Recent unrest of Changbaishan volcano, northeast China:
A precursor of a future eruption?

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[1] Over 12 years of continuous monitoring of Changbaishan volcano in the border region of China and North Korea by means of volcanic seismicity, ground deformation, and volcanic gas geochemistry yields new evidence for magmatic unrest of the volcano between 2002 and 2006. In this so-called “active period,” the frequency of volcanic earthquakes increased by about 2 orders of magnitude compared to that of the background “inactive periods.” The active period was also accompanied by ground inflation, high values of CO₂, He, H₂, and high ratios of N₂/O₂ and ³He/⁴He in volcanic gases released from three hot springs near the caldera rim. The monitoring evidence implies pressurization of the magma chamber, possibly caused by incremental magma recharge. The ground deformation data from both GPS and precise leveling are modeled to suggest the corresponding deformation source is at 2–60 km depth beneath the volcano’s summit, where earthquake swarms were detected in 2002 and 2003. Our findings suggest that the magma chamber beneath Changbaishan volcano has awakened and resumed activity after remaining dormant since AD 1903. There is an urgent need to keep close watch on this active and very hazardous volcano in northeast China. Citation: Xu, J., G. Liu, J. Wu, Y. Ming, Q. Wang, D. Cui, Z. Shangguan, B. Pan, X. Lin, and J. Liu (2012), Recent unrest of Changbaishan volcano, northeast China: A precursor of a future eruption?, Geophys. Res. Lett., 39, L16305, doi:10.1029/2012GL052600.

1. Introduction

[2] Changbaishan (also known as Baitoushan in Korea) volcano is located in the border area between China and North Korea (Figure 1; 42°00’N; 128°03’E). As a potentially hazardous intraplate stratovolcano about 1200 km west of the west Pacific subduction zone, the volcanism of Changbaishan volcano is not well understood. Recent studies from seismic wave tomography, magnetotelluric soundings, and volcanic rock geochemistry have yielded new evidence to support a subduction-related model that explains the geological origin of Changbaishan volcano [e.g., Tang et al., 2006; Zhao et al., 2009; Wei, 2010; Kuritani et al., 2011].

In this model, the west Pacific plate subducts underneath the Eurasian plate along the Japan arc island at a dip angle of 20° to the west to reach to the mantle transition zone at a depth of ~600 km, where the subducting slab becomes stagnant (Figures 1b and 1c). Deep dehydration of the slab and convective circulation in the mantle wedge cause upwellings of high-temperature asthenospheric materials, leading to the formation of Changbaishan volcano.

[3] Changbaishan volcano has undergone three major evolutionary stages. During the stage of shield formation (29–1 Ma), a total area of about 20,000 km² was covered by basalt. During the stage of composite cone formation (1–0.01 Ma), a trachyte cone with a height of about 4 km and a base radius of 8–14 km formed. During the stage of ignimbrite forming eruptions (0.01–0 Ma), the so-called millennium eruption at AD 946 took place (J. Xu et al., The millennium eruption of Changbaishan volcano in northeast China: High-precision wiggle-match radiocarbon chronology and implications, unpublished manuscript, 2012), forming a 5-km-diameter caldera [Liu et al., 1998] (Wei et al., Review of activity at Tianchi volcano, Changbaishan, and implications for future eruptions, Bull. Volcanol., submitted manuscript, 2012). This millennium eruption, speculated to be one of the largest eruptions of the past 2,000 years [Oppenheimer, 2011], produced pyroclastic flow deposits covering an area extending roughly 50 km from the crater. The fallout pumice ash spread to the east and reached as far as the southern Kuril trench [Nanayama et al., 2003]. At least three small-scale eruptive activities of the volcano were historically documented in AD 1668, 1702 and 1903 after the millennium eruption.

[4] In this paper, we first report new results from our 12-year continuous monitoring of Changbaishan volcano by seismicity, ground deformation, and gas geochemistry. We then discuss the possible correlation between these changes and the magma system beneath the volcano.

2. Data Collection

[5] Changbaishan volcano observatory (CHVO) was set up in 1999 and comprises 11 seismic stations, 15 campaign GPS measurement sites, 2 precision leveling lines, and 3 hot spring gas monitoring stations, and covers the volcano uniformly except for some “blind spots” on the North Korean side of the border (Figure 1a). Among seismic stations, 7 are broadband seismometers with a period of either 60 or 120 seconds, while the other 4 stations are short-period seismometers with a period of 2 seconds. To obtain more seasonal data around
the caldera region for about three months in the summer annually from 2002 to 2006.

