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The global distribution of human population and recent volcanism

Christopher Small[a,*], Terry Naumann[b]

[a] *Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA*
[b] *Department of Geology, University of Alaska, Anchorage, Anchorage, AK 99508, USA*

Abstract

This study quantifies the spatial relationship between the global distribution of human population and recent volcanism. Using recently compiled databases of population and Holocene volcanoes, we estimate that almost 9% (455×10^6 people) of the world's 1990 population lived within 100 km of an historically active volcano and 12% within 100 km of a volcano believed to have been active during the last 10,000 years. The analysis also indicates that average population density generally decreases with distance from these volcanoes (within 200 km). In tropical areas, the elevation and fertile soils associated with volcanic regions can provide incentives for agrarian populations to settle close to potentially active volcanoes. In Southeast Asia and Central America higher population densities lie in closer proximity to volcanoes than in other volcanic regions. In Japan and Chile, population density tends to increase with distance from volcanoes. The current trends of rapid urbanization and sustained population growth in tropical developing countries, combined with agricultural intensification of fertile volcanic terrains could alter the relationship between humans and volcanoes so as to increase both local and global consequences of volcanic eruptions in the future. © 2002 Published by Elsevier Science Ltd.

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1. Introduction

Recognition of the far-reaching societal impacts of environmental catastrophes has resulted in an increased awareness of the importance of natural hazards beyond the local areas that are directly impacted. Increasing economic globalization combined with rapidly growing populations in developing countries seems likely to further this trend. If so, it will become increasingly necessary to consider natural hazards and their potential impacts in a global context. Understanding the relationships between human populations and their environments may facilitate mitigation of the hazards inherent to the environment. The analysis presented here is an attempt to quantify some fundamental aspects of the spatial relationships between human population and recent volcanism. The overall objective of the analysis is to provide a quantitative global perspective on the current human settlement of volcanic terrains and to discuss some of the implications for volcanic hazards beyond the areas directly impacted. This is not intended to be a global assessment of volcanic risk but rather a comparative study of population distribution in volcanic environments.

The nature and potential impact of a hazard depends on the relationship between the hazard and the population or asset that is at risk. The consequences of volcanic eruptions depend on both the physical hazards associated with the volcanic event, such as pyroclastic flows and ash falls, as well as the vulnerabilities of people and assets. Volcanic Risk thus equals Hazard × Vulnerability × Value. (Fournier d'Albe, 1979). In the case of spatially localized hazards, such as volcanoes, the physical proximity of a population to the source of the hazard is a fundamental component of the vulnerability. For this reason, it is important to quantify the spatial distribution of population relative to the source of the hazard. This is routinely done for local populations and individual volcanoes in the form of a risk assessment (see Blong, 2000 for a recent summary). Detailed risk assessments are now conducted for many individual volcanic regions but the comparative study of different populated volcanic regions has received less attention. Considering the relationship between populations and volcanoes in a global context

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*Corresponding author. Tel.: +1-845-365-8354; fax: +1-845-365-8179.

E-mail addresses: small@LDEO.columbia.edu (C. Small), aftrn@uaa.alaska.edu(T. Naumann).

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may provide some insights into the nature of the relationship that is not apparent in individual cases. A quantitative global description of contemporary human settlement patterns in active volcanic regions may also facilitate understanding of both past and future habitation of these environments. The United Nations declared the years 1990–2000 the International Decade for Natural Disaster Reduction (IDNDR) and has encouraged the indexing of hazards and risks at the world's active volcanoes. It is difficult to determine the global significance of volcanic hazard to the human population from individual hazard assessments made by different individuals or governments. A comparative study may emphasize cross cultural similarities in settlement patterns and tendencies. One objective of this analysis is to provide a self-consistent quantitative estimate of the number and distribution of people potentially impacted by volcanic activity worldwide.

The systematic study of volcanic hazard is not new but it has made great advances with respect to monitoring and mitigation in recent years as a result of advances in physical volcanology, geochemistry and geophysics (see Scarpa and Tilling, 1996; Sigurdsson, 2000 for compendia). While advances in understanding how volcanoes work benefit hazard mitigation, the sociocultural factors that influence habitation of volcanic zones are also critical to mitigation. Several authors have noted that a disproportionate number of the people at risk from volcanic hazards live in societies that may lack the resources to mitigate the hazards associated with volcanic activity (Macdonald, 1972; Warrick, 1979; Hodge et al., 1979; Grayson and Sheets, 1979; Blong, 1984; Chester, 1993; Chester et al., 2001). Tilling (1992) specifically addressed the fact that some of the most volcanically active regions of the world are also the sites of dense and rapidly growing populations and warned that the impact of volcanic activity is likely to increase as a result of resource-limited populations expanding into hazard zones. A global study by Peterson (1986) estimated that 9.6% of the world's population lived in areas that may be affected by volcanic activity. Peterson's study, based primarily on national scale population estimates from the 1970's, emphasized the point that many volcanic regions lie within developing countries. We take the important points made by these earlier works as the starting point for our study.

2. Distributions of volcanoes and human population

Volcanism on Earth occurs predominantly on the seafloor and the vast majority of the known volcanoes on Earth, both active and extinct, are in the Pacific Ocean basin (Menard, 1964; Chapel and Small, 1996). Submarine volcanism accounts for an estimated 83% of the total global volcanic output (Crisp, 1984) but has little direct impact on human lives. The spatial distribution of recently active subaerial volcanoes is primarily concentrated along plate boundaries (Fig. 1) (Simkin and Seibert, 1984, 1994; Francis, 1993). The majority of these subaerial volcanoes are associated with subduction zones at convergent plate boundaries and form elongate chains that often emerge as island arc complexes and archipelagos. Several of these convergent plate boundaries coalesce to form the "Ring of Fire" around the periphery of the Pacific Ocean basin where denser oceanic plates are subducted beneath more buoyant overriding plates. The initial phases of melting of the subducted plates produces high viscosity, volatile rich silicic lavas which erupt more explosively than the lower viscosity effusive lavas erupted at divergent plate boundaries (e.g. Iceland) and intraplate settings (e.g. Hawaii). The composition and dynamics of subduction zone volcanoes have two primary consequences for Earth's human population. A positive consequence is that the ash and lava ejected from the volcanoes tend to form prominent edifices which weather rapidly to create nutrient rich soils. A negative consequence is that the activity at these volcanoes tends to take the form of episodic, explosive eruptions that often occur with little advance warning. As a result, the populations in the vicinity of these active volcanoes derive benefits from the volcanic activity while being at risk from a variety of related hazards.

Human populations are also localized, primarily on coastal plains and interior drainage basins of continents where volcanism is relatively rare (Fig. 2). Although there is a marked tendency for human populations to settle at low elevations (Cohen and Small, 1998) and in close proximity to coastlines (Small and Cohen, 1999), the majority of low coastal elevations on Earth are located adjacent to passively subsiding extensional continental margins rather than at the active convergent margins and island arc complexes where most explosive volcanoes are concentrated. In many areas, however, sizable populations do settle in close proximity to volcanoes. This occurs primarily around the Pacific "Ring of Fire" and Southeast Asian arc systems, several smaller isolated subduction complexes (e.g. Italy, Greece, W. Indies), the East African Rift system, and numerous oceanic islands formed by intraplate or "hotspot" volcanism (e.g.-Hawaii, Azores, Iceland).

