of Coscomatepec (all shown in black) depict flow inundation height boundaries as shown in Fig. 10. Yellow = maximum lahar, Magenta = case I lahar, Cyan = case II lahar, and Blue = case III lahar as explained in the text and Table 3. Red line = proximal hazard zone boundary defined by energy cone (Malin and Sheridan, 1982) of 0.251 relative to the summit of Citlaltepetl.

canopy areas where elevation values can potentially be over-predicted by as much as 4.5 m using manual stereo plotting methods (Bolstad and Stowe, 1994). Also, “bald-earth” topography as used throughout is defined as a “digital terrain model” (or DTM), as opposed to a digital surface model (or DSM) which can include canopy, buildings, and other anthropogenic structures and modifications to the landscape.

3.1.2. SRTM

SRTM was flown on board the Space Shuttle Endeavor between 11 to 22 February 2000 at an altitude of 233-km. Both C-band (5.6 cm wavelength) and X-band (3.1 cm wavelength) interferometric synthetic aperture radar (IFSAR — Zebker and Goldstein, 1986) were collected using 60-m separated receiving antennas, a 57° orbital inclination and dual transmitter-receiver

“look angles” between 30–60° (Hensley et al., 2000; Rabus et al., 2003). This configuration allowed for the generation of DEM coverage for 80% of the total Earth landmass between 60° N and 56° S latitudes. In particular, the C-band data were processed using 225-km wide data swaths from ascending and descending orbits, which notably leaves gaps in the corresponding X-band data coverage which is only about 25% as wide (Hensley et al., 2000; Rabus et al., 2003).

The C-band SRTM data used in this study (see shaded relief rendition — Fig. 5d) were obtained from the National Map Seamless Data Distribution system provided by the USGS (<http://seamless.usgs.gov>). Only the level 1 (3 arc second, or ~90-m resolution) data are available for areas outside of the United States and territories, and are distributed as a product of resampling from the original level 2 (1 arc second, or ~30-m resolution) data using the center cell value from a nine-pixel kernel (USGS, 2003). Although “research-grade” level-1 data resampled through cubic convolution methods are available by the Jet Propulsion Laboratory (JPL — <http://www2.jpl.nasa.gov/srtm/>), we use the USGS distributed product because it is in a spatially continuous GIS format, and preserves the original (i.e. not averaged) elevation values, albeit coarsened to a lower spatial resolution by the use of the nearest neighbor reassignment of the original pixel values.

In areas devoid of canopy and man-made constructions, estimates of the vertical accuracy of C-band SRTM data yield RMSe values between 1.1–4 m (Kellndorfer et al., 2004) to as much as 5 m (e.g. Sun et al., 2003). Both estimates are better than the pre-mission baseline specification of <16 m (<http://www.jpl.nasa.gov/srtm/datafinaldescriptions.html>). However, in canopy-covered terrains, microwave radar <30 cm wavelength interacts with volume scatters such as leaves, branches, stems and understory vegetation, and surface scatterers such as moist soils (Lillesand and Kiefer, 2004 — chapter 8) to produce mean scattering phase center heights well above the “bare-earth” surface (Kellndorfer et al., 2004 — Fig. 1). For example, Sun et al. (2003) and Kellndorfer et al. (2004) measured canopy-related height errors in C-band SRTM data as large as 26–40 m at various forest covered study sites.

3.1.3. ASTER

ASTER is one of several sensors on board NASA’s Terra satellite, orbiting the Earth at an altitude of 705 km with a repeat-pass interval of 16 days. ASTER consists of three subsystems that provide 14-band multispectral capability and two telescopes that provide along-track stereo capability (Fujisada, 1995). Briefly, the 15-m

resolution visible near-infrared (VNIR) subsystem measures reflected radiation in three spectral bands between 0.52–0.86 μm ; the 30-m resolution short wavelength infrared (SWIR) subsystem measures reflected radiation in six spectral bands between 1.6–2.43 μm ; and the 90-m resolution thermal infrared (TIR) subsystem measures emitted radiation in five spectral bands between 8.125–11.65 μm . Stereo coverage is obtained in the 15-m resolution near-infrared band (NIR: 0.78–0.86 μm) using a nadir- and an aft-viewing telescope which yields a pair of images (bands 3N and 3B, respectively), with Base-to-Height ratio (B/H) of 0.6 and ground intersection angle of 27.7° (Fujisada, 1995).

For this study, we obtained a 30-m resolution relative DEM (mosaic-subset 6, Fig. 4b) from the EOS Data Gateway system maintained by the USGS’ Eros Data Center (EDC). In contrast to absolute DEMs, relative DEMs are not “absolute” measures of elevation, but rather terrain heights measured relative to the lowest elevation within the scene using only accompanying satellite ephemeris data, with no ground or geographic control from any other source (Lang and Welch, 1999). Initial validation studies conducted around the world by members of the ASTER DEM validation team (Hirano et al., 2003) yield RMSe vertical accuracy estimates between ± 7 and ± 15 m for absolute DEMs, and ± 8.6 for a relative DEM obtained from EDC. However, the authors also note that the presence and magnitude of height errors in the relative DEM increase with increasing terrain elevation, with height errors reaching as much as nearly 100 m for a test area in the Southern Appalachians.

Our relative DEM was generated from an ASTER level 1A scene acquired on 31 January 2002 (Table 1). Unfortunately, because of ASTER’s limited swath width (60 km) which covers only a portion of our study area (Figs. 2 and 4b) and EDC’s limited rate of production of ASTER DEMs, we derived additional DEMs from five ASTER level 1A scenes to cover the remainder of our study area. Notably, as of the time of writing, EDC has since switched to a more rapid automated algorithm for deriving “on demand”, relative DEMs from ASTER level 1A data (<http://lpdaac.usgs.gov/aster/aster-dem-details.asp>). The level 1A scenes used in this study were acquired during the course of three nearly cloud-free orbital swaths collected on 29 March, 30 April and 23 May 2002 (mosaic-subsets 1–5, Fig. 4b and Table 1). Notably, an additional one or two orbital swaths of ASTER level 1A data would be needed to generate complete DEM coverage all the way to the gulf coast of Veracruz, which has been inundated by large coastal-reaching debris flows from the volcanoes of the CCPVR

Table 1
Index of ASTER mosaic-subsets

ASTER mosaick subset #	Acquisition date of Level-1A scene	# of GCPs used as tie points for absolute DEM generation ^b	Horizontal RMS error (using 1st order model and based on DTED-1 horizontal resolution)	Output elevation range ^a (total relief)
1	05-23-2002	71	1.8	2078
2	05-23-2002	40	2.1	1376
3	03-29-2002	125	9.9	3898
4	03-29-2002	74	2.8	5149
5	04-30-2002	30	3.1	2476
6	01-31-2002	Relative DEM	N/A	5243

^a Excluding “feature-matching” algorithm failed areas, and flagrant blunders which were edited out. See Fig. 4b.

^b Note that additional ground control points were used to facilitate horizontal registration and mosaicking as discussed in the text.

in the past (Fig. 2) (Carrasco-Núñez et al., *in press*). This lack of continuous (>60 km) cross-track coverage for volcanoes with east–west trending drainage systems could limit the utility of ASTER DEMs for rapid-response mitigation or real-time hazard assessments for downstream population centers at risk.

The PCI Geomatica software was used to derive 30-m resolution absolute DEMs from the five level 1A ASTER stereo pairs, using between 30–125 geographic control points (GCPs) per scene depending on the amount of overlap with our DTED-1 coverage used for geographic control and registration (see study area, Fig. 2). These GCPs were also used as “tie points” to facilitate correlation between the stereo images. Briefly, the software uses a feature-matching algorithm developed by Toutin (1995) and an epipolar projection to isolate parallax due to terrain between the stereo pairs. The basis of this feature-matching algorithm is the need for repeat-pass imagery containing minimal radiometric inconsistencies caused by (for example) temporal changes in landcover, snowcover, atmospheric, hydrologic and lighting conditions. ASTER solves this problem by acquiring stereo images within one minute of each other along the same orbital path and period (Lang and Welch, 1999). Terrain heights are then derived from the parallax measurements using standard photogrammetric methods (Lillesand and Kiefer, 2004 — chapter 4; PCI, 2001). Absolute DEMs generated from ASTER using the PCI software can achieve RMSe vertical accuracy of <10 m for flat agricultural or cleared areas (Eckert et al., 2005), between 15 and 20 m in hilly terrain (Eckert et al., 2005), less than 30 m for mountainous terrain (Toutin, 2002; Eckert et al., 2005), and up to 30–50 m on forested slopes (Eckert et al., 2005).

The resulting horizontal accuracy of our absolute DEMs (Table 1) varies from an RMSe of 1.8, for a scene covering the western portion of the volcanic massif (subset 1, Fig. 4b), using 71 GCPs distributed across a total relief gradient <0.035, up to an RMSe of nearly 10, using 125 GCPs for a scene covering the eastern portion of the volcanic massif which has a much steeper topographic gradient of about 0.065. This asymmetric topographic distribution of the CCPVR is not only an important factor in why the eastern side of the volcanic range is considered more dangerous with respect to deadly volcanic flows than the western side (Carrasco-Núñez et al., *in press*), but was an obstacle in our preparation of a “seamless” mosaic coverage using the relative and five absolute DEM subsets (see shaded relief rendition — Fig. 5b).

