Precursory inflation of shallow magma reservoirs at west Sunda volcanoes detected by InSAR

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Received 7 September 2012; revised 3 October 2012; accepted 4 October 2012; published 10 November 2012.

[1] We use 2006–2009 ALOS Interferometric Synthetic Aperture Radar data over the entire west Sunda arc, Indonesia, home of 13% of the world's active volcanoes, to derive arc-wide time-dependent ground deformation data. We present unambiguous evidence of inflation at six volcanoes, three of which erupted after the observation period. We show that these volcanoes have shallow magma reservoirs at ∼1–3 km depth below the average regional elevation. A global comparison of reservoir depths at arc volcanoes suggests that volcanoes in extensional and strike-slip settings (west Sunda) can develop shallow reservoirs whereas volcanoes in compressional settings may lack them. Thus, magma ascend through the upper crust could be influenced by intra-arc tectonic settings.
Citation: Chaussard, E., and F. Amelung (2012), Precursory inflation of shallow magma reservoirs at west Sunda volcanoes detected by InSAR, *Geophys. Res. Lett.*, *39*, L21311, doi:10.1029/2012GL053817.

1. Introduction

[2] Monitoring of volcanoes in advance of the onset of activity can lead to timely and accurate identification of volcanic hazards. Most eruptions are preceded by days to months of subtle seismic activity caused by the ascent of magma and ground uplift due to the pressurization of magma reservoirs [*Dzurisin*, 2003]. Basaltic volcanoes generally inflate prior to eruptions [*Lu et al.*, 2010; *Poland et al.*, 2012; *Wicks et al.*, 2002] but the significance of uplift at explosive, andesitic volcanoes remains more difficult to interpret. There are many observations of edifice inflation without eruptions (e.g., Peulik, Akutan [*Lu et al.*, 2007]; Hualca-Hualca, Uturuncu, Lazufre [*Pritchard and Simons*, 2004]; Laguna del Maule, Cordon Caulle, Cerro Hudson [*Fournier et al.*, 2010]), as well as of eruptions without precursory inflation (e.g., Shishaldin, Pavlov, Chiginagak, Veniaminof [*Lu et al.*, 2007]; Sabancaya, Ubinas, Lascar, Irrupuntuncu, Aracar, Ojos del Salado [*Pritchard and Simons*, 2004]; Nevado del Chillan, Copahue, Llaima, Villarica, Chaiten, Reventador, Nevado del Tolima [*Fournier et al.*, 2010]; Galeras [*Parks et al.*, 2011]). The first set of observations can be explained by magma overpressure remaining below a critical threshold [e.g., *Pinel and Jaupart*, 2004], by dikes stopping at various crustal levels without reaching the surface [*Gudmundsson*, 2006], or by changes in geothermal systems [*Tait et al.*, 1989]. The second set of observations suggests that volcanoes were in a critical state in which small perturbations lead to eruptions, or that they are lacking reservoirs at depths shallow enough to create detectable ground deformation. Observations of pre-eruptive deformation at explosive andesitic volcanoes are limited to isolated cases (e.g., Tungurahua and Cerro Blanco [*Fournier et al.*, 2010]) probably because only a fraction of the worldwide ∼800 potentially active arc volcanoes have geodetic monitoring.

[3] The west Sunda arc, composed of the islands of Sumatra, Java and Bali, is among the most active volcanic regions in the world. Of the 84 volcanic centers' 76 have been historically active, 10 of which between 2006 and 2010 [*Simkin and Siebert*, 2002]. Most of the Indonesian volcanoes are andesitic to dacitic strato-volcanoes. They produce explosive eruptions that have caused 67% of the worldwide volcano-related fatalities [*Simkin and Siebert*, 2002; *Blong*, 1984], the two deadliest eruptions are the 1815 eruption of Tambora and the 1883 eruption of Krakatau [*Blong*, 1984]. They also produced some of the largest known eruptions. The eruption of Toba volcano 74,000 years ago left behind the Earth's largest Quaternary caldera [*Simkin and Siebert*, 2002]. More recently, the 1963 eruption of Agung in Bali caused over 1,100 fatalities and influenced the Earth's climate [*Hansen et al.*, 1978]. Despite the threat posed to 18 million Indonesians, these volcanoes are sparsely monitored by ground-based methods, emphasizing the need for remote sensing monitoring.