The spatial coincidence of volcanoes and populations is currently increasing. Our understanding of how volcanoes work has improved drastically in the past 200 years but the frequency of (non-famine) fatality has not decreased significantly (Simkin and Seibert, 1984, 1994; Blong, 1984; Tilling, 1989). Since 1700, volcanic disasters have taken an estimated toll of more than 270,000 lives (Simkin et al., 2001; Sigurdsson, 2000). Since 1800, at least 480 volcanoes have produced more

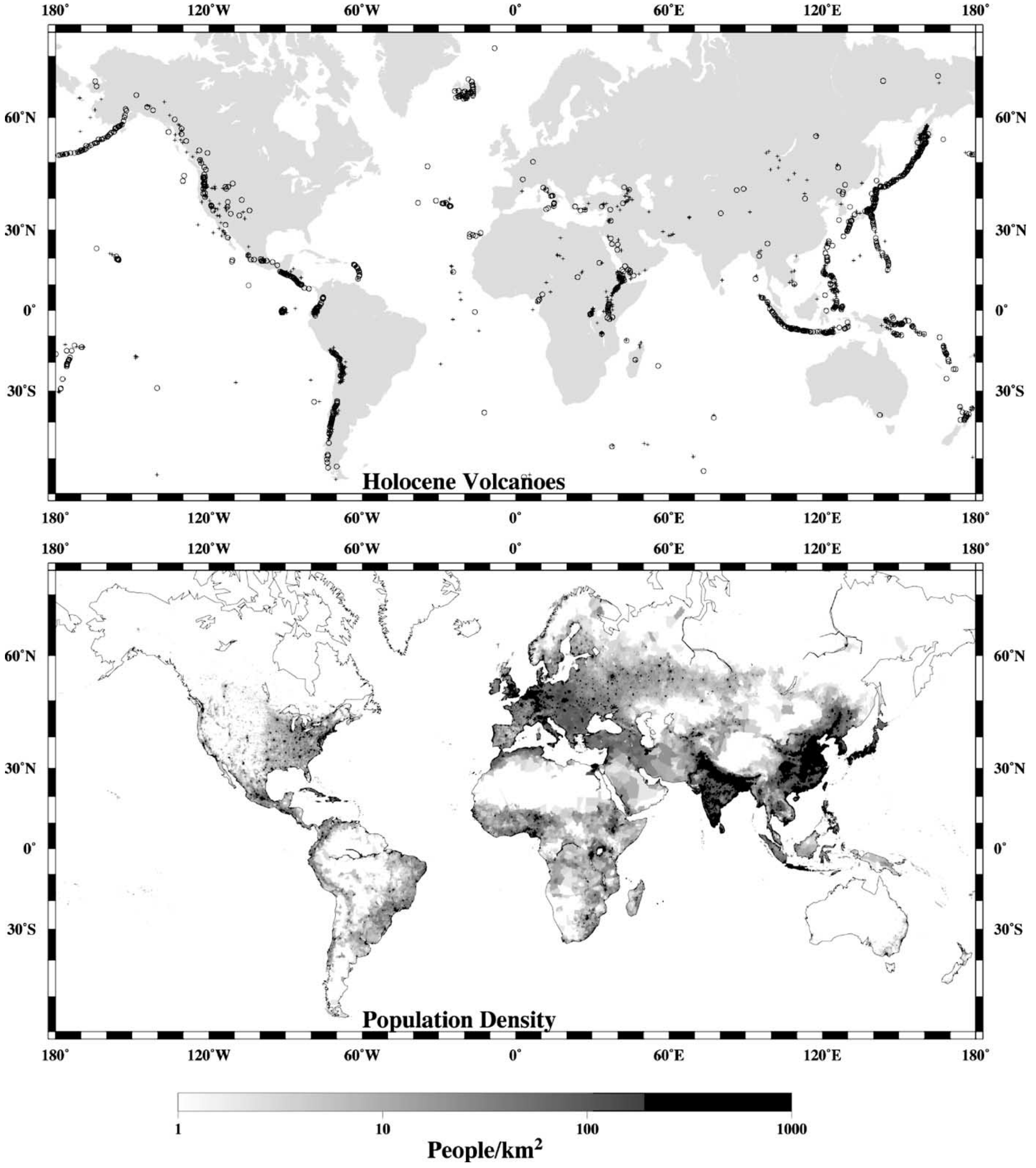

Fig. 1. The global distribution of Holocene volcanoes and human population. Historically active volcanoes are shown as circles and Holocene volcanoes without historical eruptions are shown as crosses. Population density, derived from 127,105 census estimates, is shown on a logarithmic scale. A more detailed color version of this figure is available from http://www.LDEO.columbia.edu/~small/PopVol.html.

than 7886 eruptions (Simkin and Seibert, 1994). More than 400 of these documented eruptions are believed to have produced fatalaties (Simkin et al., 2001). During this time, the rate of subaerial volcanism has not changed significantly (Simkin and Seibert, 1994) but the number of people on Earth has doubled twice and

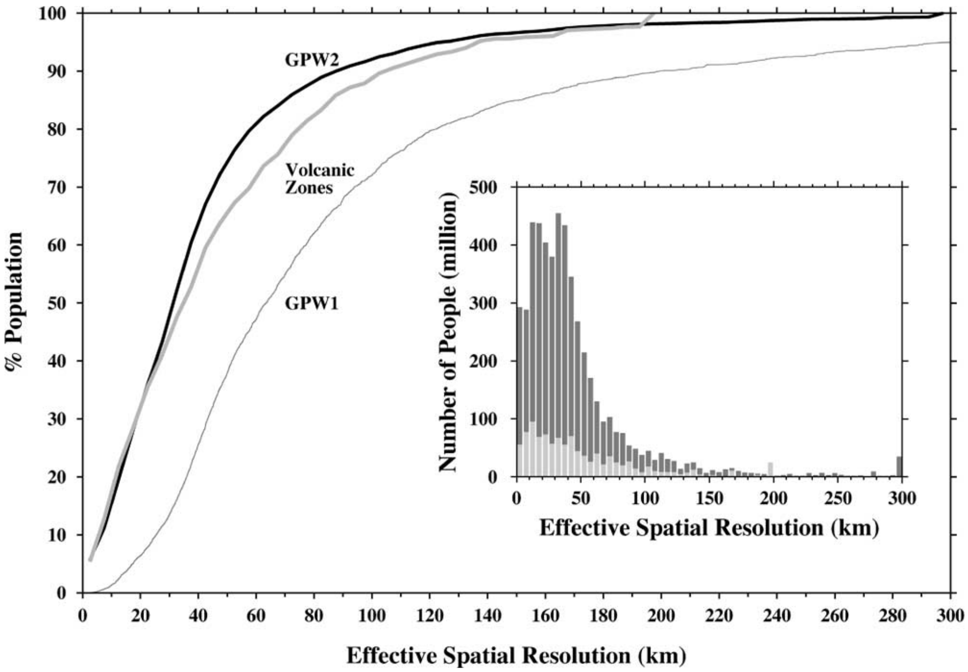

Fig. 2. Resolution analysis for the population data used in this study. Dark inset histogram shows number of people as a function of the spatial resolution of the census data. Lighter histogram shows resolution distribution for populations within 200 km of a Holocene volcano. Cumulative resolution curves show the percentage of the populations that can be located to within a particular spatial certainty. GPW2 shows the improvement in resolution from the earlier GPW1 data set.

the present global population is more than five times the global population in 1800 (Cohen, 1995). Fortunately, fatalities related to volcanic activity have not increased proportionally to the growth of Earth's human population but volcanic events claiming more than 100 lives occurred as frequently in the 20th century as they did in the 19th (Simkin and Seibert, 1994). While the study and monitoring of volcanoes has seen great advances since 1800, population growth in volcanically active areas has increased the potential impact of volcanic activity in spite of these advances. The average number of documented eruption-caused deaths per year is 845 for the 20th century, and 315 for the 17th–19th centuries (Tilling, 1990). While this difference may partially reflect the inaccuracy of older fatality counts in developing countries, it is also likely to be a real consequence of increasing population in several volcanically active regions. Many of these areas are currently experiencing dramatic increases in population growth, urbanization and economic development.

3. Data

3.1. Global distribution of Holocene volcanoes

The global distribution of recently active volcanoes (Fig. 1) is described by the Holocene Volcano Database maintained by the Smithsonian Institutions Global Volcanism Program (http://www.nmnh.si.edu/gvp/volc-data/index.htm). This database catalogs 1509 individual volcanoes and volcanic features believed to have been active during the Holocene era (the past 10,000 years). Each volcano is assigned to one of eleven age categories on the basis of its most recent activity. A total of 702 volcanoes had documented historical eruptions and 703 additional volcanoes are believed to have been active sometime during the Holocene on the basis of either hydrothermal activity, radiocarbon dating or geologic mapping of recent ejecta deposits. An excellent analysis and discussion of the data set and the characteristics of Holocene volcanism is given by Simkin and Seibert (1994). From this data set, we consider the 1405 volcanoes that lie above sea level and within the populated non-polar latitudes.