As we will detail in the following section, we adjusted the elevation values of the SRTM DEM and all six ASTER DEM subsets to fit the DTED-1 dataset, after registration but prior to mosaicking. The largest residual vertical displacement (>150 m) producing the most prominent seam occurs in the southwestern quadrant of the mosaic between the boundary of relative DEM subset 6 and absolute DEM subsets 2 and 4 (Figs. 4b and 5b). In comparison with the DTED-1 DEM and 1:50,000 scale INEGI topographic maps, the relative DEM derived by EDC without the aid of GCPs overestimates the height of parts of the western basin of Serdan-Oriental by as much as 120 m in the seam area, just as was documented by Hirano et al. (2003) using a relative ASTER DEM generated for the Huntsville, AL area (~100 m height error within Southern Appalachians). Together with an estimated 30 m vertical accuracy for ASTER relative DEMs (<http://edcdaac.usgs.gov/aster/ast14dem.asp>) the offset at the seam between relative and absolute DEMs can be reasonably explained. The following section gives more details on co-registration between the three DEM datasets for further analyses.

3.2. Horizontal and vertical co-registration

The DTED-1 dataset was used throughout as a “bald-earth” reference topographic surface. Therefore, we first registered the DTED-1 from its original “geographic” (ie. latitude and longitude decimal degrees) coordinate system (NGA, 1996) to the UTM coordinate system of the 1:50,000 scale INEGI topographic maps covering our study area (Fig. 4a). This was done using >100 identifiable ground control points, 1st order rotation and nearest neighbor resampling with RMS error <1 pixel.

We then ensured that the ASTER and SRTM datasets were both horizontally and vertically tied to the DTED-1

dataset for the purpose of: 1) measuring and identifying the source of height errors, 2) extracting precisely located cross-valley profiles across known and suspected debris deposits, and 3) comparing the results of LAHARZ simulations. Although the ASTER data was resampled to the ~ 90 m resolution and UTM grid system of the DTED-1 and SRTM datasets for tasks 1 and 3, the ~ 30 m resolution datasets were preserved for the purpose of better resolving ancient debris avalanche/flow deposits using cross-valley profiles (task 2).

Prior to mosaicking, the six ASTER DEM subsets of varying horizontal accuracy (Table 1), were warped to the DTED-1 coordinate grid using additional (>100) control points per scene, 2nd order polynomial transformations and nearest neighbor resampling, yielding an average RMSe <1.5 pixel. The same procedure was applied to the SRTM dataset, originally distributed in a geographic coordinate grid, yielding an output horizontal registration accuracy <1.5 pixel. Color Fig. 5a shows a composite mosaic image of ASTER VNIR bands using the same control points and transformation used to register and mosaic the ASTER DEM subsets. Despite accurate registration of topographic landforms visible in the image, seasonal differences in vegetation cover on terrain features are striking even after several corrective enhancements were applied, and are due to the fact that the images were acquired over a four month period (Table 1).

After horizontal co-registration, the SRTM DEM and ASTER DEM mosaic were randomly sampled against the DTED-1 dataset, using sample densities between 0.014–0.056% depending on the size of the ASTER subsets and 0.060% for the SRTM dataset. The results were plotted (Fig. 6) to show the correlation and scatter in elevation, which are height errors mostly due to canopy, slope effects and perhaps even errors inherent in the DTED-1 data itself, used here to represent the “bald-earth” surface. As expected, all plots show strong ($>89\%$) correlation between the topographic datasets and RMSe vertical accuracy ranging from ± 24 m at best for absolute ASTER DEM subset 3 (Fig. 6c, see Fig. 4b for location) to ± 58 m at worst for relative ASTER DEM subset 6 (Fig. 6f, see Fig. 4b for location), with SRTM in between at ± 39 m. Again, these vertical accuracy measurements are based on randomly sampled pixels from all over the extent of our study area, which reflects the variety of vegetation landcover types ranging from montane cloud forests on the flanks of the volcanoes to desert shrub and chaparral in the west to mostly clear-cut pastoral/agricultural lands in the east (Figs. 3d and 5a, Table 2). The linear regression equations shown in each of the plots were used to adjust (or “fit”) the ASTER DEM subsets and the SRTM DEM to DTED-1, so that height difference images between

SRTM and DTED-1 and ASTER and DTED-1 can be computed to show the magnitude and distribution of height errors illustrated in the individual scatter plots shown in Fig. 6.

3.3. LAHARZ and paleohydrologic debris flow inundation

At Mount Rainier, Washington, Scott and Vallance (1995) and Scott et al. (1995) used paleohydrologic methods to define the magnitude and frequency of subpopulations of debris avalanches, flows and lahars likely to occur again in the future. For example, the height and extents of ancient debris deposits preserved in valley-fill terrace deposits were used to record the peak stage of the receding flows and the inundated cross-sectional areas of the paleo-channel (Scott and Vallance, 1995; Scott et al., 1995). These cross-sectional areas were then extrapolated to other drainage basins around the volcano likely to be inundated by flows of such magnitude and frequency again in the future.

Inherent in their methodology is 1) that the frequency and specific drainage basins likely to be affected by lahars are unpredictable (though improvements in predicting the latter of the two are being made through edifice stability studies — e.g. Zimbelman et al., 2004), 2) the assumption that all the drainage basins have similar hydraulic characteristics in how they channel flows, and 3) that all drainage basins share the same probability of occurrence such that the risk can be extrapolated as well. For this study, we apply the same methodology by using the “bald-earth” DTED-1 data and fieldwork conducted at various times by five authors between 1998 and 2002, to locate ancient debris avalanche/flow deposits, characterize their valley-fill stratigraphic relationships, measure their cross-sectional areas and determine their peak stage volumes to be used as the basis for hazard zone boundaries mapped using LAHARZ and our three DEM datasets. In the case of volcan Citlaltépetl, we determine the magnitude and frequencies of ancient debris avalanche/flow deposits from throughout the volcanic range (Fig. 2 and Table 3) and extrapolate their inundation characteristics to the river valleys draining the eastern flanks of Citlaltépetl.

The LAHARZ model represents an automated implementation (Schilling, 1998) of the cross-valley cross-sectional area extrapolation approach developed by Scott and Vallance (1995). Briefly, it runs in ARC/INFO using a DEM, user input flow volumes, hydrologic grids for deriving stream networks and routing flows downstream (Jenson and Domingue, 1988), and the predictive equations developed by Iverson et al. (1998) for deriving

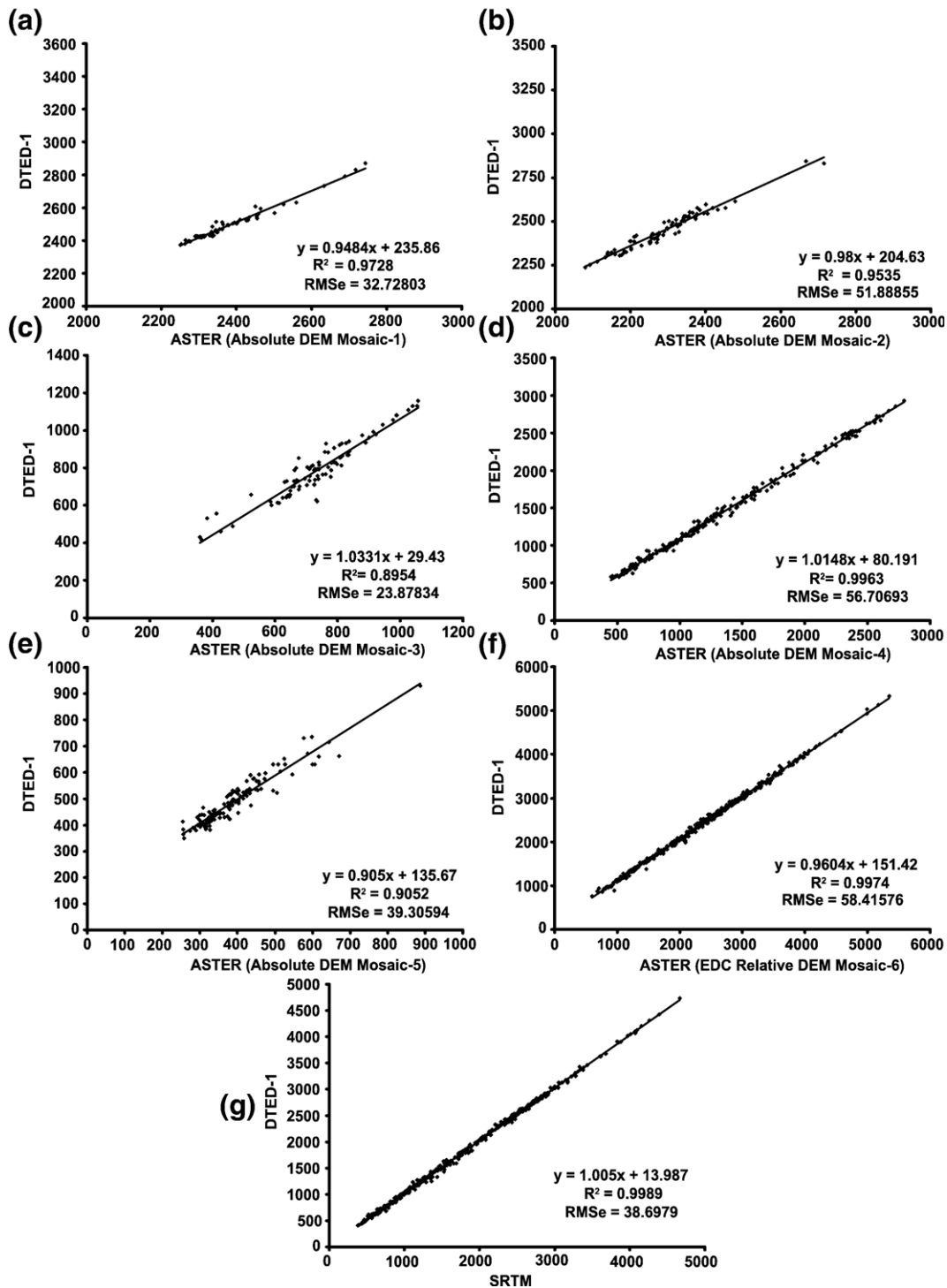


Fig. 6. Correlations between surface heights for DTED-1 DEM and (a) ASTER absolute DEM subset 1, (b) ASTER absolute DEM subset 2, (c) ASTER absolute DEM subset 3, (d) ASTER absolute DEM subset 4, (e) ASTER absolute DEM subset 5, (f) ASTER relative DEM subset 6, and (g) SRTM DEM. Also shown are relative vertical accuracy and linear regression equation used to vertically tie all seven DEM segments to DTED-1 for further height error analyses (See Fig. 4b for ASTER subset locations).