The GPS network around the caldera covers an area of 1,200 km². Of the 15 GPS sites, 8 were installed in 1999 and measurements started in 2000. The other 7 sites were installed in 2006 and measurements started in 2007. GPS surveys have been conducted each year in August with dual-frequency geodetic receivers. Precision leveling survey has been carried out along two routes on north and west slopes of the caldera each year since 2002 to identify vertical ground deformation. So far, we have conducted 10 leveling surveys on the north slope and 6 on the west slope.

Since the establishment of CHVO, routine gas chemical observations have been performed year-round. Gas samples from the Julong hot spring are collected twice a week and analyzed with a SP-3420 gas chromatograph to measure the contents of major gas components, such as CO₂, He, H₂, O₂ and N₂. Gas samples from the Jinjiang and Hubian hot springs are collected in September each year, and analyzed with a VG-5400 mass spectrometer to measure the ³He/⁴He ratio.

3. Results

3.1. Earthquake Activity

We recorded about 3,900 volcanic earthquakes with M_L ≥ 1.0 within 50 km of the caldera between July 1999 and December 2011. The temporal distribution of seismicity defines three distinct periods. During the “inactive periods” from 1999 to 2002 and from 2006 to 2011, there were about 7 seismic events per month, which is considered to be the background for the region. During the “active period” from 2002 to 2006, the number of seismic events increased

Figure 1. (a) Monitoring network of CHVO. (b) Tectonic location of Changbaishan volcano. (c) A-B profile in Figure 1b showing the west Pacific plate subduction, the Wadat-Benioff seismic zone, and the magmatic system of Changbaishan volcano.
to 72 per month. The seismicity peaked in November 2003 with 243 seismic events (Figure 2a). The maximum magnitude sequence of the seismic events and the cumulative moment of the earthquakes for the same period shows a similar pattern in which the seismic energy released is much higher in the “active period” than in the “inactive periods” (Figure 2b).

[9] During the mobile seismic campaign in the summers of 2002 and 2003, a large number of micro-earthquakes and a series of earthquake swarms were detected. We found that almost all earthquakes were volcano-tectonic (VT) events. Preliminary hypocenters show that most of the earthquakes occurred beneath the caldera clustered in two regions: in the northeastern part and the southwestern part of the caldera (Figure 2c). The depths of most earthquakes are about 5 km (Figure 2d). Such seismic events are often interpreted as evidence for a magmatic unrest [e.g., Hill et al., 1990; Dziak and Fox, 1999].

[10] High-precision relative relocation of earthquake swarm events revealed that the hypocenters were distributed along a NW-SE plane inclined to SW with a dip angle of about 80°. We also found that the swarm hypocenters migrated upward over time from deep to shallow and deeper seismic events had upward first motions at almost all stations, indicating a possible magma intrusion.

[11] By examining the waveforms and spectra of recorded events, we found some events that differ from regular volcano-tectonic earthquakes. The waveform recordings of these seismic events in the time domain look similar to those of ordinary earthquakes (Figure 2e), but their spectra (especially the averaged spectrum) consist of a series of evenly-spaced peaks (Figure 2f). This type of event resembles the harmonic events of Hough et al. [2000] and is considered to be associated with a fluid-controlled source. The fundamental frequency of the harmonic events during our mobile seismic campaign ranges from 0.6 to 7.0 Hz and their magnitudes are less than \( M_L 1.4 \). The harmonic events are generally located less than 5 km beneath the caldera, and they are co-located with other volcano-tectonic seismicity. Since earthquake swarms and harmonic earthquakes are

Figure 2. Seismic activity of Changbaishan volcano from 1999 to 2011. (a) Monthly number of earthquakes. (b) A time series of the monthly maximum magnitude and cumulative seismic moment. (c) Earthquake swarms detected by mobile seismic campaign during the summers of 2002 and 2003. (d) Relocated earthquake hypocenter distribution at depths around 5 km. (e) The original recordings of the vertical component of a typical harmonic event recorded in 2003. (f) The corresponding normalized Fourier spectra of Figure 2e, where the one at bottom is an averaged spectrum. The shaded area in Figures 2a and 2b represents the “active period.”
Figure 3. Surface deformation from GPS and precision leveling survey. GPS horizontal displacements with 95% confidence ellipses of (a) 2000–2002, inactive period; (b) 2002–2006, active period with inflation; and (c) 2006–2010, inactive period. Vertical displacements along the precision leveling routes for the periods of (d) 2002–2005 on the north slope, (e) 2006–2011 on the north slope, and (f) 2006–2011 on the west slope. The horizontal axis in d-f represents the distance between the survey site and the reference site (i.e., Benchmark north and Benchmark west in Figure 1a).
often associated with magma movement [Chouet, 1996; Falsaperla et al., 2003; Napoli et al., 2011], it is reasonable to speculate that the earthquakes beneath the summit of Changbaishan volcano were caused by magmatic and hydrothermal activities due to pressurization of a magma chamber at a depth of about 5 km.