3.2. Global distribution of human population

The global distribution of population (Fig. 1) is described by data sets originally produced in 1995 by the National Center for Geographic Information and Analysis (University of California, Santa Barbara). Tobler et al. (1997) collected census information from 217 countries partitioned into a total of 19,032 secondary administrative subdivisions (corresponding to counties in the United States). These data were used as the basis for a mass-conserving spatial redistribution, to produce gridded population estimates with a horizontal grid spacing of 5 arcminute (Tobler et al., 1997). Our initial investigation of population and volcanism (Small and Naumann, 1998; Naumann and Small, 1998) was based on the original population data set produced by Tobler et al. (1997) but the analysis presented here is based on an updated and expanded gridded population model (GPW2) produced by CIESIN (2000) (http://www.ciesin.org/GPW.html). The census years range from 1967 to 1999 and were projected to a common base year of 1990. Country specific exponential growth rates were used to interpolate or extrapolate populations from the nearest census year to 1990. The revised data set is based on 127,105 census estimates and provides considerably improved spatial resolution in many parts of the world (Fig. 2) allowing the data to be gridded at an interval of 2.5 arcminute (4.6 km at the equator). The total 1990 population estimated in this way was 5.2 billion people. The uncertainty of this estimate probably exceeds 2%, based on censuses in developed countries. The polygons occupied by humans totaled $130 \times 10^6\,\text{km}^2$, 25.9% of the earth's surface area and 98% of ice-free land. Of the 127,105 census estimates used in the global data set, the centroids of 25,927 of these were located within 200 km of a Holocene volcano—totaling just over 1 billion people—representing 20% of the estimated world population in 1990. This is a maximum estimate because not all of the administrative units lie entirely within 200 km of a Holocene volcano. For this reason, our analysis will use the gridded population data set so as to count only the areal proportion of the administrative units that lie within a given distance of a volcano.

The spatial resolution of the census data imposes a fundamental limitation on the conclusions that can be drawn from this analysis. Fig. 2 shows the distributions of administrative unit areas for both the global data set and the subset with centroids less than 200 km from a Holocene volcano. Also shown is an estimate of the cumulative spatial uncertainty for both the initial and updated global population data sets as well as the volcano-proximal subset described above. The spatial uncertainty within a given administrative unit corresponds to the size of the unit. The larger the unit, the greater the uncertainty as to where within the unit the inhabitants are located. The Effective Spatial Resolution (ESR) of a census estimate is therefore proportional to the square root of the area of the administrative unit. Since the units consist of arbitrarily shaped polygons the horizontal dimension of a polygon will generally be proportional to the square root of the area (unless the polygon is extremely elongate). The inset histogram shows the number of people as a function of the spatial resolution of the census data for the GPW2 data set used for this analysis. It is apparent that most of the census data consist of units with resolutions much finer than 100 km. In the GPW2 data set most of the administrative units have a horizontal dimension less than 50 km. These distributions can be summed to give an estimate of the total number of people (or percentage of the global population) that can be located to within a given distance (ESR) as is shown by the smooth curves in Fig. 2. These curves indicate that the original population data set located 50% of the world's population to within 63 km while the updated GPW2 data set can locate 50% of the world's population to within 31 km and 80% to within 60 km. Similarly, 50% of the populations near (within 200 km) volcanoes can be located to within 37 km and 90% to within 120 km. Population density maps in subsequent figures show that in most of the areas considered in this study the spatial resolution is actually better than the global average for the data set. The choice of the 200 km radial distance is explained in the analysis section below.

The median population density of occupied land described by this data set is less than 10 person/km^2, reflecting the fact that most of Earth's land area is sparsely populated (Small and Cohen, 1999). In this gridded model the total population of each census tract is assumed to be uniformly distributed over the area of that tract. It is unlikely that many of these tracts were actually uniformly populated with no intratract clustering but the uniform distribution assumption represents an extremal bound on the population distribution within the constraints of the data set. The other extremal bound would correspond to maximal intratract clustering in which the entire population of the tract was localized at a single point leaving the remainder of the area of the tract uninhabited. Because this single point could be located anywhere within the tract, there are effectively an infinite number of possible spatial distributions corresponding to the maximal clustering case. Given the mobility of human populations at a range of temporal and spatial scales, it seems far more logical to assume uniform distribution within a tract than to adopt an unsubstantiated assumption about clustering. Because population densities vary over at least five orders of magnitude, we will generally present population counts and densities on a logarithmic scale as shown in Fig. 1.

The spatial accuracy of the population data is likely to be greater in more densely populated areas because more detailed censuses are conducted in these areas. Sparsely settled regions tend to be lumped into larger, lower density administrative units. Within these larger units there generally exists spatial clustering into small settlements surrounded by uninhabited areas. Because the spatial accuracy of the census data are a function of the size of the administrative unit, the smaller, denser units provide stricter constraints on the location of larger numbers of people. The implication is that any conclusions drawn about the spatial proximity of people to volcanoes will be more accurate in densely populated regions. This is discussed in more detail below.

We emphasize that the spatial resolution of this data set is not adequate for detailed volcanic hazard assessments in many of the areas considered in this study. While the horizontal dimension of administrative units in most areas is comparable to striking distance of some volcanic hazards such as pyroclastic flows and tephra falls (discussed below), it is not sufficiently detailed to allow important factors such as topography, wind direction and infrastructure to be taken into account. Volcanic hazard assessments for individual volcanoes must incorporate the specific eruptive characteristics of the volcano as well as local topography, drainage patterns, infrastructure and detailed settlement patterns in order to make meaningful statements about the risk associated with a particular type of eruption (e.g. Connor et al., 2000, 2001; Iverson et al., 1998; Wadge et al., 1994).

4. Analysis

The primary objective of this analysis is to quantify human proximity to active volcanoes on a global basis. This is accomplished by co-registering the locations of the volcanoes with the gridded population estimates. Because the spatial resolution of the population data set varies geographically, it is necessary to quantify the effective resolution in the areas of greatest interest if we are to interpret the results rationally. In this study, we are concerned with the population within 200 km of the volcanoes. We limit the region of analysis to 200 km because it encompasses the primary direct impacts of explosive volcanic eruptions (Connor and Hill, 1993; Connor et al., 2001; IAEA, 1997). Lava flows from silicic volcanoes pose a negligible threat to populations more than ~50 km from the eruption (Kilburn, 2000; Peterson and Tilling, 2000), but pyroclastic flows and surges (Nakada, 2000), and lahars (Rodolfo, 2000) may occasionally extend to distances of 100 km and substantial tephra falls can occur at distances as great as 200 km (Crandell et al., 1984; Houghton et al., 2000). Previous hazard assessment schemes have used a distance of 150 km for direct effects of volcanic eruptions (Connor and Hill, 1993). A more detailed discussion of the spatial aspects of volcanic phenomena in hazard assessment is given by McGuire (1998).

Pioneering studies which documented the relationship of explosivity and the preceding time interval (Smith, 1979; Simkin and Seibert, 1984, 1994; Simkin, 1993) found that the volcanoes that erupt least frequently tend to erupt most explosively and produce more fatalities. Simkin and Seibert (1984) emphasize that 17 of the 21 largest historical eruptions have occurred at volcanoes that had experienced no previous historical eruptions. For this reason, we subdivide the volcano database into those for which a historical eruption has been documented and those that are believed to have been active in the Holocene but have no documented historical eruption. This subdivision is admittedly ad hoc since the existence of a recorded historical eruption at a particular volcano depends as much on the historical proximity of human habitation as it does on the actual eruptive frequency of the volcano. Nonetheless, given the spatial clustering that characterizes volcanic belts and the fact that most of the currently populated volcanic regions have been populated at low to moderate densities for hundreds or even thousands of years, it seems unlikely that a significant number of recently active volcanoes in populated areas will have experienced large undocumented eruptions. Volcanic eruptions rarely go unnoticed by local inhabitants. We segregate the volcano data set in order to allow for the possibility that the volcanoes that have not experienced historical eruptions are statistically those either most, or least, likely to experience a large explosive eruption in the future. Also, some volcanic fields composed of monogenetic cones may have experienced recent eruptions but the actual edifices would not be expected to erupt again.

From the perspective of populated and unpopulated volcanic regions, we first consider the distribution of population with respect to individual volcanoes with respect to population. This allows us to categorize each individual volcano according to its proximal population density and determine which volcanoes are most, and least, densely populated. It also allows us to determine, on a global scale, the relative percentage of recently active volcanoes that are inhabited. Distributions of population and land area as functions of radial distance calculated within 200 km of each volcano provide a basis on which to rank the volcanoes. Fig. 3 shows the distribution of all individual Holocene volcanoes as well as those for which a historical eruption has been documented. Because population density varies over such a large range, the distribution is given as a function of the Log_{10} of the population within 100 km.