Table 2
Canopy landcover types within our study area*

Canopy type/class	Height (m)	Crown density	Comments
Semi-deciduous “high” forests with mixed tropical montane species	25–40	Closed	Predominantly in the easternmost part of the study area in limestone area immediately south of the Jamapa river (<1200 masl)
Tall species “upper montane” pine forest	25–30	Open	Predominantly “ <i>Abies religiosa</i> ” (>2700 on western flanks, >3200 on eastern flanks)
Short species “upper montane” pine forest	20–30	Open	Predominantly “ <i>Pinus hartwegii</i> ” (>2700 on western flanks, >3200 on eastern flanks)
Semi-deciduous/ semi-coniferous montane “cloud” forests with mixed pine-oak	15–25	Open	Two types on eastern flanks: pine>oak at 2700–3200masl and oak>pine at 1800–2700 masl
Mixed broadleaf evergreen forest	15–25	Closed	Not necessarily containing pine species (predominantly in areas south and east of the city of Orizaba along Rio Blanco valley)
Lower montane mixed “rain” forests with tropical montane and deciduous broadleaf species	15–20	Closed	Predominantly at elevations between 1000–1800 masl on the eastern flanks of the volcanic massif
Semi-deciduous “low” forests with mixed tropical montane species	<15	Closed	Predominantly in the northeastern parts of the study area in well-developed drainage basins north of Jamapa river (<800 masl)
Oak forest	10–15	Open	Large areas around upper Rio Blanco watershed, west of the city of Orizaba, and elevations <1000 masl in northeastern part of study area north of Jamapa river
Chaparral (incl. “Tascate” tree woods)	<15	Open	Predominantly on the western side of the volcanic massif

*Canopy height, altitude and ecological descriptions based on Lauer (1973) and INEGI (1983) 1:250,000 landcover vegetation maps based on airphoto interpretation. See Fig. 3d for spatial distribution of open and closed canopy types based on INEGI vegetation landcover. See text for detailed discussion on crown density as related to scale and resolution of remote sensing imagery.

cross-sectional areas along four transects per stream cell and planimetric area from the sum of all the transects (Schilling, 1998). The predictive equations are based on a log-linear scaling law that relates input volume to mapped planimetric area and valley-fill cross-sectional area (Iverson et al., 1998). Lahar inundation begins at the point of intersection between a user-specified proximal hazard zone boundary (Malin and Sheridan, 1982) and the point in the stream valley where lahar deposition begins (Iverson et al., 1998). In this case we define our proximal hazard zone boundary using an energy cone (Malin and Sheridan, 1982) of 0.251 (red outline, Fig. 5b–d), which is a best fit between the most proximal extent of the 16 ka. Teteltzingo lahar deposit on the eastern flank (Carrasco-Núñez et al., 1993) and the most distal extent of the 4 ka block-and-ash and lahar deposit on the western flank (Siebe et al., 1993).

We also use the inverse of the volume to cross-sectional area equation derived by Iverson et al. (1998) to estimate debris flow volumes for ancient debris flow deposits either not mapped or for which the mapped extents is poorly constrained as noted in the caption of Table 3:

$$V = (A/0.05)^{3/2} \quad (1)$$

where V is volume and A is the cross-sectional area. Cross-valley profiles extracted from the “bald-earth” corrected DTED-1 are then used to measure cross-sectional areas of the deposits using ARC/INFO, and for showing stratigraphic context for drainages with multiple episodes of valley-fill deposits. We also extract cross-valley profiles along the same transects for all representative valley-fill deposits using the ASTER and SRTM datasets, for comparative purposes. Notably, estimated volumes of the deposits based on fluvial terrace heights provide only a minimum estimate of the magnitude of the actual flow event, because the full hydrograph of the flow (e.g. fluid fraction and flow duration) is never preserved in the geologic record.

4. Results

4.1. DEM height and hydrographic errors

Fig. 3 shows ASTER minus DTED-1 (a) and SRTM minus DTED-1 (b) difference images that have been density sliced to show the distribution of height error values >70 m (dark gray) and those ≤70 m (light gray). In the case of ASTER-DTED, noticeable displacement seams persists at the southern boundary of subset 6 and the eastern boundary of subset 3, even after all negative

Table 3
Summary of ancient debris avalanche/flow deposits and magnitudes

Debris flow/avalanche deposit	Source(s) of detailed information on deposit size and characteristics	Map and/or cross-section figure(s) as discussed in text	Measured cross-sectional area ^a (m ²)	Estimated volume ^a (m ³)	Relative log scale volume (magnitude)	LAHARZ input used in this study? ^b
Las Cumbres debris avalanche and runout debris flows	Rodríguez (1998) Hubbard (2001) Carrasco-Núñez et al. (in press)	Figs. 2, 7a,b, 8a and 9a,b	NM	$>6.0 \times 10^{10}$	>10.8	No
1920 Huitzilapan (“seismogenic”) debris flow	Hubbard (2001) Carrasco-Núñez et al. (in press)	Figs. 2 and 7a	3.8×10^3	4.4×10^7	7.6	Yes (Case II)
Xico debris avalanche	Carrasco-Núñez et al. (in press)	Fig. 2 only	NM	1.1×10^9	9.1	No
Rio Pescados debris flow	Carrasco-Núñez et al. (in press)	Figs. 2, 7b and 9a,b	2.5×10^4	3.5×10^8	8.5	Yes (Case I)
Jamapa debris avalanche and runout debris flows	Carrasco-Núñez and Gomez-Tuena (1997) Carrasco-Núñez et al. (in press)	Figs. 2 and 7c	NM	$>2.0 \times 10^{10}$	>10.3	No
Excola secondary lahar	this study	Fig. 7c	1.7×10^4	2.0×10^8	8.3	No
Teteltzingo lahar	Carrasco-Núñez et al. (1993) Carrasco-Núñez et al. (in press)	Figs. 2, 7d and 9c,d	NM	2.2×10^9	9.3	Yes (max-lahar)
Metlac debris avalanche	Carrasco-Núñez et al. (in press)	Figs. 2 and 7e	NM	1.1×10^8	8.0	No
Fortin secondary lahar (^c)	This study	Figs. 7f and 9e,f	1.0×10^3	2.8×10^6	6.5	Yes (Case III)
La Perla block-and-ash flow and lahar terrace	Carrasco-Núñez (1999)	Figs. 7g and 8b	6.8×10^3	5.0×10^7	7.7	No
Western block-and-ash flow and lahar fan	Siebe et al. (1993)	Figs. 3a,b,d and 5a	NM	4.8×10^7	7.7	No

NM = not measured.

^a Based on cross-sectional area measured using DTED-1 DEM, ARC/INFO and debris flow volume scaling formula of Iverson et al. (1998) for 1920 Huitzilapan debris flow, Rio Pescados debris flow, Excola lahar, Fortin lahar and La Perla block-and-ash and lahar terrace deposits. All other volumes based on published sources and/or mapped planimetric areas and average thicknesses. Does not apply to debris avalanche deposits.

^b Debris flow event of the magnitude of the Teteltzingo lahar is considered maximum lahar for planning purposes on the north and east sectors (drainages) of Citlaltépetl only. See text for details and explanation.

^c Smallest deposit resolved using ~90 DTED-1 DEM, and smallest volume simulated using LAHARZ and DTED-1, SRTM and ASTER DEMs.

difference values were converted to positive values. For the ASTER-DTED and SRTM-DTED difference images, minimum threshold values of >35 m and >15 m respectively, were chosen in order to map the extent of the Holocene (4 ka) block-and-ash and lahar deposit (Siebe et al., 1993), which also forms a prominent land-use class feature on the INEGI landcover map (arrows — Fig. 3a, b and d). Notably ASTER-DTED values are consistently 15–20 m higher than the corresponding SRTM-DTED values over this pine forest covered deposit. The average height error over the deposit is ~30 m for ASTER-DTED and ~15 m for SRTM-DTED, for a forest type which should display tree heights as high as 20–30 m (short species “upper montane” pine forest — Table 2). This confirms that ASTER yields elevation values above the height of the canopy, while SRTM yields elevation values somewhere between the top of the canopy and bald-earth surface depending on the wavelength of the radar and properties of the surface (Kelndorfer et al., 2004).

In general, the spatial distribution of height errors in both datasets collectively match the distribution of open and closed canopy types mapped by INEGI, especially in the west, south and far east portions of our coverage area (Fig. 3a, b, d and Table 2). However, the most striking difference between the ASTER-DTED and SRTM-DTED difference images and the INEGI landcover map is a sparser distribution of canopy-related height errors in the difference images. Notably, the INEGI landcover map was compiled from airphoto interpretation in 1983 with limited or no photorevision. Visible changes reflect the increasing demands for agricultural and pastoral lands and urban development on the eastern side of the range since the INEGI map was compiled. This resulted in widespread clear-cutting of open canopy forests in the valleys and floodplains, and thinning of the original dense montane cloud forest around the upper parts of the eastern flanks of the volcanoes (Fig. 3d). Also, the definition of closed and open canopy (see

Table 2) depends on the crown diameter of individual trees comprising the forest type, and the scale and resolution of the airphoto or satellite image used (USDA, 1978; Sayn-Wittgenstein, 1981; Hudson, 1991; Lillesand and Kiefer, 2004 — chapter 3.7). For example, dense stand pine forests with individual crown diameters in excess of nine meters can appear closed in 15-m resolution ASTER imagery, but appear open in 1:3000 to 1:8000 airphotos (Sayn-Wittgenstein, 1981; Lillesand and Kiefer, 2004 — chapter 3.7).