[4] The west-Sunda arc results from the subduction of the Australian plate under the Sunda plate at rates varying from 47, in North Sumatra, to 72 mm/yr in Java [*McCaffrey*, 2009]. The subduction obliquity increases towards the west and results in dextral strike-slip tectonics in the overriding plate, expressed by the 1900 km long Sumatra fault. In Java several active strike slip faults have also been documented such as the Cimandiri fault in west Java [*Dardji et al.*, 1994] and the Opak fault in central Java responsible for the May 2006 Yogyakarta M_w 6.2 earthquake [*Abidin et al.*, 2009]. In Bali no active faults have been reported but strike slip regime is also considered dominant [*Hughes and Mahood*, 2011].

2. InSAR Results

[5] We conduct an InSAR survey over the west Sunda arc covering 400,000 km^2 and using over 800 SAR images acquired between 2006–2009 by the ALOS satellite of the Japanese Space Exploration Agency. ALOS acquired L-band SAR data, which enable deformation mapping of highly vegetated areas [*Sandwell et al.*, 2008], providing for the first time consistent data of entire volcanic arcs without spatial and temporal gaps. InSAR measures ground displacement that occurred between two SAR acquisitions in the radar line-of-sight (LOS) direction [*Rosen et al.*, 2004]. We obtain the

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0094-8276/12/2012GL053817

time history of LOS displacement from a network of interferograms using the Small Baseline (SB) technique with DEM error correction [*Berardino et al.*, 2002; H. Fattahi and F. Amelung, DEM error correction in InSAR time-series, submitted to *IEEE Transactions on Geoscience and Remote Sensing*, 2012] (see auxiliary material, Text S4).[1] A map of the averaged LOS velocity identifies actively deforming volcanoes related to subsurface magma or hydrothermal movements (Figure 1a). Positive LOS velocity (red colors) represents movement towards the satellite (e.g., uplift) and negative LOS velocity (blue colors) movement away from the satellite (e.g., subsidence).

[6] We detect seven volcanoes with significant deformation: Sinabung and Kerinci in Sumatra, Slamet, Lawu, and Lamongan in Java, and Agung in Bali are inflating at rates of 3–8 cm/yr, while Anak Krakatau in the Sumatra Strait is deflating at $\sim$5 cm/yr. Kerinci, Slamet and Agung show a clear uplift signal in a circular area centered on the edifices' summits. Sinabung and Lawu show similar but noisier signals because of lower interferometric coherence (see Text S1, Figure S1.1). Lamongan is characterized by uplift north of the summit, also noticed by *Philibosian and Simons* [2011]. At Anak Krakatau subsidence occurs on the northwest flank, the loss of coherence near the summit being related to the 2007–2008 eruptions [*Agustan et al.*, 2012]. For the remaining 68 historically active volcanoes no deformation is detected. The measurement noise is $\pm$2 cm/yr (green-yellow colors) and varies along the arc depending on the number of SAR acquisitions and the atmospheric conditions.

[7] For most volcanoes the time history of LOS displacement (Figure 1b) shows deformation at nearly constant rates suggesting relatively stable magma supply. The exception is Lamongan where 12 cm of LOS displacement occurred between September and December 2007, suggesting a single magma intrusion.