From the perspective of local human proximity to volcanoes we consider the distance to the nearest volcano for all populated areas within 200 km of a Holocene volcano. This allows us to estimate the cumulative numbers of people living at various distances from multiple volcanoes. Because volcanoes tend to be spatially clustered, persons living near one volcano are likely to be living near several. For each gridpoint estimate of population, we calculate the distance to the nearest Holocene volcano and the distance to the nearest volcano with a recorded historical eruption.

Most subaerial volcanism occurs clustered along island arcs and continental margins so proximal land area does not generally increase in strict proportion to the square of the distance from the volcano. The

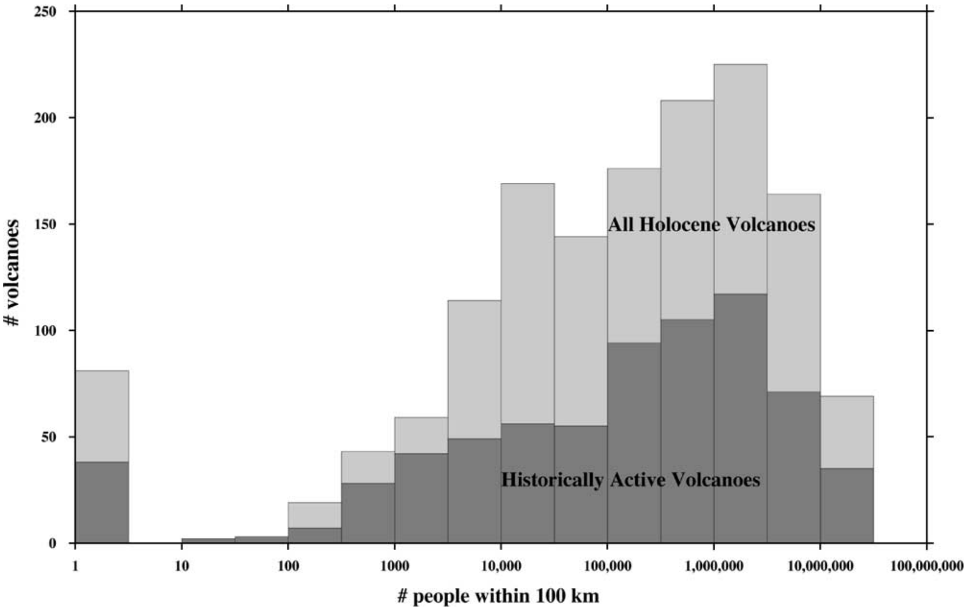

Fig. 3. Distribution of Holocene volcanoes with respect to human population. Histograms show the number of Holocene volcanoes as a function of the number of people residing within 100 km. Volcanoes with less than 30,000 people within 100 km correspond to population densities of less than 1 person/km^2 and are considered sparsely populated. There are 457 densely populated volcanoes (222 historically active) with more than 1 million people living within a 100 km radius.

distribution of population will therefore be limited by the availability of land area as a function of distance from each volcano. For this reason, we calculate both the distribution of population and the distribution of land area as functions of distance from each volcano. This allows us to normalize the population for the available land area and obtain average population density estimates (total number of people within X km/total land area within X km) as functions of distance from each individual volcano as well as the nearest volcano. It is important to maintain the distinction between actual point population density estimates and the average density estimates which normalize the total population in a given distance range by the total land area within that range. Because populations are not distributed evenly, the average density is a radial average of the actual population densities within that distance range.

An example of this distance calculation is shown for the Trans-Mexican Volcanic Belt in Figs. 4 and 5. The estimated numbers of people and land area are summed in 20 km bins, shown by the histograms, and the cumulative number of people within a given distance is given by the curves in the uppermost plot. Analyses are conducted using the distribution of all Holocene volcanoes and using only the subset with historical eruptions to emphasize the different relationship of each distribution to the settlement pattern. The plots indicate that most of the population in this region of Mexico lives between 20 and 60 km from a Holocene volcano with proportionally more people living closer to volcanoes without historical eruptions than to those with. This is largely a consequence of the expansion of Mexico City to encompass the Chichinautzin, Tenayo and Santa Catarina volcanic fields. The summit of Popocatapetl is located approximately 60 km from the most densely populated part of Mexico City but only 20 km from estimated population densities of 1000 people/km^2. By dividing the total number of people at each distance range by the total land area within that range we obtain estimates of the average population density at that range as shown in the lower plot of Fig. 4. This plot indicates that population density in central Mexico is highest in the range of 20–40 km from historically active volcanoes while it is highest for distances less than 20 km for all Holocene volcanoes, as a result of several volcanic fields in densely settled areas that have not experienced historical eruptions. Taken together, the plots quantify what the map shows geographically—most of the densely settled land area in central Mexico is less than 100 km from a Holocene volcano while the areas further from the volcanic belt are more sparsely settled.

5. Results

Fig. 3 shows the global distributions of Holocene volcanoes with respect to human population. The lighter shaded histogram shows the distribution of all Holocene volcanoes as a function of the estimated number of people living within 100 km while the darker histogram shows the distribution of volcanoes with historical eruptions. We limit ourselves to 100 km here because