The highest magnitude height errors (> 70 m, as high as 500 m) in the ASTER-DTED and SRTM-DTED difference images exceed those expected for the different canopy types found in the area (Table 2). These values mainly occur in areas of steepest slopes ($\geq 45^\circ$), in folded and faulted limestone terrains and along steeply incised gorges of the Huitzilapan, Jamapa, Metlac and Orizaba river valleys, which are also bounded by dipping limestones (labeled HP, JA, M, and OZ, Fig. 3a–c). We will discuss this in more detail in a later section using DEM profiles across these valleys. In particular, the most extreme height errors occur in the northeastern extent of the ASTER-DTED difference image. These are caused by a combination of effects such as 1) greater differences in the elevation values derived for closed canopy areas on steep slopes than for open canopy areas on similar slopes (e.g. Toutin, 2002; Eckert et al., 2005), and failure of the DTED-1 dataset to fully resolve the complex rill and gully erosion features within the large Cumbres debris avalanche/flow deposit (Figs. 2 and 3a–c). We will further discuss how much better ASTER and SRTM resolve such hydrographic details than DTED-1.

Because LAHARZ routes debris flows along the paths of stream cells derived directly from the input DEM (Schilling, 1998), it is worth comparing and checking the DEM-derived stream hydrography networks with those digitized from other higher-accuracy map and remote sensing sources (e.g. Stevens et al., 2002). In this case, we digitized the streams from the 1:50,000 scale INEGI topographic maps (Fig. 3d), which were derived by INEGI from airphoto inspection (INEGI, 2005). In general, ASTER and SRTM shaded relief images (Fig. 5b and d, respectively) display a greater degree of erosional dissection of the volcanic deposits on the eastern side of the volcanic range than does the DTED-1 shaded relief image (Fig. 5c). However, the hydrographic networks were derived from the three input DEMs using the same LAHARZ default value for cell to cell flow accumulation (Jenson and Domingue, 1988). Therefore, the level of detail of the stream network derived from ASTER (Fig. 3a), SRTM (Fig. 3b) and DTED-1 (Fig. 3c)

is noticeably less than that derived from the INEGI maps (Fig. 3d). None the less, examples of hydrographic errors of different sources can be found when comparing the three DEM hydrographic networks with the more accurate airphoto inspected source.

The DTED-1 dataset does not resolve the drainage divide between the Carbonera and Encino drainages as well as ASTER and SRTM (CA and EN labeled streams, Fig. 3a–d). In fact, DTED-1 derives the source of the Carbonera river as the actual source of the Encino river, the former of which does not extend as far up towards the volcano as the Encino river (Fig. 3c — circled area 1 downstream and circled area 2 upstream, compared with Fig. 3d which shows the correct source and paths of the two rivers). This hydrographic error can mean the difference between lahars inundating the city of Ciudad Mendoza as shown by LAHARZ simulations routed using the ASTER and SRTM datasets (Fig. 5b and d, respectively), or lahars following a different path to the Carbonera river thereby causing them to miss Ciudad Mendoza as shown by running LAHARZ on the DTED-1 dataset (Fig. 5c). Appropriately, Sheridan et al. (2002, 2004b) solved this problem with the DTED-1 dataset by using a nested, three-level (high, medium, low) hazard zone mapping methodology (cf. Sheridan et al., 2002, 2004a,b), which includes Ciudad Mendoza in the low probability pyroclastic flow hazard boundary, but medium probability lahar hazard boundary.

Another example of incorrect drainage course is exhibited by the routing of the Tliapa-El Seco river close to, and perhaps into, the Rio Blanco, at the edge of the ASTER DEM (circled area 3 near labels TEL and RB, Fig. 3a); as well as the routing of the Jamapa south of its correct path (circled area 4, Fig. 3a). These problems are perhaps caused by the seam between absolute DEM subsets 4 and 5 (Figs. 4b — index and 5b — shaded relief). The former example could mean the difference between debris flows of the magnitude of the 16 ka Teteltzingo lahar deposit overbanking into the Rio Blanco (black circled area, Fig. 5b), or widespread inundation, correctly restricted along the El Seco and sparing the towns along the Rio Blanco (see corresponding sections of yellow-colored inundation zone in DTED-1 and SRTM LAHARZ results, Fig. 5c and d, respectively).

Another example of hydrographic error illustrated by Stevens et al. (2002) using TOPSAR data covering Ruapehu, is the presence of breaks in flow paths caused either by voids resulting from radar shadowing effects (e.g. SRTM — Rabus et al., 2003), or areas beyond the optical line of sight due to extreme parallax resulting from topography and/or off-nadir pointing (e.g. ASTER — Toutin, 2002; Eckert et al., 2005). Fig. 3a (circled area 5)

shows such a break in flow path along the Jamapa river in the ASTER dataset, which causes LAHARZ to abruptly terminate before larger volume debris flow reach the limit of the DEM (see Fig. 5b). Fig. 3b (circled areas 6 and 7) shows a break in flow path along the Huitzilipan river in the SRTM dataset, which causes another abrupt termination during LAHARZ simulations of a large seismogenic debris flow that occurred along this valley in 1920 (Scott et al., 2001; Hubbard, 2001; Carrasco-Núñez et al., in press). The results of the latter LAHARZ simulations are shown in cross-sectional profiles (Figs. 2 and 7a), which are discussed in more detail in the next section. Such data voids in the SRTM data and “feature-matching” algorithm failures and blunders in the ASTER data, persist even after interpolation (e.g. Stevens et al., 2002, 2004) and illustrate places where cross-sectional valley morphology is most suspect. A possible solution for fixing such hydrographic errors and terrain blunders in the ASTER and SRTM datasets is to fill gaps in SRTM DEMs with adjusted ASTER DEMs and vice versa.

4.2. Morphology, magnitude and frequency of ancestral debris avalanche/flow deposits

Table 3 summarizes all of the major debris avalanche/flow deposits for which the morphology and stratigraphic context are resolved in cross-sectional profiles (Fig. 7, see Fig. 2 for locations) extracted from the three co-registered DEM datasets. Detailed descriptions of the bedrock geology shown, and the textural characteristics and origin of the valley-fill deposits are described elsewhere (Negendank et al., 1985; Rodríguez, 1998; Carrasco-Núñez, 2000; Hubbard, 2001; Carrasco-Núñez et al., in press). This is by no means a complete record of debris avalanche, debris flows and lahar deposits produced by the volcanoes of the CCPVR (Carrasco-Núñez et al., in press), but lists only those deposits for which their volume and magnitude (i.e. log scale comparison between flow volumes) are constrained either by direct measurement of their cross-sectional area using the “bald-earth” DTED-1 DEM (Table 3), or from their mapped planimetric area (Fig. 2) and observed field thicknesses as reported in preceding papers (Table 3). Included in Table 3 is one of two ≥ 7.0 magnitude historic debris flows generated by the CCPVR (1920 Huitzilipan d.f., Figs. 2 and 7a). The other originated in 1938 as a glacial outburst flow from the Toro glacier of Citlaltépetl (Siebe et al., 1993; Hubbard, 2001).

Hubbard (2001) determined a volume of $4.4 \times 10^7 \text{ m}^3$ for the 1920 Huitzilipan debris flow by running LAHARZ simulations on the “bald-earth” DTED-1 topography (see Fig. 5c) to fit the runout (Fig. 2) and $\sim 65 \text{ m}$

floodwave height (Fig. 7a) reported from eyewitness accounts and later validated by measuring the height of the deposit terrace in the field (Hubbard, 2001; Carrasco-Núñez et al., in press). The ASTER and SRTM cross-valley profiles are narrower (Fig. 7a) and yield higher inundation heights using the same LAHARZ derived cross-sectional areas. We will further discuss how differences in cross-valley morphology derived from the three DEM datasets impact of debris flow inundation levels mapped using LAHARZ in the last section.

Several of the debris deposits shown in Fig. 7 profiles are excluded from further analysis (Table 3) either because 1) their ancestral “valley-fill” cross-sectional areas could not be determined because of erosion and deposition of younger lahar deposits (e.g. the pre-Teteltzingo heterolithologic lahar deposit in the Tliapa river valley, Fig. 7d) or 2) it is unclear if they represent one or more episodes of lahar deposit spaced over time, therefore requiring more study (e.g. the heterolithologic lahar deposits in the Metlac river valley, Fig. 7e and f). For example, the area between the Tliapa-El Seco and Metlac-Rio Blanco rivers forms a continuous flat plain of heterolithologic lahar deposits (or falda) which extends laterally from the Metlac towards an unresolved contact with the 16 ka Teteltzingo lahar deposits exposed along the Tliapa (Carrasco-Núñez et al., 1993). The falda appears smooth in shaded relief (Fig. 5b–d, see Fig. 5a for label and location) and further study is needed to map the extent of individual flow units, correlate them with deposits upstream, and date them.

The frequency of flows shown in Table 3 appears to decrease with decreasing magnitude which is contrary to standard volcano and lahar hazard assessment behaviour (Tilling, 1989; Scott and Vallance, 1995). Also, lahars < 6.4 magnitude are absent from Table 3, yet they most certainly have occurred frequently in the past at Citlaltépetl (e.g. Palacios et al., 1999) and the other volcanoes of the CCPVR. This can be explained by the fact that smaller-sized deposits are either not well studied because of their low risk or impact potential, not recognized in the field, poorly exposed, poorly preserved, eroded or buried by larger deposits, or simply not adequately documented in the literature. However, deposits smaller than 6.4 magnitude cannot be resolved using our three DEM datasets because they lack sufficient horizontal resolution and vertical accuracy. Also, the extent and hazard effects of these lahars are either restricted to areas closest to the volcano (e.g. Palacios et al., 1999) such as within our proximal hazard zone boundary (Fig. 5b–d), or in closest proximity to the walls and channel floodplains of landslide-prone canyons.