[8] It is remarkable that three of the six uplifting centers erupted 0.3 to 2 years after the observation period (Sinabung, Kerinci and Slamet). In September 2010, Sinabung had its first Holocene eruption, a significant explosive eruption from the central vent accompanied by phreatic explosions and pyroclastic flows [*Simkin and Siebert*, 2002]. InSAR detects 8 cm of uplift of the summit between 2007–2008.8. In April 2009 Kerinci had small eruptions, associated with 500–1,000 m tall plumes. InSAR detects 10 cm of uplift between 2008 and 2009. Kerinci has been producing explosive eruptions every few years since the beginning of the 1990's and frequent ash and gas plumes. During April-September 2009 Slamet was in a period of unrest with several explosive eruptions from the central vent. This volcano had similar activity periods about once per decade since the 1900s. InSAR detects 13 cm of uplift between 2007.5 and 2009.1.

[9] The others three centers presenting ground deformation have all been historically active [*Simkin and Siebert*, 2002]. Lawu's only historical eruption was in 1885. Lamongan was intensively active from 1799 through the end of the 19th century with frequent explosive eruptions and lava flows. Agung's last eruption in 1963–1964 mentioned above, was one of the worldwide largest 20th century eruptions.

[10] These observations suggest that edifice inflation is of magmatic origin and represents the pressurization of reservoirs caused by ascent of new magma. They further suggest that inflation is a common precursor of unrest at west Sunda volcanoes. Precursory inflation occurs at previously inactive volcanoes (Sinabung) as well as at occasionally or frequently erupting volcanoes (Kerinci and Slamet). The inflation of Lawu, Lamongan and Agung also likely indicates the arrival of new magma. If inflation has continued after 2009, we would expect unrest or eruptions. At Lamongan, several seismic swarms occurred in March-April 2012 [*Simkin and Siebert*, 2002].

[11] However, not all eruptions are preceded by inflation. Merapi, Java's most active volcano, erupted in 2007, 2008 and 2010 without any evidence of precursory inflation. Merapi's regular activity and the presence of a lava dome suggest that the volcano has an open conduit. Open systems do not usually show significant inflation. Our data do not show inflation prior to the January 2009 eruptions of Mt. Dempo (south Sumatra) and of Dieng volcanic complex (central Java). But these results are inconclusive because of the limited number of SAR acquisitions (3 for Dempo, see Text S4) and because of the low interferometric coherence.

[12] Our two years of data don't constrain how much the volcanoes inflated before they erupted. The fact that half of the inflating volcanoes erupted after 8–12 cm of uplift suggest that for the west Sunda strato-volcanoes inflation could be a reliable eruption precursor. In contrast, silicic calderas may inflate by tens of centimeters without eruption [*Battaglia et al.*, 2003; *Newman et al.*, 2001].

3. Depths of Magma Storage in West Sunda

[13] We use geophysical inverse modeling methods to infer constraints on the magmatic systems. We model the sources as pressurized finite spheres in an elastic half-space [*McTigue*, 1987] with topographic correction [*Williams and Wadge*, 1998]. We used a Gibbs sampling inversion technique [*Brooks and Frazer*, 2005] to determine the optimal sources positions and overpressures and we simultaneously solve for a linear ramp to compensate for long-wavelength artifacts remaining in the time series. Each parameter of the model is described through its a-posteriori probability density distribution (see details in Text S1).

[14] Throughout this paper we express source depths relative to the average elevation of the arc to facilitate comparisons among regions. We find that all the inflating volcanoes have shallow sources at 0.7–3.4 km depth (Figure 2). The estimated source depths are roughly normal distributed with 95% confidence intervals between 0.3 and 1 km, indicating that they are well constrained (Figure 2). The actual source depths could be $\sim$1 km deeper than estimated because of our assumption of structural homogeneity [*Hautmann et al.*, 2010].

4. Discussion

[15] Our results indicate that the west Sunda volcanoes have shallow reservoirs. Other regions, for example portions of the Andes (a region with a compressive stress regime) lack them [*Pritchard and Simons*, 2004], suggesting that there may be a regional control on the depth of magma storage. We use a global data set to test whether the intra-arc stress regime could provide such a control.

[16] We collected comparative data on 71 andesitic volcanoes (from basaltic-andesitic to andesitic-dacitic volcanoes)

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL053817.