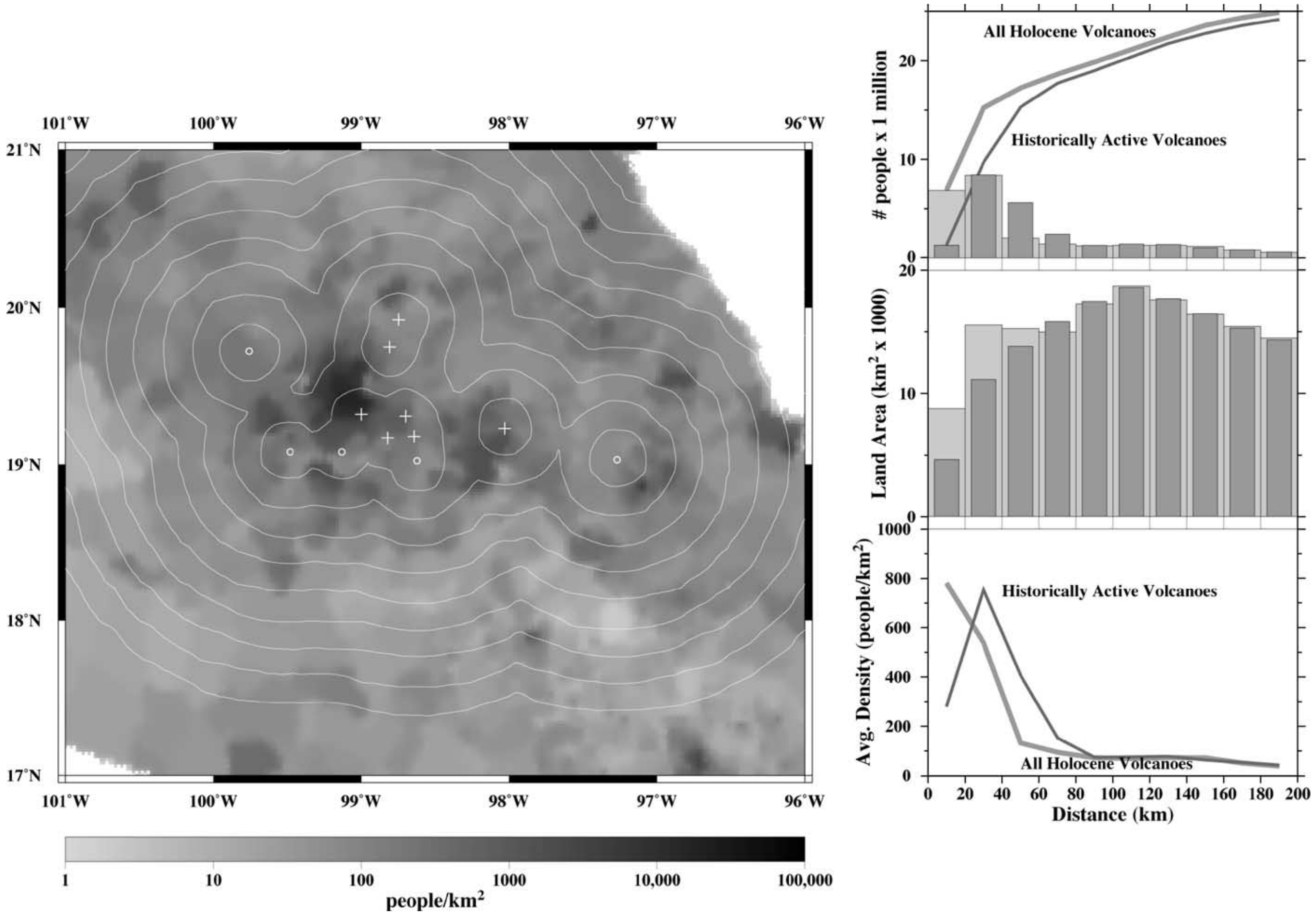

Fig. 4. Proximity of population to volcanoes in central Mexico. Distance contours superimposed on population density estimates show the geographic coincidence of population to Holocene volcanoes. Note that the population density scale is logarithmic. Histograms show the distributions of population and land area as functions of distance from the nearest Holocene volcano and the nearest historically active volcano. Adjusting the number of people at each distance for the available land area gives estimates of average population density, shown by the curves. While average population density increases abruptly within 40 km of Holocene volcanoes overall, the historically active subset tend not be settled as densely at distances less than 20 km. Colour figure available from: http://www.LDEO.columbia.edu/~small/PopVol.html

we are concerned with the populations living on the volcanic edifice itself rather than all the population within striking distance of a hazard. The volcanoes with less than 10,000 people can be considered sparsely populated as they correspond to population densities of less than one person/km^2 at which density the population data are likely to have the greatest uncertainty. The histograms indicate that most Holocene volcanoes lie in inhabited regions and that a significant number are in areas that are densely populated. This is significant because most of Earth's ice free land is very sparsely populated (Small and Cohen, 1999).

In comparison to other geologic terrains, volcanic regions appear to be one of the most densely populated on Earth. For the purpose of this discussion, volcanic regions are considered those with a significant number of persistently active volcanoes, such as island arcs, as opposed to regions with isolated volcanic features, such as those in central and western Asia and the western interior of North America (Fig. 1). Of the 1405 Holocene volcanoes considered, we estimate that 457 volcanoes (222 historically active) had more than 1 million people living within a 100 km radius while 311 were relatively uninhabited with average population densities less than 1 person/km^2. The land around the 702 volcanoes with recorded historical eruptions had a median population density of 23 people/km^2 (within 200 km) as compared with the global median population density of less than 10 person/km^2 for all occupied land area on Earth. Of the populated volcanoes, 34 had average population densities greater than 500 people/km^2 (within 100 km). A summary of the ten most heavily populated active Holocene volcanoes in the world is given in Table 1. Almost all of these volcanoes lie in close proximity to other active volcanoes. In some cases where several volcanoes lie in close proximity to one another and a large population we give the name of the more active, or potentially dangerous, of the

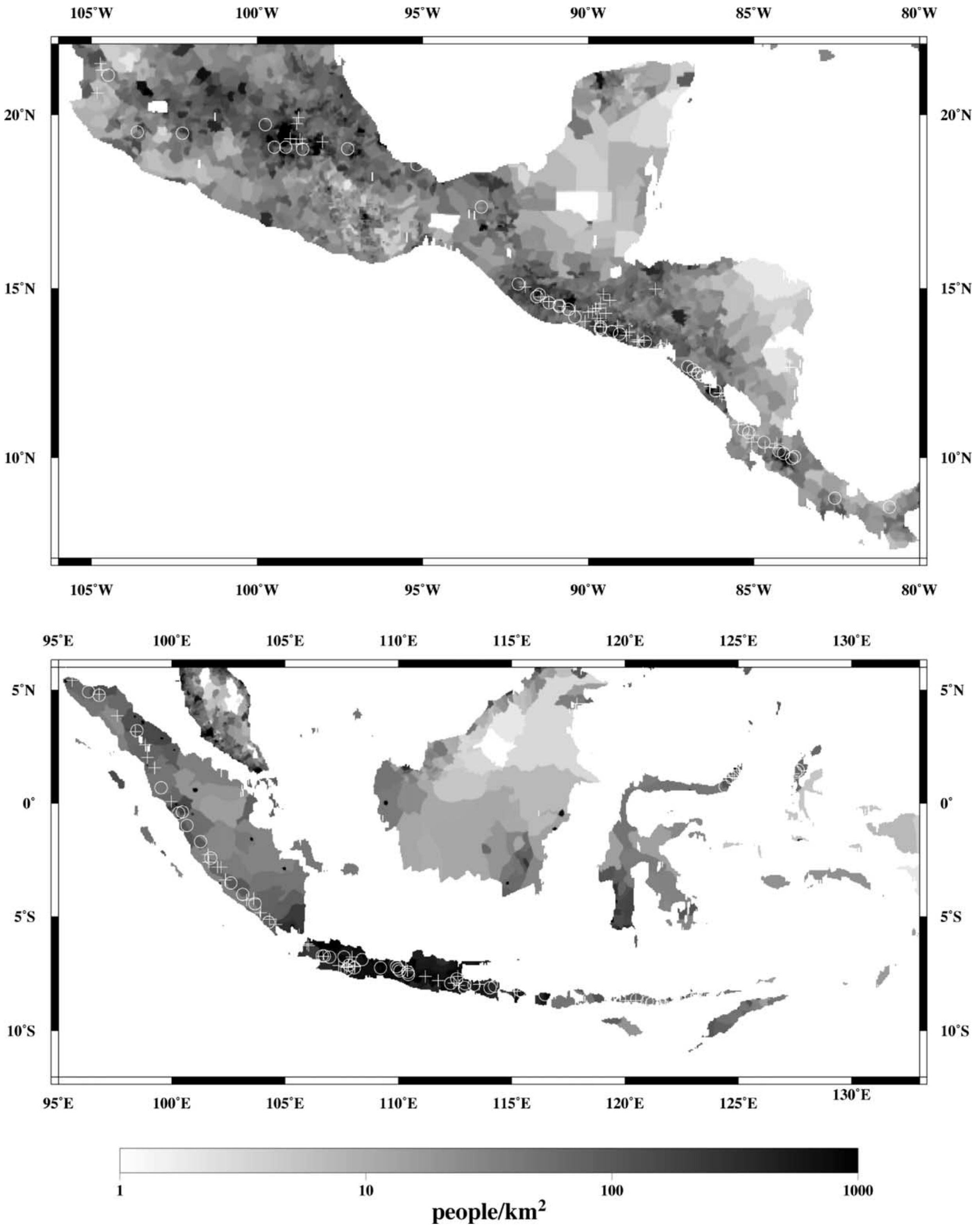

Fig. 5. Populated volcanic regions in Central America and Southeast Asia. Locations of Holocene volcanoes (crosses) and historically active volcanoes (circles) are superimposed on population density estimates. http://www.LDEO.columbia.edu/~small/PopVol.html

volcanoes. Population estimates are rounded to the nearest thousand reflecting the uncertainty in the census data.

Three regions in particular, Central America, Japan and Southeast Asia, show a pronounced coincidence of dense population and persistent recent volcanism. In

Table 1
Ten populous active volcanoes

Volcano	Country	Last erupted	1990 Population	People/km^2
Gede	Indonesia	1957	29,417,000	1085
Fuji	Japan	1707	27,326,000	1067
Tangkubanparahu	Indonesia	1985	25,896,000	931
Izu-Tobu	Japan	1989	20,311,000	1324
Merbabu-Merapi	Indonesia	1996	20,064,000	788
Popocatepetl	Mexico	2001	20,034,000	633
Sundoro	Indonesia	1971	19,437,000	877
Kelut	Indonesia	1990	19,030,000	776
Galunggung	Indonesia	1984	18,991,000	756
Asama	Japan	1990	13,800,000	442

Japan the highest population density tends to be localized on coasts and farther away from the active volcanoes but, with few exceptions, both Central America and the archipelagos of Southeast Asia show the highest population densities in close proximity to volcanoes and lower density elsewhere. The maps in Fig. 4 show the locations of the volcanoes superimposed on the population density maps of these areas. In the case of Southeast Asia, most of the land area is comprised of small to moderate sized islands but the volcanic islands (e.g. Java, Sumatra, Luzon) are more densely populated than the nonvolcanic islands (e.g. Kalimantan, Irian Jaya). The spatial coincidence of population and volcanoes is even more pronounced in Central America where there is abundant land area. The settlement patterns here are distinctly different from those observed in most other pre-industrial cultures where populations settle on coastlines and in fluvial sedimentary basins (Small and Cohen, 1999).