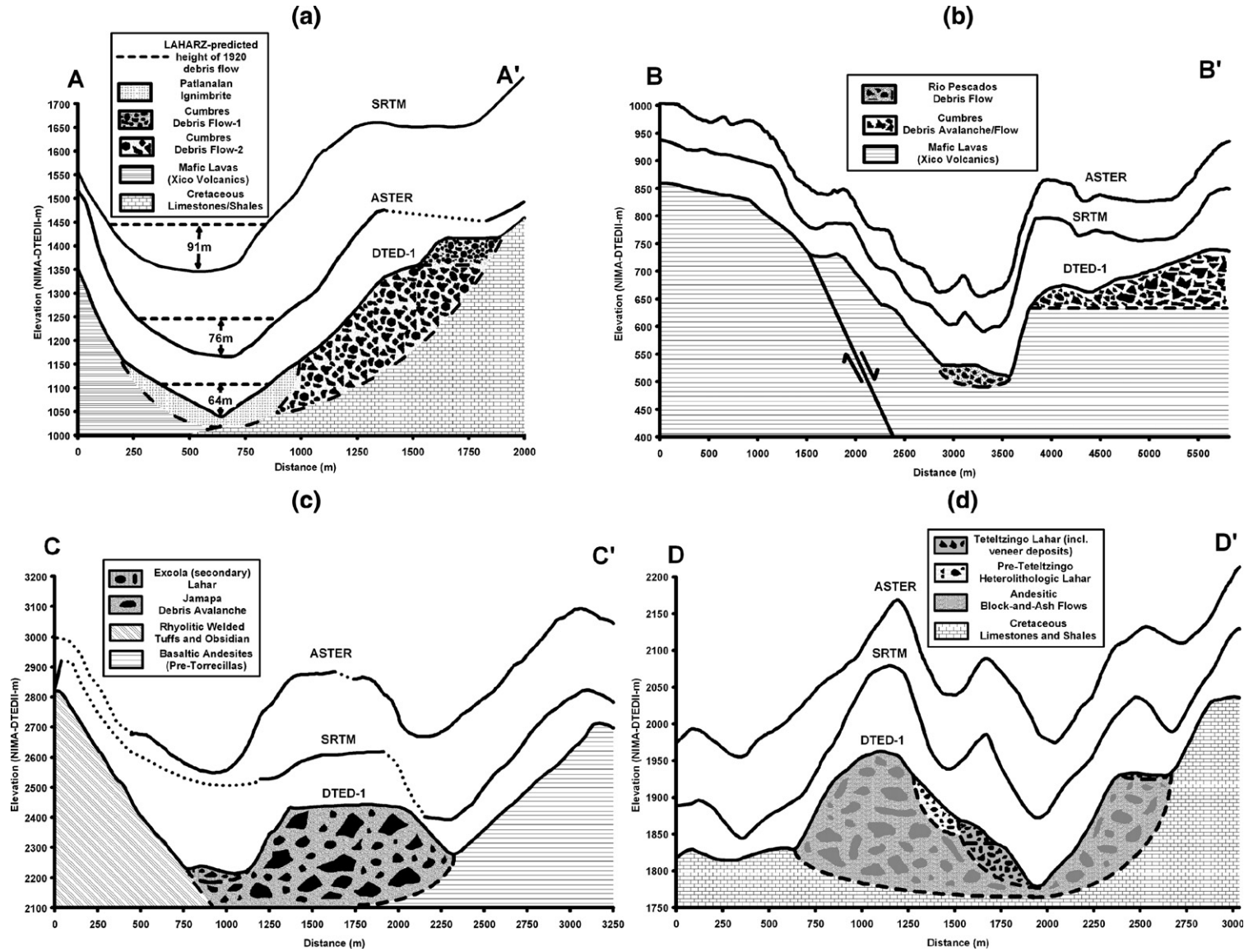


Fig. 7. Cross-valley profiles showing bedrock geology and valley-fill deposit stratigraphy with transect locations shown in Fig. 2. Results of Paleohydrologic analysis of deposit cross-sectional area (if appropriate), volume and magnitude are summarized in Table 3. References to background sources on the bedrock and valley-fill geology are explained in the text and in accompanying Table 3.

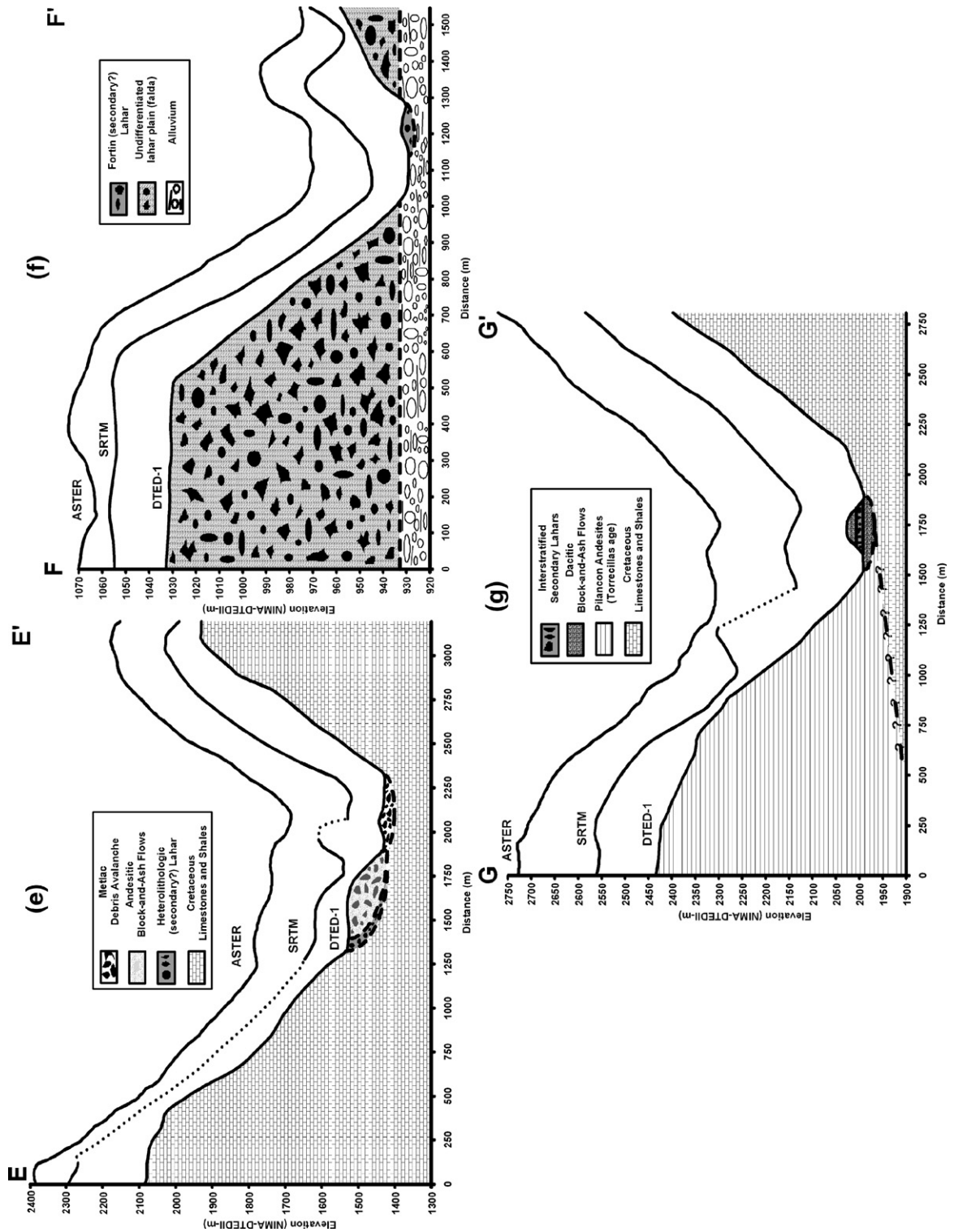


Fig. 7 (continued).

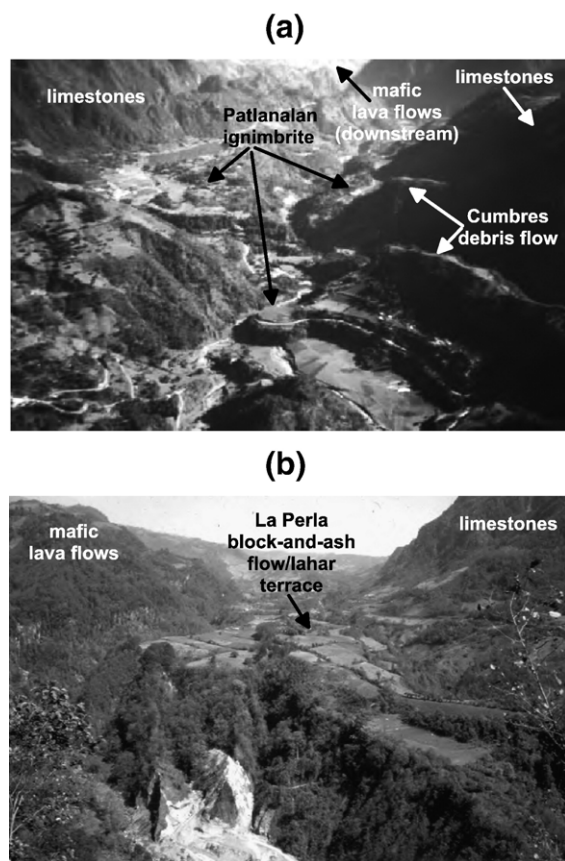


Fig. 8. (a) Aerial photo of the Huitzilapan valley just upstream of profile transect A–A' (Fig. 7a). (b) Ground photo of 40 m high terrace of block-and-ash flow and lahar deposits in the Orizaba river valley at the site of transect G–G' (Fig. 7g). Modified after Carrasco-Núñez (1999).