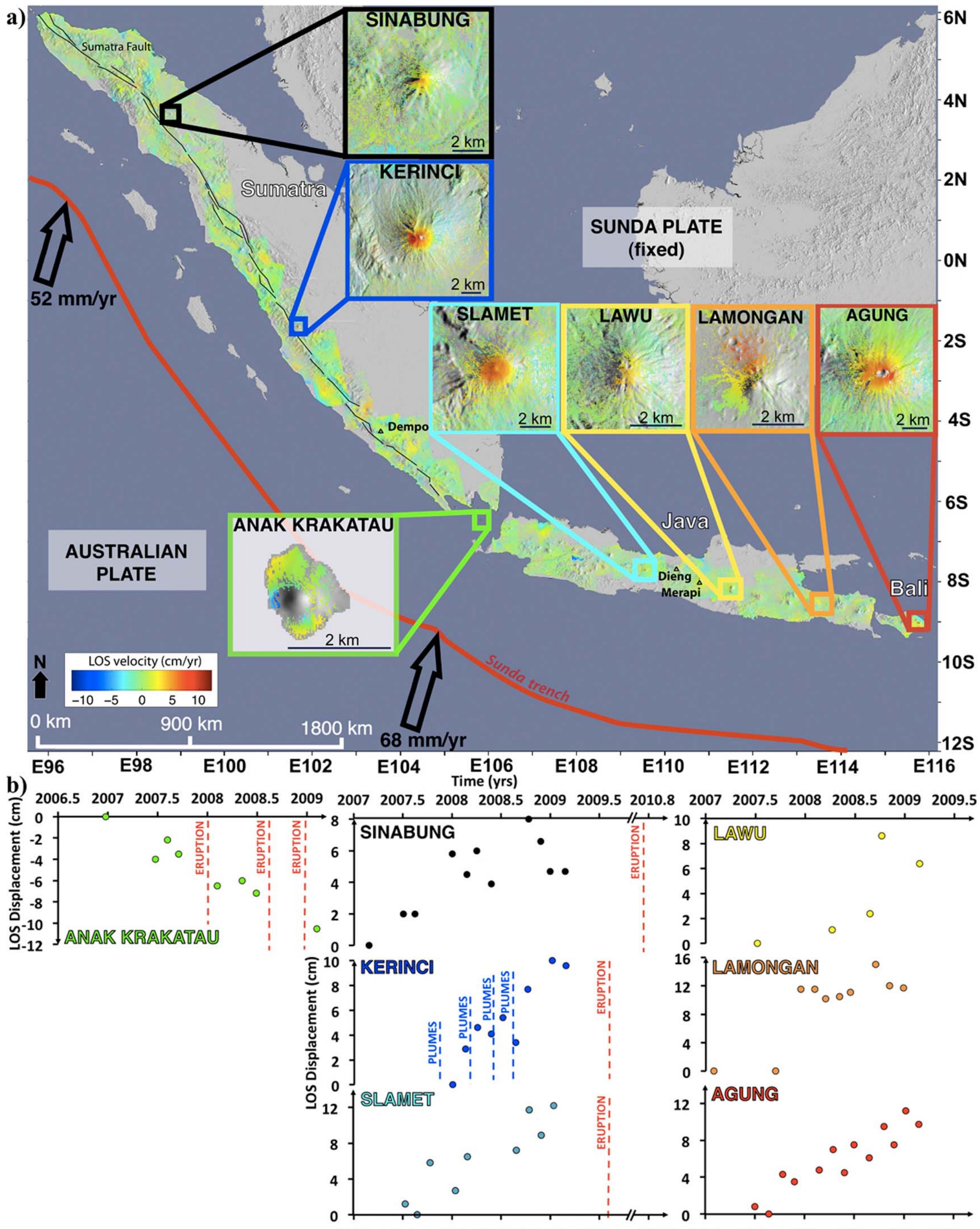

Figure 1. (a) Averaged 2006–2009 LOS velocity map of the west Sunda volcanic arc, Indonesia, from ALOS InSAR time series, overlaying SRTM V4 DEM. Only pixels with a temporal coherence larger than 0.6 are shown. Black arrows: relative plate convergence rates at the Sunda trench (red line). Insets: zoom into 7 deforming volcanic centers, upper left: inflating volcanoes, lower right: deflating volcano. (b) LOS displacement time series for the 7 deforming volcanic centers. Left: deflating volcano, center and right: inflating volcanoes. Dashed vertical bars indicate activity periods. The total LOS displacements for Anak Krakatau, Sinabung, Kerinci, Slamet, Lawu, and Agung, are −10.5, 8, 10, 12.2, 8.6, and 11.2 cm, corresponding to linear deformation rates of −4.7, 2.7, 7.7, 6.8, 4.7, and 5.7 cm/yr, respectively. At Lamongan 11.5 cm of LOS displacement occurred between September and December 2007. The variance of the time dependent displacement depends mainly on the atmospheric conditions and corresponds to the measurements noise.

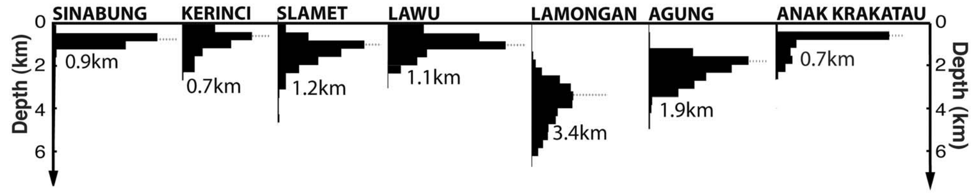

Figure 2. Marginal posterior density distributions (PPD) and maximum likelihood sources depths for each deforming volcanoes from Figure 1 (see more details in auxiliary material, Text S1). The depths are expressed relative to the average elevation of the region (0.7, 0.5, and 0 km above sea level for Sumatra, Java, and Anak Krakatau, respectively, see Text S2). The corresponding depths relative to the summits of each edifices are 2.6, 3.8, 4.1, 3.9, 4.5, 4.4, 1.5 km for Sinabung, Kerinci, Slamet, Lawu, Lamongan, Agung, and