For comparison, we consider East Africa and Japan. Japan is comparable to Indonesia in terms of geologic terrain, area and population size (Fig. 6). In both cases populations live on volcanic island arc complexes but in Japan the populations are concentrated on the coastlines while in Indonesia they are more evenly dispersed over the islands. East Africa and Central America are less similar geologically but in both cases the volcanic regions tend to be the most densely populated. Mexico and Ethiopia are two examples of densely populated volcanic plateaux with the densest populations surrounding the Holocene volcanic belts.

The effect of continental physiography and limitations of land area can be minimized somewhat by normalizing the number of people living at a specific distance from a volcano by the land area available to obtain the average population density as described above. These comparisons, summarized in Fig. 7, indicate that the greatest number of people living in proximity to volcanoes are in Japan and Southeast Asia with somewhat fewer in East Africa and Central America and considerably fewer in northern and southern South America. These six regions account for approximately half of the people in the world living near Holocene volcanoes. Normalizing the numbers of people at each distance from the nearest volcano by the amount of land area at that distance reveals a different pattern. Nearest the volcanoes, Southeast Asia, Japan and Central America have considerably higher average population densities than the other areas. In Southeast Asia and Central America the average population density decreases with distance from volcano while in Japan it increases, peaking between 60 and 80 km before decreasing.

The overall global pattern reflects that seen in Central America and the archipelagos of Southeast Asia (Fig. 8). The highest average population densities are nearest the volcanoes and decrease with distance from volcanoes. Because there are many areas worldwide with isolated Holocene volcanoes that would not necessarily be considered "volcanic regions", and may bias the results, we conduct the same analysis for only the volcanoes with historical eruptions. The results show the same pattern seen for all Holocene volcanoes (Fig. 8).

6. Discussion

A pioneering study by Peterson (1986), using different data and methods, estimated that 9.6% (357×10^6 people) of the global population lived in areas influenced by volcanoes in the 1970s. It is tempting to compare our results to those of Peterson's study but it may be difficult to draw meaningful conclusions from the comparison. Peterson mentions that the populations within 300 km of a volcano would be at greatest risk whereas we quantify population distributions within 200 km and focus on the populations within 100 km. It is not obvious how to separate the differences in methodology and data set resolution and accuracy from whatever temporal changes in proximal populations actually occurred between the 1970s and 1990. The difference between Peterson's estimate of 9.6% living near (within 300 km) volcanoes in the 1970s and our estimate of 20% living within 200 km in 1990 is of feasible magnitude and shows an increase with time consistent with (although somewhat faster than) population growth in developing countries. Although Peterson (1986) used the best data available at the time, these data did not provide the resolution necessary to conduct a spatially explicit analysis like that presented here.

Most populations at risk from volcanic hazards are exposed to explosive (e.g. Mt. St. Helens) rather than effusive (e.g. Hawaii) volcanoes. The primary hazards associated with explosive volcanoes fall within two main categories, (a) airborne ash that advects away downwind from the vent affecting a wide area but with a (generally) low impact, and (b) density driven flows of hot ash (pyroclastic flows) and/or mud (lahars) that follow

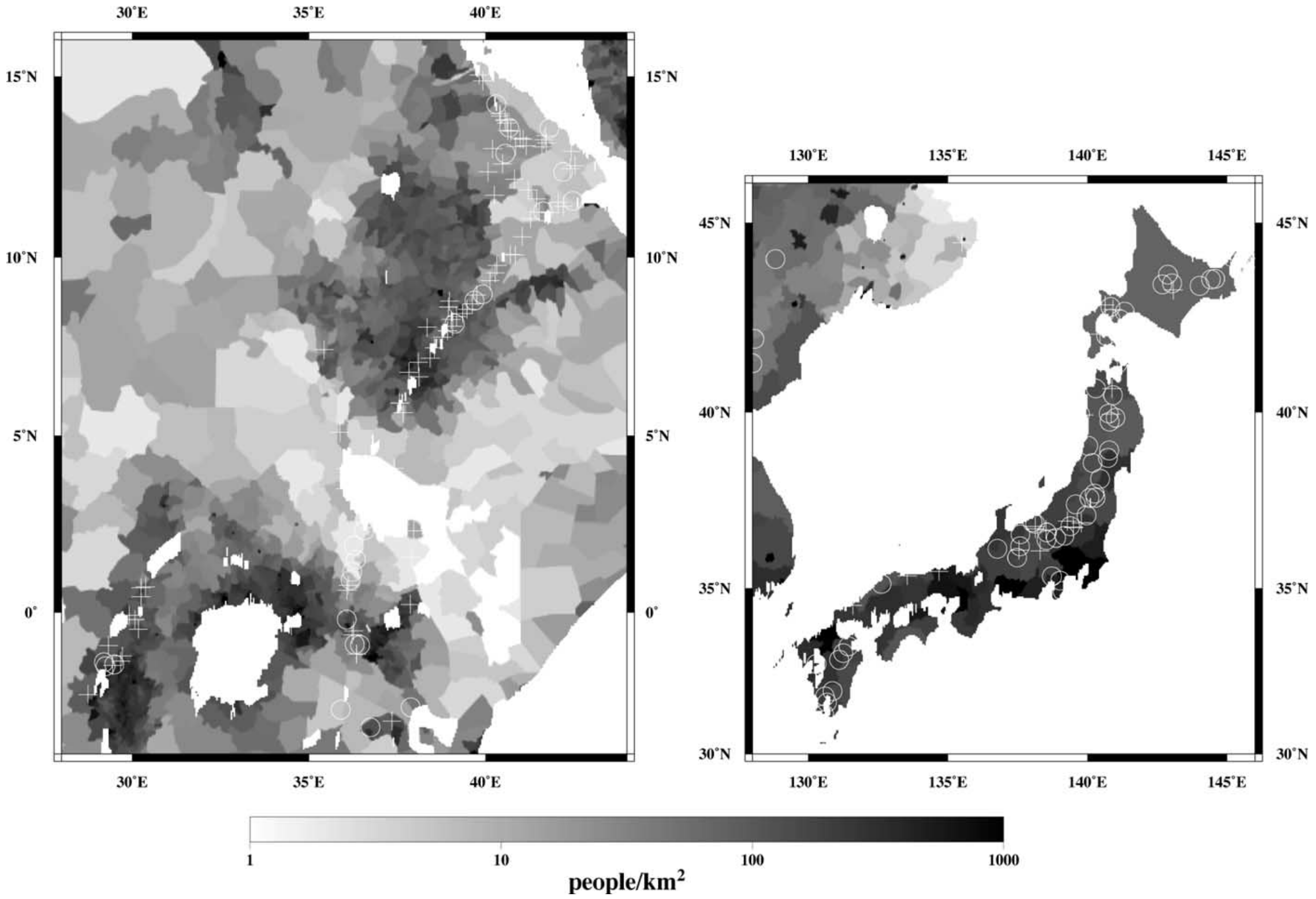

Fig. 6. Populated volcanic regions in East Africa and Japan. Locations of Holocene volcanoes (crosses) and historically active volcanoes (circles) are superimposed on population density estimates. http://www.LDEO.columbia.edu/~small/PopVol.html

topographic lows. Although these high energy/high impact hazards are limited to much more restricted areas, such as river valleys, these areas also tend to be preferentially settled by human populations. There are also volcanic hazards that are not related to eruptions. Poor slope stability on unconsolidated edifices often results in catastrophic landslides (e.g. Sheridan et al., 1999). This is but one example of the details that are of critical importance to a meaningful hazard assessment. It is important to note that we have not incorporated these details into our study. Nor have we included any volcano-specific eruptive characteristics in our analysis. We have treated all volcanoes equally, distinguishing only those with historical eruptions from those with Holocene activity. Our approach would be totally unjustified for a hazard analysis but this is not the purpose of our study. We seek only to quantify the settlement densities of volcanic regions for intercomparison and comparison with non-volcanic regions.