Fig. 8a and b are ground truth photos taken from the air and on high ground near the locations of profiles A–A' across the Huitzilapan valley (Fig. 7a) and G–G' across the Orizaba valley (Fig. 7g), respectively. Both show the key topographic and morphological elements of valley-fill debris deposits resolved by the three topographic datasets. In particular, ASTER and SRTM better resolve the lowermost Patlanalan ignimbrite terrace labeled in Fig. 8a, though not surprisingly they all resolve the rather large terraces of the Cumbres debris avalanche/flow deposit exposed higher up against the valley wall. Steeply sloped valley walls, in most cases comprised of dipping limestone beds, are apparent in both photos (Fig. 8) and are the major cause of gaps and voids in both the ASTER and SRTM datasets, as mentioned previously. For example, in profile G–G' across the LPBAFD deposits in the Orizaba valley (Fig. 7g), the SRTM profile shows a prominent data void on the north side of the valley, as well as a “hump” shaped artifact that

is perhaps caused by the closed canopy visible on top of the lava flows (left side of photo, Fig. 8b).

Profile C–C' across the Jamapa river valley (Figs. 2 and 7c) shows the large (magnitude > 10.3, Table 3) and easily resolved Jamapa debris avalanche/flow deposit. In contrast, profiles E–E' across the Metlac river valley (Figs. 2 and 7e) shows the smaller (magnitude 8.0, Table 3) and less obvious Metlac debris avalanche deposit. The Jamapa deposit has previously been described by Carrasco-Núñez and Gomez-Tuena (1997), but exposures of the Metlac deposit were identified during the course of this study using the DTED-1 data and INEGI 1:50,000 scale maps used in the field. Across the Jamapa valley (profile C–C', Fig. 7c), only ASTER and DTED-1 resolves the 8.3 magnitude Excola lahar deposit (Table 3), derived from the Jamapa avalanche (Hubbard, 2001). Interpolation across the data gap in the SRTM data clearly cannot resolve the Excola lahar terrace shown in the ASTER and DTED-1 profiles in Fig. 7c. Across the Metlac valley (profile E–E', Fig. 7e), all three topographic datasets resolve the Metlac debris avalanche terrace (towards the right) and the larger block-and-ash deposit terrace (towards the left). However, the SRTM profile shows a gap and ~60 m height error above the terrace, perhaps caused by C-band radar backscatter within valley-floor canopy.

Profiles B–B' (Figs. 7b and 9a, b), D–D' (Figs. 7d and 9c, d) and F–F' (Figs. 7f and 9e, f) are used to illustrate the effects that canopy- and morphology-related height errors can have on the utility of DEMs for resolving ancient debris flow deposits of various sizes, and determining their magnitude. More precise profile locations are shown on subsets of the ASTER color composite image (Fig. 9a, c, and e) shown in Fig. 5a, but contrast enhanced separately to facilitate our interpretation of where closed canopy areas occur along the transects shown in Figs. 7b, d, f and 9b, d, f respectively. In general, darker shades of green are indicative of chlorophyll reflectance from tree crowns mixed with shadows cast within the understory. However, the brightness of closed canopy in remote sensing imagery can vary depending upon the slope of the underlying terrain, the angle of the sun and the reflective characteristics of the understory vegetation (e.g. Goel, 1988).

The Teteltzingo lahar deposit from Citlaltépetl (Figs. 2, 7d and 9c, d) exhibits a complex erosional topography and tributary drainage network in both the ASTER image subset (Fig. 9c) and in topographic profile (Fig. 7d). In fact, the ASTER-DTED and SRTM-DTED (Fig. 9d) shows numerous height errors below the mean difference values, which are caused by the failure of the DTED-1 “bald-earth” dataset to resolve the complex underlying hydrography of the area. Additional height errors < 60 m

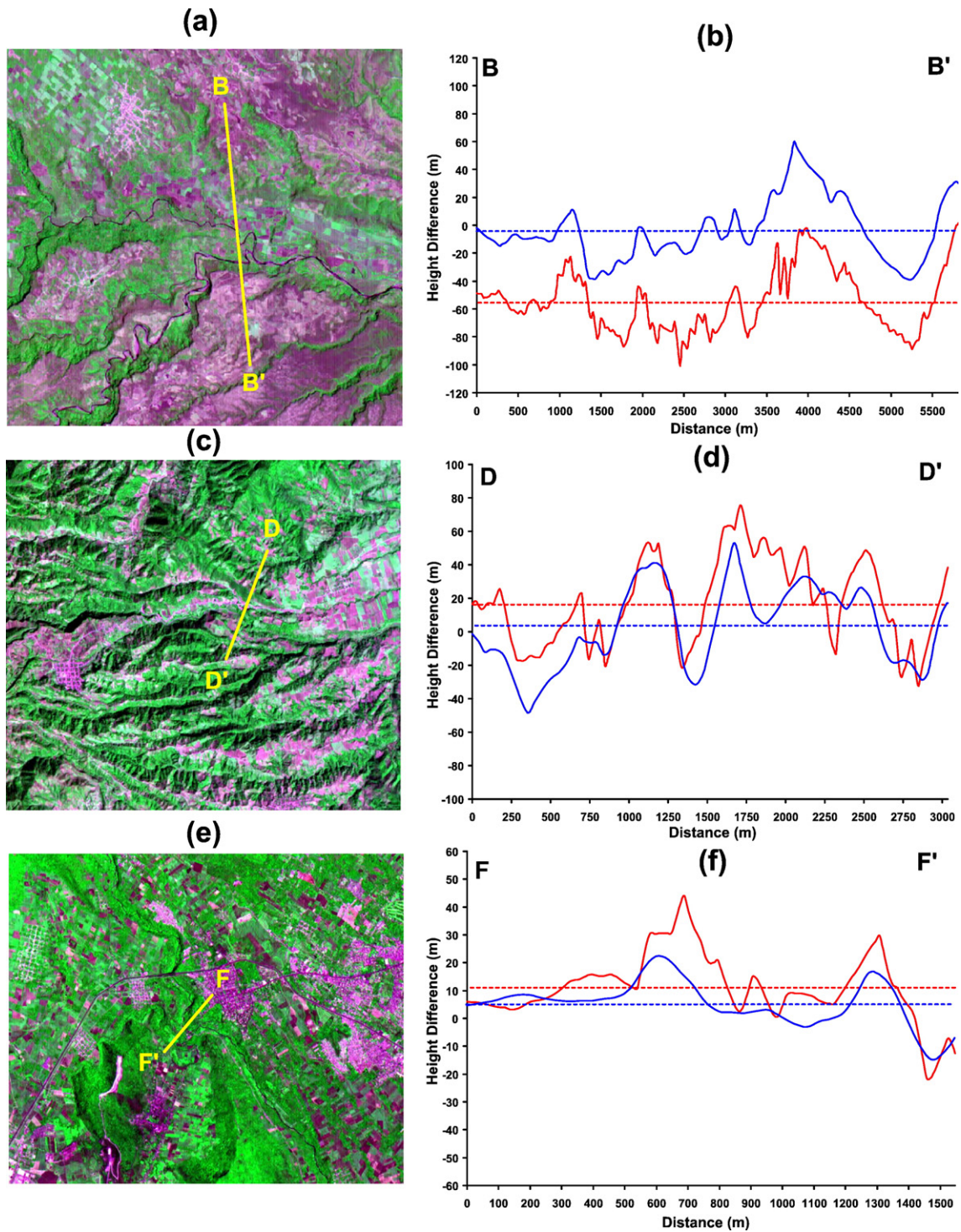


Fig. 9. Subsets of the ASTER 15 m resolution VNIR color composite shown and described in Fig. 5a. Yellow lines show more precisely the locations of transects B–B' (Fig. 7b), D–D' (Fig. 7d) and F–F' (Fig. 7f). Also shown to the right of each ASTER subset image are SRTM minus DTED-1 difference profiles (blue lines) and ASTER minus DTED-1 difference profiles (red lines) along the same transect lines and scales as shown in corresponding Fig. 7 profiles. Dashed lines show the mean height differential for SRTM minus DTED-1 (blue) and ASTER minus DTED-1 (red).

above the mean elevation difference (Fig. 9d) are caused by closed canopy on both sides of the Tliapa river.

The Rio Pescados debris flow deposit from Cofre de Perote (Figs. 2, 7b, and 9a, b) lies within a normal fault-bounded basin surrounded by monogenetic lava flow fields on both sides of the river (Negendank et al., 1985). The south side of the river is capped by mesa-form debris flow deposits from the catastrophic collapse of Cerro las Cumbres (Figs. 2 and 7b). ASTER and SRTM resolve at least three sets of tectonic terraces north of the river, while DTED-1 resolves only two (Fig. 7b). The lowermost terrace of the Rio Pescados debris flow deposit is resolved within all three datasets (Fig. 7b). However, the ASTER and SRTM profiles show prominent height error “artifacts” as much as 12 m (Figs. 7b and 9b) above the mean elevation difference, for what is an otherwise flat-lying terrace as resolved from the 1:50,000 scale INEGI topographic maps. Interpretation of the bright-green vegetation signatures in ASTER image subset (Fig. 9a) suggests open canopy as the cause of these height error artifacts in the ASTER and SRTM profiles, although larger height error differences (>60 m) occur along the southern edge of the canyon due to closed canopy on the Cumbres debris deposit (Figs. 7b and 9b), which appears dark-green (Fig. 9a).