Anak Krakatau, respectively. We use a uniform grid to sample the data from the LOS velocity field, assume unit variance, and estimate PPDs using a Gibbs sampler. We use elastic half space models with topographic approximation. The sources are modeled as finite spheres of 1 km radius (for Lamongan 1.5 km radius) because of the tradeoff between source size and overpressure.

in 8 continental and transitional arcs (Text S2, Table S2.1). We use the depth of the shallowest detected magma reservoir and we estimate the stress regime in each volcano's vicinity from the World Stress Map project [*Heidbach et al.*, 2008] and Centroid Moment Tensor solutions of earthquakes (Text S3). Figure 3a shows that the reservoir depths correlate with the tectonic settings. Shallow reservoirs (reservoirs at less than 5 km depth) occur in extensional (Kamchatka and Mexico), transtensional (Aleutian-Alaska Peninsula and south Japan), strike-slip (central America, Sumatra and Cascadia) or transpressional (Java, central Japan, southern Andes), but not in compressional settings (north Japan, northern Andes, south part of the central Andes).

[17] This suggests that the intra-arc stress regime influences magma ascent to shallow levels. A conceptual model for how the tectonic setting affects magma ascent in the brittle upper crust is shown in Figure 3b. In the lower crust the tectonic stress is unlikely to be important because of viscoelastic relaxation, while in the shallowest 1–3 km below the surface local effects related to heterogeneities, such as sediments layering, dominate the stress field [*Gudmundsson*, 2006].