The area and maximum distance affected by any type of volcanic hazard will depend on the character of the eruption and the topography of the region as well as numerous other factors. Volcanoes constructed on mountainous terrain like the Andes or Cascades will have very different risk distributions than those which produce extensive ring plains like East Africa or the north island of New Zealand. A catastrophic collapse or directed blast will effect a wider area to larger radius on flat terrain whereas ash flows or lahars will usually be confined to narrow valleys in mountainous terrain. A more detailed discussion of human vulnerability and volcano specific hazards is given by Chester et al. (2001). While it may not be surprising that some populations live within the hazard affected radius of active volcanoes, it is interesting that the densest populations so often lie well within this radius and that population density generally decreases further from the locus of active volcanism.

6.1. Relative importance of environmental factors

Several environmental factors influence the habitation of volcanically active regions. Many volcanoes form islands and archipelagoes in strategic locations where populations often settle near or directly on the volcanic

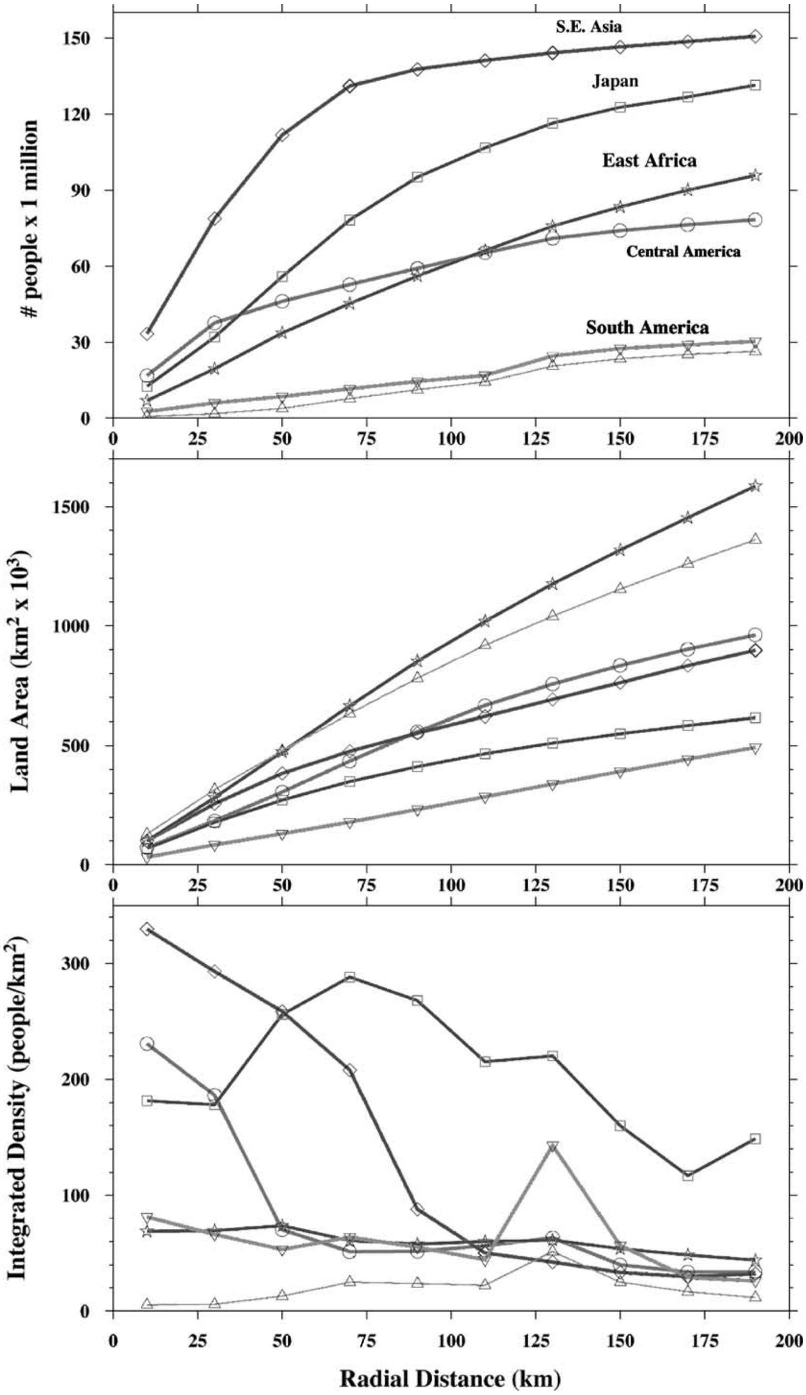

Fig. 7. Comparison of populated volcanic regions. Cumulative population, land area and average population density estimates are analogous to those described in Fig. 4. The thicker curves for South America correspond to the northern Andes (e.g. Colombia, Ecuador, Peru) and the thinner curves correspond to the southern Andes (e.g. Chile). Note the contrasting population density distributions for Southeast Asia and Central America in comparison to Japan. Color figure: http://www.LDEO.columbia.edu/~small/PopVol.html

edifices themselves. In addition, tropical volcanoes provide climatic advantages relative to surrounding regions. The progressive decrease in air temperature with increasing elevation on the flanks of volcanoes provides both adequate precipitation and a more habitable climatic range relative to tropical lowlands. While these factors may also provide sufficient incentive to any tropical or temperate population, active volcanoes also provide a critical natural resource for agrarian cultures. An extensive discussion of environmental factors conducive to human habitation of volcanic terrains is given by Sheets and Grayson (1979).

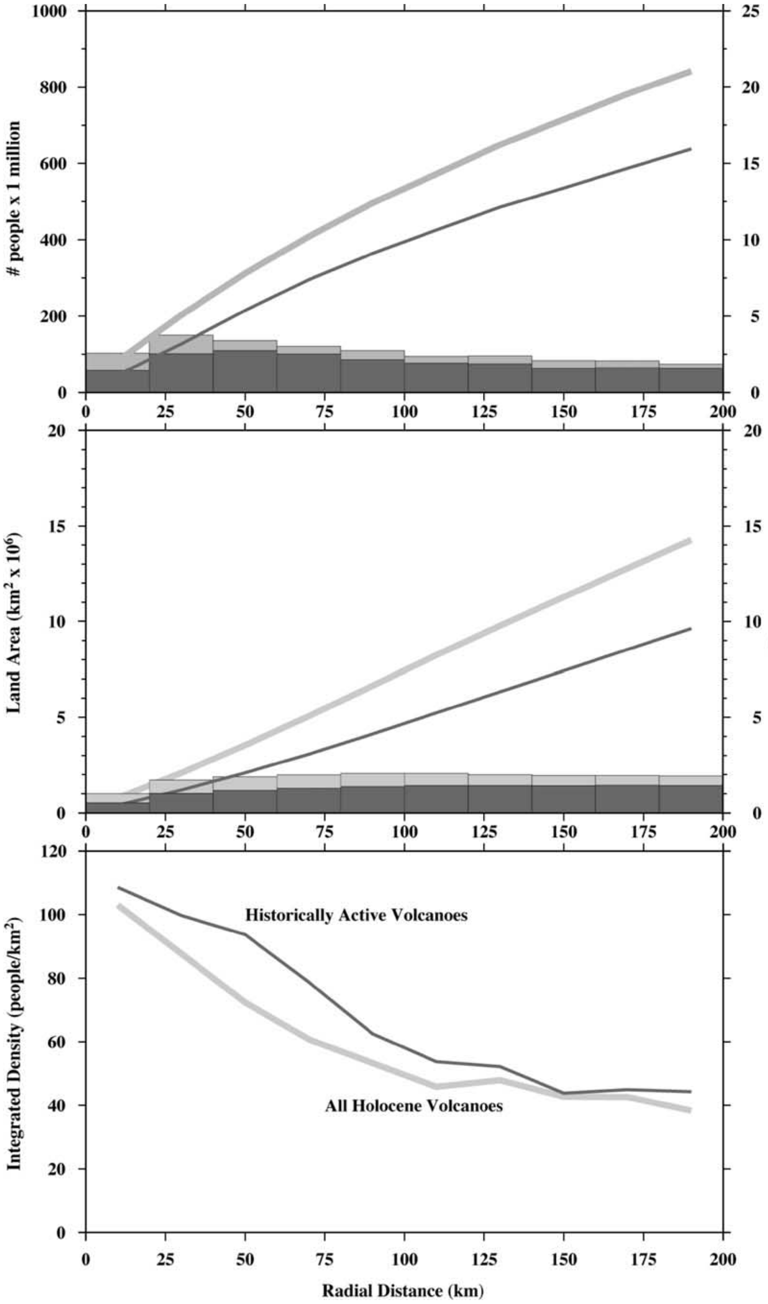

Fig. 8. Global distribution of population in volcanic areas. Lighter curves and bars show distributions for all Holocene volcanoes and darker curves and bars correspond to the historically active subset. The overall pattern shows monotonically decreasing population densities with increasing distance within 100 km but little change at greater distances.