Profile F–F’ (Figs. 7f and 9e, f) was extracted down slope of the suburban town of Fortin de las Flores on the Metlac river, which is also quite distinct in the ASTER composite image (Fig. 9e). The Fortin lahar (Fig. 7f) represents the smallest debris flow terrace resolved using our DTED-1 dataset and the 1:50,000 scale INEGI topo maps both verified it in the field. Although further field studies are needed, a possible origin is flow transformation (e.g. Scott et al., 1995, 2001) from the Metlac avalanche exposed further upstream (Figs. 2 and 7e). Unfortunately, dense closed canopy along the floodplain of the Metlac river (Fig. 9e) exaggerates the size of this terrace in the ASTER and SRTM profiles (Fig. 7f), and obscures its shape which should be flat-lying at this vertical scale as displayed in the DTED-1 profile (Fig. 7f). Both the ASTER and SRTM elevation profiles (Fig. 7f) and the ASTER-DTED and SRTM-DTED difference profiles (Fig. 9f) suggest canopy-related height errors >20 m.

The results of our analysis of these cross-valley profiles beg the question of what is the impact of these height- and valley morphology errors on the utility of global coverage ASTER and SRTM DEMs for determining the volume and magnitude of ancient debris avalanche/flow deposits, especially for volcanoes in inaccessible areas or for which little is known about their past history? We address this issue by measuring

cross-sectional areas for the Teteltzingo (Fig. 7d), Rio Pescados (Fig. 7b) and Fortin lahar (Fig. 7f), which are all orders of magnitude different in size (Table 3). We then use Eq. (1) and a base ten log conversion to derive magnitude estimates for valley-fill capacity based on similar assumed paleo-valley morphology for each of the three DEM datasets. In particular, DTED-1 provides a “bald-earth” baseline estimate, while the other two datasets (ASTER and SRTM) include height errors and valley morphology mistakes related to canopy cover.

For the Teteltzingo lahar deposit, DTED-1, SRTM and ASTER cross-valley profiles (Fig. 7d) yield estimated flow magnitudes of 9.0, 9.1 and 9.2 respectively which are each increasing by increments of 0.1. These exclude deposits of Teteltzingo lahar which flowed up onto higher than expected slopes (i.e. veneer deposits) as a result of super elevation effects (Carrasco-Núñez et al., 1993) as shown in the DTED-1 profile of Fig. 7d. For the Rio Pescados debris flow, DTED-1, SRTM and ASTER cross-valley profiles (Fig. 7b) yield estimated flow magnitudes of 8.5, 8.7 and 8.9 respectively which are each increasing by increments of 0.2. For the smallest resolved Fortin lahar, DTED-1, SRTM and ASTER cross-valley profiles (Fig. 7f) yield estimated flow magnitudes of 6.5, 7.3 and 7.7 respectively which are each increasing by increments ≥ 0.4 . Notably, the largest magnitude derived using ASTER and including maximum height errors (7.7) is larger than that of the historic 1920 Huitzilapan debris flow (7.6 — Table 3). Apparently, canopy-related height errors have negligible effects on volume estimates for very large debris flow deposits, but 30 m errors could well be significant for flow modelling and subsequent hazard assessment. However, from a hazards perspective it is always better to err on the conservative side (Tilling, 1989), which demonstrates the utility of high resolution and vertically accurate DEMs, even those which have not been canopy height-corrected.

Following Scott and Vallance (1995) who define the Osceola mudflow as their “maximum” possible lahar at Mount Rainier, we define the 9.3 magnitude Teteltzingo lahar (Table 3) as our maximum lahar for risk assessment and planning purposes. This choice is substantiated by edifice stability studies (e.g. Zimbelman et al., 2004) which suggest that E–W trending fractures exposed in the upper summit cone of Citlaltépetl could provide a surface for future failure and collapse, yielding 0.04–0.5 km³ of debris from the modern edifice. The latter volume would yield an estimated 8.7 magnitude debris avalanche/flow, not considering the effects of volume bulking (e.g. Scott et al., 1995, 2001). Zimbelman et al. (2004) also highlight the uneven distribution of collapse potential around the flanks of the upper

summit cone. Hubbard (2001) estimates a volume of $\sim 0.12 \text{ km}^3$ of mostly hydrothermally altered rock in the “Sarcafago” structure of Citlaltépetl, which is the remnants of the ancestral Espolon de Oro edifice which collapsed to produce the Teteltzingo lahar (Carrasco-Núñez et al., 1993). Collapse of the entire remaining “Sarcafago” structure would generate an estimated 8.7 magnitude debris avalanche/flow prior to volume bulking. For those reasons and a past history of collapse towards the east and northeast sectors (see most proximal extents of Teteltzingo avalanche-lahar and Jamapa avalanche, Fig. 2), we use LAHARZ to simulate the maximum lahar in the two drainages most likely to be affected by collapse in either direction, the Jamapa and Tliapa. For all the remaining drainages surrounding Citlaltépetl, including the Jamapa and Tliapa, we define the magnitude 8.5 Rio Pescados (Table 3) as our Case I

flow (high magnitude, low frequency — Scott and Vallance, 1995), the magnitude 7.6 Huitzilapan debris flow (Table 3) as our Case II flow (medium magnitude, medium frequency — Scott and Vallance, 1995) and the magnitude 6.5 Fortin lahar as our Case III flow (low magnitude, high frequency — Scott and Vallance, 1995) for LAHARZ hazard zone simulations.

4.3. LAHARZ-predicted debris flow inundation heights and vulnerability

Fig. 5b–d show the results of LAHARZ simulations of our maximum lahar (yellow), case I (magenta), case II (cyan) and case III (blue) flows. Several aspects of the results have been compared and discussed already such as stream hydrography terminations and flow paths. Here we compare the different flow inundation levels

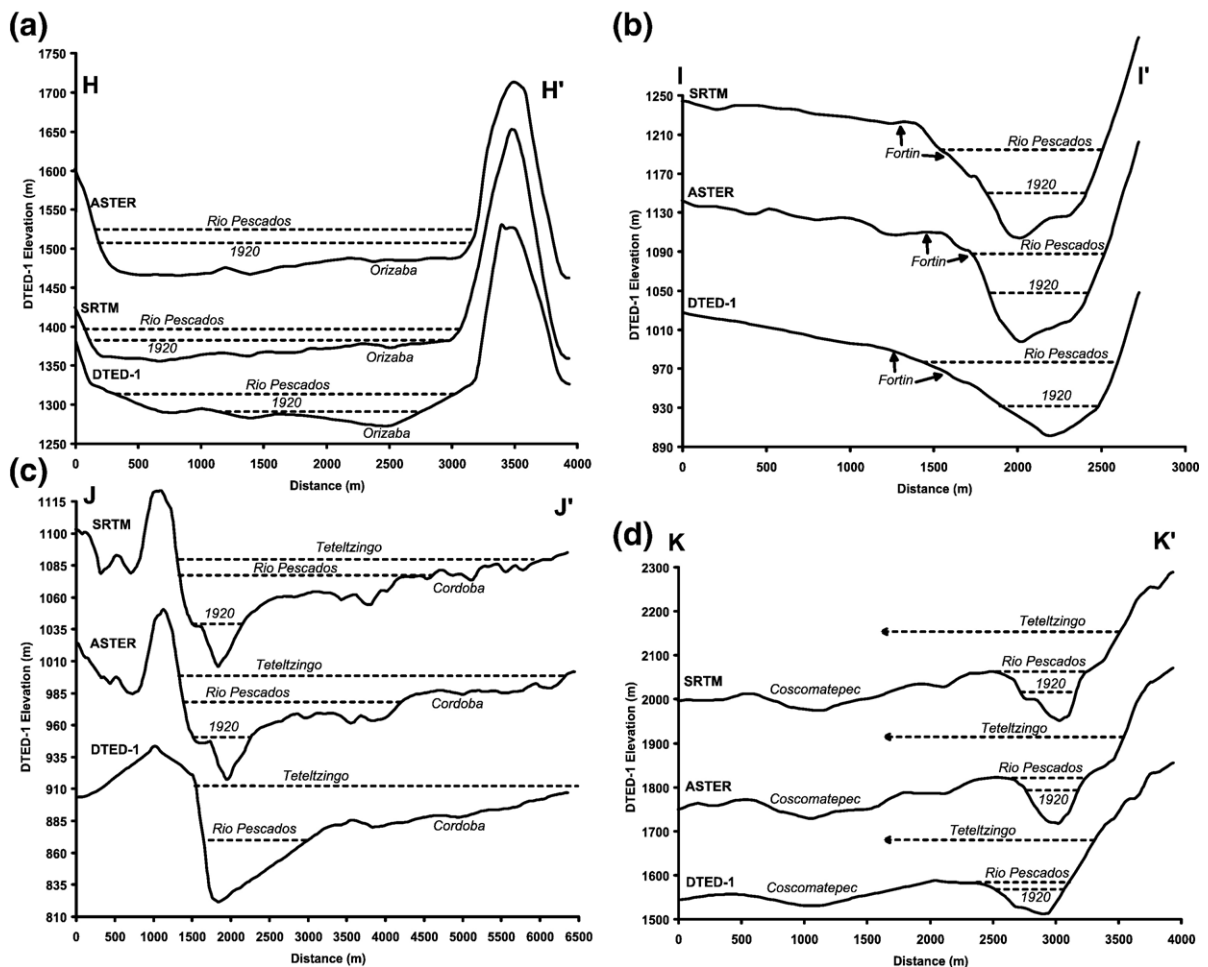


Fig. 10. LAHARZ-predicted flow inundation height boundaries with transect locations across the following cities and towns: (a) Orizaba, (b) Fortin de las Flores, (c) Cordoba, and (d) Coscomatepec, as shown on color Fig. 5. Accompanying Table 4 shows the calculated inundation heights for each city above the respective ASTER, SRTM and DTED-1 height-corrected topography.

predicted by LAHARZ using valley-fill cross-sectional areas for modeled flows of the same magnitude but different input DEM sources. In the process, we extract cross-valley profiles across four major cities and towns likely to be impacted in the future by flows similar in magnitude to those that have occurred in the past throughout the CCPVR (Carrasco-Núñez et al., *in press*).