[18] Magma ascends from a deep reservoir at the base of the crust [*Kavanagh et al.*, 2006; *Gudmundsson*, 2000] to intermediate crustal levels where it stalls [*Annen et al.*, 2006] and forms a reservoir by amalgamation of successive sill intrusions [*Gudmundsson*, 1990], possibly aided by neutral buoyancy [*Vigneresse et al.*, 1999]. The intra-arc stress regime can influence magma ascent from this intermediate reservoir in two ways. First, it determines whether the conditions are favorable for vertical dike propagation, i.e. maximum tensile stress σ_3 in the horizontal plane [*Anderson*, 1951], which is the case in extensional or strike-slip settings (including transtension and transpression [*Vigneresse et al.*, 1999]). In contrast, in compressional settings (vertical σ_3) vertical cracks get deflected towards the horizontal at a rate depending on the magma excess pressure [*Takada*, 1989]. Second, the stress regime determines the type of pre-existing structures [*Corazzato and Tibaldi*, 2006; *Acocella et al.*, 2008; *Moran et al.*, 2011]. Steep normal faults (in extensional settings) and near-vertical strike-slip faults (in transtensional to transpressional settings) can extend to great crustal depths and are more likely to act as magma pathways than low-angle thrust faults (in compressional settings).

[19] Extensional and strike-slip settings, such as in west Sunda, may favor vertical magma migration by propagation of dikes or by flow through existing cracks or faults. For a sufficient magma supply rate and excess pressure, magma ascends to shallow crustal levels until it encounters lithological contrasts that act as barriers and determine where shallow reservoirs form [*Menand*, 2011; *Gudmundsson*, 2011]. We interpret that this is the type of reservoir we see in west Sunda. In contrast, in compressional settings (where horizontal magma migration is favored) only dikes with significant overpressure can propagate vertically without adjusting to the principal stress direction to feed eruptions [*Mériaux and Lister*, 2002]. These highly overpressurized dikes are not frequent enough to develop shallow reservoirs. Thus, in extensional and strike-slip settings the top of a volcanic plumbing system is more likely to be a shallow-level reservoir; the absence of such a reservoir could indicate a lower magma supply rate or local complexity. In contrast, in compressional settings the top of the plumbing system is more likely to be an intermediate-level reservoir. This qualitative interpretation is consistent with a recent study showing that arcs in extensional or strike-slip settings have a higher magma production rate and extrusion-to-intrusion ratio [*Acocella and Funiciello*, 2010].

[20] Our model explains regional trends of magma reservoirs depths and is not intended to constrain local processes. Other factors potentially influencing the development of reservoirs are magma density, viscosity, volatile content, crystal content, local crustal structure, and heterogeneities [e.g., *Gudmundsson*, 2006; *Moran et al.*, 2011].

5. Summary and Conclusions

[21] We use 2006–2009 ALOS InSAR time-series to monitor deformation at the west Sunda volcanoes. We detect six inflating volcanoes, three of them erupted after the time span of our survey. This suggests that edifice inflation represents reservoir pressurization by magma injection and that in many cases it is a precursor for unrest and eruptions.

[22] The west Sunda volcanoes are fed by shallow magma reservoirs. A qualitative global analysis of arc volcanoes shows that shallow reservoirs occur in extensional and strike-slip settings but not in compressional settings. The regional tectonic setting could be an explanation for the presence of reservoirs at shallow levels at volcanoes in other geodynamic settings and is consistent with observations in the East African rift [*Biggs et al.*, 2011].