Volcanoes provide a continually renewable source of nutrients in addition to the climatic conditions necessary to produce fertile soils. The chemical composition of volcanic ash supplies nutrients in a form that is often easily weathered to produce high quality soils. In the tropics, the volcanic elevation provides the appropriate temperature range and the renewable supply of ash provides the chemical components to form fertile Andisol soils (see Ping, 2000 for a review) while inhibiting the excessive leaching and biodegradation endemic to low altitude tropical soils. Andisols offer good aeration and drainage and high water retention as well as rapid release of nutrients. In the tropical climates of Southeast Asia and Central America agriculture depends on iron and aluminum rich oxisol and ultisol soils that are rapidly depleted through extreme leaching, erosion, and single crop agricultural practices. These low-fertility soils transition to more fertile Andisol soils with increasing elevation primarily as a result of the decline in temperature with a concomitant decline in the rate of bacterial action. A more detailed discussion of the relative advantages of tephra and lava derived soils and their roles in antiquity is given by James et al. (2000).

The results of our analysis should not be taken as an argument in favor of geographical determinism (e.g. Huntington, 1963). Our aim is to provide a comparative analysis of habitation patterns in different regions and to address some of the environmental characteristics that may contribute to these patterns. While these environmental factors undoubtedly influence habitation of volcanic regions, we acknowledge that there are many other socioeconomic and cultural factors that are of equal or greater importance.

6.2. Implications of tropical urbanization for volcanic hazard

The correspondence between population density and volcanic proximity is markedly different between the tropical and temperate countries considered in this study but this is not solely a result of climatic factors. Some sparsely inhabited volcanoes exist in the tropics and densely inhabited volcanoes are sometimes found at higher latitudes so there are clearly other factors that influence population distribution in these areas. Socioeconomic, political and cultural differences between agrarian populations in the tropics and industrial and post-industrial populations at the higher latitudes plays at least as great a role in determining the utility of populating volcanically active regions. Most of the populated volcanoes at higher latitudes are found in Japan, Chile and New Zealand where most of the population ($>78\%$) (United Nations, 1999) is concentrated in urban areas—often along coasts. Most of the populated volcanoes at tropical latitudes are found in Indonesia, the Philippines, Mexico and several Latin American countries with large rural populations. Many of these tropical countries are, however, currently experiencing rapid rates of urbanization (see Table 2). Interestingly, many socioeconomic influences on population distribution are themselves influenced by the climatic and geologic factors discussed here. Global historical socioeconomic differences between agrarian, industrial and post-industrial populations have long been believed to be influenced by climate and physical geography (e.g. Smith, 1776; Gallup et al., 1999). Nonetheless, we do not wish to convey the impression that these factors can be considered in isolation.

One of the fundamental observations quantified by this study is that some of the densest populations in volcanically active areas are in tropical developing countries which are currently experiencing sustained population growth. Some implications of this observation have been discussed previously by Blong (1984), Peterson (1986, 1988), Tilling (1989, 1990) and others. An observation that has received less attention is the fact that settlement patterns in volcanic zones vary markedly in relation to climate and socioeconomic factors and that rapid urbanization in some tropical developing countries may result in significantly more people at risk from volcanic hazards in the near future than in the past. The United Nations projects that almost all of the global population growth expected in the next 30 years will be concentrated in urban areas and that most of this growth will occur in urban areas in less developed regions (United Nations, 1999). The 1999 revision of the UN World Urbanization Prospects goes on to point out that the largest increments of population growth expected in developing countries in the next 30 years will not be in the presently largest cities but in a large number of currently smaller cities. If these smaller cities coalesce in areas that are now moderately densely settled then tropical volcanic zones may contain not only more people but more localized population centers in areas at risk from volcanic hazard. In this sense, an increasing number of people would experience long term environmental change, not only as result of the environment of a particular location changing, but as a result of migration and growth centers shifting to different environments. Many volcanic regions have a long history of human habitation at low to moderate densities but increasing localization of populations into urban centers in potentially hazardous locations may result in more people at risk from localized hazards like volcanoes. A recent study by Chester et al. (2001) also discusses some of the implications of urbanization and volcanic hazard with respect to the strategic position of the threatened city and the potential for regional and national consequences.

One of the primary caveats of this study is the limited accuracy and resolution of the population data from which the results are derived. The median spatial resolution of the census data in the volcanically active regions is a significant fraction of the 100–200 km radial distance containing most of the immediate volcanic hazards. Meaningful hazard analyses obviously require more types of information at significantly higher resolution than what we have used. Moderate resolution satellite imagery, such as that provided by the Landsat series, could provide more spatially explicit quantifications of settlement patterns on the flanks of potentially active volcanoes. A systematic spatial analysis of human settlement patterns in different volcanic zones worldwide could substantially enhance our perspective of the physical factors that compel and constrain human habitation of volcanic zones. Detailed spatial information on human settlement patterns could also be used to conduct cross-cultural tests of socioeconomic hypotheses of habitation preference and behavioral hypotheses of risk perception. Both active and passive remote sensing systems provide a wealth of synoptic, high

Table 2
Comparative socioeconomic data

Country	GDP/ capita US$ 1997	% Urban 1990–99	Δ% Urban per annum	Δ Population % per annum
Nicaragua	431	55	3.3	2.7
Indonesia	1055	36	4.2	1.4
Philippines	1151	54	3.7	2.1
Ecuador	1648	60	3.6	2.0
Guatemala	1691	39	3.2	2.6
El Salvador	1935	45	2.7	2.0
Colombia	2384	72	2.5	1.9
Mexico	4265	73	1.9	1.6
Chile	5271	84	1.7	1.4
New Zealand	17359	85	1.1	1.0
USA	28789	76	1.1	0.8
Japan	33265	78	0.4	0.2

Source: Statistics and indicators are provided by the United Nations Statistics Division from the World Statistics Pocketbook and Statistical Yearbook, New York, 2000.

resolution information that can be combined with different types of ground based measurements to provide more complete spatial and temporal observations of the relationship between human populations and active volcanic systems. Combinations of remotely sensed and in situ physical measurements can also provide economical means to monitor the activity of populated volcanoes (see Mouginis-Mark et al., 2000 for an example).

Understanding human vulnerability to natural hazards requires more than merely quantifying exposure. The social, cultural and economic dimensions are at least as important as the physical components. Combining detailed observations of population dynamics and settlement patterns on volcanoes with physical models of eruptive processes could facilitate a more integrated assessment of volcanic hazards but risk also depends on vulnerability. Understanding the relationship between the physical and sociocultural dimensions of natural hazards will be necessary for sustainable population of volcanic regions in the future. It is not obvious that the adaptive strategies evolved by agrarian cultures throughout history will allow for sustainable settlement of volcanic zones by urbanized cultures. Understanding this dynamic will require a cross-disciplinary integration of a physically based understanding of volcanic phenomena and a socioculturally based understanding of collective and individual behavior. The importance of cross-disciplinary integration of physical and social sciences to natural hazard mitigation has been discussed by Hamilton (1999) with specific reference to urban populations.

A more complete understanding of the dynamics of both the volcanoes and the societies in these areas could help mitigate some volcanic hazards. This understanding might be implemented in the form of hazard sensitive settlement incentives or the establishment of ecological reserves in volcanic regions. In many areas, preservation of unique volcanic landscapes and ecosystems may provide greater economic returns from tourism than from agriculture. If more people, and assets, in tropical volcanic zones are at risk then it may be in the best interest of populations in less vulnerable environments to help mitigate the risk to the vulnerable populations and their assets. A modest increase in investment in technology transfer, education and integrated hazard assessment in these vulnerable areas could yield benefits in the form of increased political and economic stability in the future. The economic impact of recent earthquakes in Taiwan for the global computer industry provides an example of the far reaching socioeconomic consequences of localized natural disasters (www.wired.com/news/topstories/0,1287,21869,00.html). In light of current trends in economic globalization, mitigation of volcanic hazards in developing tropical countries may help to avert unforeseen consequences of an eruption at a volcano that may be sparsely populated today but densely populated in the future.

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