Our profiles do not necessarily correspond to those of the stream valley transects generated by the LAHARZ software (Schilling, 1998), but rather represent the levels at which the resulting LAHARZ inundation boundaries intersect the topography as shown in Fig. 10. Table 4 summarizes the maximum elevation at which this intersection occurs, the minimum elevation of the stream channel cell for each DEM, and the predicted flood height difference. The location of the cities and towns along each transect are shown with respect to the predicted flood heights (Fig. 10), in order to illustrate their relative vulnerabilities to modeled flows of various magnitude. The cities chosen include the two largest, Orizaba (Fig. 10a) and Cordoba (Fig. 10c), and two smaller towns either built on or protected by high terraces of older debris deposits, Fortin de las Flores (Fig. 10b) and Coscomatepec (Fig. 10d).

All of the topographic profiles and LAHARZ-predicted flood inundation heights show remarkable consistency and agreement between the DTED-1, ASTER and SRTM datasets. This cross-validates the level of risk that each of the four cities is at from flows of magnitude ≥ 7.6 . However, each of the simulations were done using input DEMs of comparable ~ 90 m resolution cell size,

which may not resolve the cross-sectional areas of smaller flows well enough to prevent early flow terminations such as they all yield for the magnitude 6.5 Fortin lahar (Fig. 5b–d). In fact, Stevens et al. (2002) note that small volume ($\leq 10^7$ m³) lahars fall short in length by 1–2 km for LAHARZ simulations on 30- and 90-m resolution DEMs, though we make no attempt to compare the outputs using DEMs of different cell size because this is beyond the scope of our work. However, some notable minor differences do occur between the LAHARZ results obtained from the three input datasets.

For example, at Orizaba (Fig. 10a) ASTER and SRTM cross-valley profiles show low points beyond the point along the floodplain at which the stream cell occurs, which is hydrographically incorrect, but does not affect the correct routing of the flow by LAHARZ. A possible reason for this is perhaps buildings and trees in the built-up areas of the floodplain, which can create DEM sinks and depressions left unfilled by ARC/INFO (Jenson and Domingue, 1988). This produces higher flow inundation heights for the SRTM and ASTER datasets than for DTED-1 (Table 4). Also, the ASTER and SRTM profiles (Fig. 10a) show no safer, “higher ground” for flows of the magnitude of the 1920 Huitzilapan debris flow, while DTED-1 does.

At Cordoba, magnitude 7.6 flows either terminate just prior to the point at which the El Seco river flows past (e.g. DTED-1, Figs. 5c and 10c), or produce flow inundation heights ≤ 33 m (Table 4) which pose no threat to the city. Also, DTED-1 suggests that Cordoba is barely safe from a magnitude 8.5 flow, while ASTER

Table 4

Summary of LAHARZ-predicted inundation heights. Values in () are relative to low point along floodplain, but not the actual stream channel cell location. NM = not modeled. FT = flows terminated before reaching that location along stream drainage path

City	Teteltzingo			Rio Pescados			1920 Seismogenic		
	Max	Min	Height	Max	Min	Height	Max	Min	Height
<i>DTED-1</i>									
Orizaba	NM	NM	NM	1313	1272	41	1292	1272	20
Fortin	NM	NM	NM	976	901	75	933	901	32
Cordoba	913	821	92	870	821	49	FT	FT	FT
Coscomatepec	1680	1512 (1530)	168 (<150)	1581	1512	69	1570	1512	58
<i>ASTER</i>									
Orizaba	NM	NM	NM	1216	1177 (1159)	39 (57)	1197	1177 (1159)	20 (38)
Fortin	NM	NM	NM	888	798	90	849	798	51
Cordoba	818	736	82	796	736	60	768	736	32
Coscomatepec	1640	1440 (1450)	200 (<190)	1542	1440	102	1521	1440	81
<i>SRTM</i>									
Orizaba	NM	NM	NM	1273	1250 (1233)	23 (40)	1259	1250 (1233)	9 (26)
Fortin	NM	NM	NM	959	869	90	912	869	43
Cordoba	880	798	82	870	798	72	831	798	33
Coscomatepec	1682	1482 (1506)	200 (<176)	1592	1482	110	1553	1482	71

and SRTM suggest that it is not (Fig. 10c). LAHARZ simulations using all three datasets agree that Coscomatepec (Fig. 10b) and Fortin (Fig. 10d) are safe from all but the largest modeled flows in each case, which are magnitudes 9.3 and 8.5 respectively. In particular, the profile across Coscomatepec (Fig. 10b), dramatically illustrates the effects of flow overbanking of a Teteltzingo sized lahar.

5. Conclusions

Each of the three DEM datasets evaluated and compared during the course of this study has strengths and weaknesses, in regards to its utility for mapping lahar hazards from volcanoes. In particular, the two spaceborne-derived datasets, ASTER DEMs and SRTM DEMs offers global coverage at relatively higher horizontal resolution (30–90 m) and vertical accuracy (~30 m) than ever before. This presents an unprecedented opportunity for more studies on topographic mapping of volcanic deposits, volcano instability, and evaluation of potential risk to populated areas downstream.

One notable limitation of ASTER is its 60 km swath width and 8% duty cycle, which limits the possibility of obtaining cloud-free coverage of the full extent of E–W trending river valleys for volcanoes with the potential for long runout flows. A related issue is the problem of producing “seamless” mosaics from adjacent cloud-free orbital swaths of data, which is especially problematic for the relative DEMs generated as a standard data product by EDC. On the other hand, SRTM was a one-time mission with no immediate plans for update, while ASTER is still under continuous operation, though exceeding its estimated seven year lifetime. One complementary aspect of both spaceborne datasets is the potential for using SRTM as a source of geographic control for generating absolute ASTER DEMs, which in turn can be used to fill voids in SRTM data. For example, ASTER can be used to acquire multi-seasonal stereo coverage for stream valleys that were poorly oriented during the two or more SRTM orbital passes, or to update volcanoes and stream valleys that have undergone topographic changes (e.g. Stevens et al., 2004). This highlights the need for continuous spaceborne topographic mapping missions using either a cross-track stereo imaging instrument like ASTER, or another satellite platform containing either spaceborne InSAR or LIDAR. At present, the only alternative satellite datasets capable of yielding topographic information in the event that ASTER becomes inoperable are: repeat-pass SPOT imagery, IKONOS, Quickbird and Cartosat in the commercial domain.

For this study, we used ~90 m resolution DTED-1 as a baseline “bald-earth” DEM for assessing the quality and vertical accuracy limitations of the two spaceborne datasets, and found limitations in DTED-1 as well. For example, because DTED-1 DEMs are derived from interpolation of digitized topographic maps at $\leq 1:250,000$ scale, interpolation across widely spaced contours can cause subtle but important drainage divides to be missed, which is in agreement with other studies using digitized contour data (e.g. Stevens et al., 2002). Such hydrographic mistakes can have serious consequences in determining where flows will be routed on the topography, and which cities or towns are most at risk. Also, the ASTER and SRTM DEMs better resolved the complex drainage pattern and highly dissected morphologies of volcaniclastic deposits in valleys along the humid sub-tropical eastern flanks of the volcanic range than did DTED-1.

However, the ASTER and SRTM DEMs have vertical accuracy limitations related to their measurement of above- and within-canopy elevation, respectively. For example, canopy can either obscure the shape of terraces of small debris flow deposits or exaggerate their maximum extents. Also problematic are data voids caused either by steep slopes obscured by closed canopy or steep slopes facing away from the sensor or beyond line of sight due to extreme parallax. This has serious consequences for resolving the shapes of valleys, often generalized or worsened during the process of interpolation, but essential for ensuring that a valley’s fill capacity for floods and flows is properly taken into consideration when using flow routing programs.

All three DEMs were useful for locating, measuring and paleohydrologic modeling of inundation levels from ancient debris flow/avalanche deposits. In particular, the ~90 m resolution DTED-1 and 1:50,000 scale topographic maps from which they were derived demonstrate that the smallest ancient lahar deposit resolved at this resolution is about $2.8 \times 10^6 \text{ m}^3$ in volume, with a height of <5 m above the modern floodplain. However, height errors from even open canopy can cause an order of magnitude error in the estimated size of smaller debris flows, as compared with their impact on the largest ones. This has the consequence of overestimating the volume and forecasted extent of such flows in the future. For small but frequent flows of magnitude <7, airborne LIDAR offers promise for more accurate mapping (e.g. Griswold and Iverson, 2003), though here we present GIS analytical methods, that can be applied using any available DEM data source, for assessing lahar hazards at volcanoes around the world.

Finally, all three DEMs yield remarkably similar lahar hazard zone boundaries and flow inundation heights when

using flow volume magnitudes comparable to those that have occurred in the past. At Citlaltépetl, LAHARZ simulations using all three input DEMs show that the city of Orizaba is most vulnerable to flows of magnitude as large as one that occurred in 1920 in another part of the volcanic range, or larger. Other towns, built on terrace deposits emplaced by the largest ancient debris flows, are safe from all but the largest of such flows. However, the smallest magnitude flows terminate close to the proximal hazard zone boundary, suggesting that higher resolution DEMs, such as those acquired using LIDAR (e.g. Griswold and Iverson, 2003), are needed for accurately forecasting the extent of such flows in the future.

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