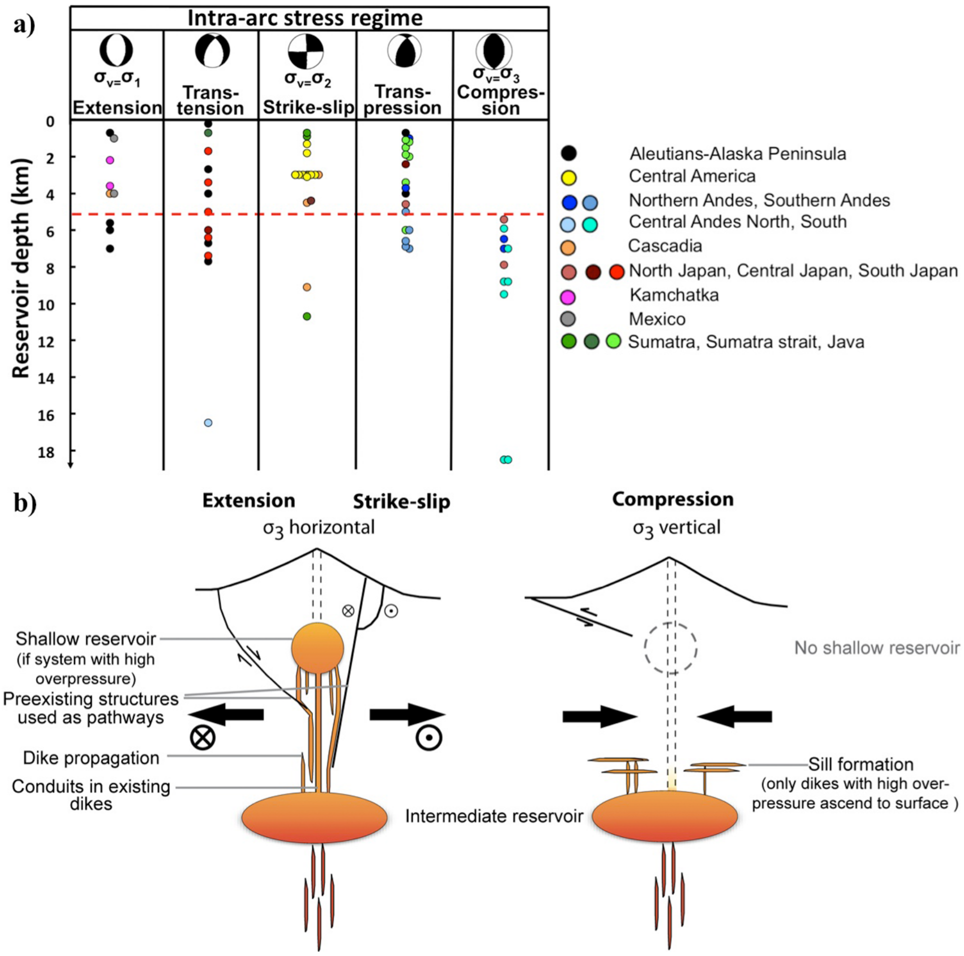

Figure 3. (a) Depths of magma reservoirs as a function of the stress regime in continental and transitional volcanic arcs, the points are color-coded by regions (see Text S2). Reservoir depths are from geodesy, seismology, gravity or petrology (in that order of preference, depending on availability). Stress regime is from seismic Centroid Moment Tensor data (CMT) and World Stress Map Project data [*Heidbach et al.*, 2008]. We assign a stress-regime to each volcanic center based on the dominant stress mechanisms in its vicinity (100 km radius, regardless of earthquake magnitude) (Text S3). We assign a hybrid stress regime if the number of two different stress mechanisms differs by less than 20% (example: a region with a similar number of strike-slip and compressive focal mechanisms is considered transpressive). (b) Interpretative cartoon showing the effect of the tectonic settings on magma ascent through the upper crust in volcanic arcs. Extensional and strike-slip settings are favorable for the development of shallow-level reservoirs while compressional settings promote the development of intermediate-level sills. We interpret that the top of the magmatic system are shallow- or intermediate-level reservoirs in extensional and strike-slip settings, depending on the magma excess pressure, and intermediate-level reservoirs in compressional settings.

[23] **Acknowledgments.** We thank the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) for support (NNX09AK72G and EAR-0810214). The ALOS-PALSAR data are copyright of the Japanese Space Agency (JAXA) and the Japanese Ministry of Economy, Trade and Industry (METI) and were made available by the U.S. Government Research Consortium (USGRC) and the Alaska Satellite Facility (ASF).

[24] The Editor thanks Valerio Acocella and Maurizio Battaglia for their assistance in evaluating this paper.

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