3.2. Ground Deformation

The horizontal displacements measured by GPS surveys from 2000 to 2010 reveal a clear inflation during 2002–2006, in accord with the “active period” as indicated by seismic activity (Figures 3a–3c). During this period, most of the observation sites displayed motion away from the Tianchi caldera lake (Figure 3b). The annual average horizontal displacements away from the caldera were 19.6 mm/a (maximum 38.3 mm/a) from 2002 to 2003, 10.2 mm/a (maximum 15.8 mm/a) in 2003–2004, and 8.6 mm/a (maximum 18.5 mm/a) in 2004–2005. No strong horizontal displacement was observed after 2006 (Figure 3c). Starting in 2008, however, when the total number of campaign GPS sites increased from 8 to 15, the observed displacement of each site had a preferred direction to the southwest, even though the displacements are small (<9 mm/a). The predominant motion rotated by about 90° from the southwest in 2009 to the southeast in 2010 (Figure 3c). Such an abrupt rotation may not be totally caused by tectonic movement, but due to the errors from the poor observation environment, because some of the newly established GPS sites are surrounded by heavy forest.

[13] Vertical movements measured by leveling surveys along the north slope of Changbaishan volcano from 2002 to 2005 are shown in Figure 3d. A total of 68.12 mm of uplift was detected during this time period, of which 46.33 mm occurred during the start of the “active period” in 2002–2003. In 2006 we switched from an optical leveling instrument to an electronic one, and we established a new leveling route on the west slope. Since there is a systematic error between the two measurement systems, leveling measurements after 2006 are plotted separately in Figures 3e and 3f. In contrast to relatively fast and large uplift during 2002 to 2005, vertical movement gradually became slow and weak after 2006. A transition from uplift to subsidence was detected with vertical deformation of ~12.72 mm/a on the north slope in 2010 (Figure 3e) and ~3.49 mm/a on the west slope in 2008 (Figure 3f), followed by a 3-year continuous total subsidence of 12.65 mm by 2011 (relative to 2006).

[14] To understand the mechanism of ground deformation during 2002–2006 and its relation to the magma activity in the volcanic region, we performed four sophisticated simulations, based on the Mogi point source model with the pressure source parameters inversed jointly from both GPS measurement and precise leveling data of the Changbaishan volcano for each adjacent two years from 2002 to 2006. In our simulation, the maximum vertical displacement is the function of the pressure source depth and the equivalent spherical radius [Mogi, 1958; De Natale and Pingue, 1996]. Our results suggest a magma reservoir at a depth of 2–6 km...
under the volcano’s summit, which is in good agreement with the location of earthquake swarms during 2002–2006.

3.3. Gas Geochemistry

[15] Composition and temperature measurements of gases from three hot springs around the caldera have been conducted since 1999. At Jinjiang hot spring gases from the crustal magma chamber move upward through faults to reach the surface directly. In contrast, gases from Julong hot spring come from a geothermal fluid reservoir through shallow faults. Hubin hot spring is located on the top of an old vent from a previous eruption, and gases emitted reflect the magma properties from the last eruption (Figure 4a).

[16] The helium isotope ratio (3He/4He) is the most reliable indicator of the source material of volcanic products because it has fixed ratios for the mantle, crust and atmosphere. Previous studies [e.g., Shangguan, 1997; Notsu et al., 2001] have shown that variation of 3He/4He in a volcanic area is usually controlled by magma activity and, therefore, reflects the behavior of the magma itself. As shown in Figure 4b, an average value around 6.5 was observed from 2003 to 2006 from Jinjiang hot spring, significantly higher than the average value of 5.35 before 2003. A sudden drop in 3He/4He to a minimum of 4.15 occurred in 2007, marking the end of the “active period.” The unusually high value of 3He/4He in the active period is most likely caused by additions of helium from magmatic degassing due to an increase in magma recharge to the magma chamber beneath Changbaishan volcano.

[17] Carbon dioxide (CO2) is a major gas component released from the Changbaishan volcanic geothermal area, with a content from 73.55% to 97.59% depending on the water temperature [Shangguan, 1997]. As shown in Figure 4c, a remarkably consistent high CO2 content from Julong hot spring was observed during the “active period.” The 96.1% CO2 content for the 4-year average is comparable to or even higher than the 93% CO2 content for the 6-year average of Obama hot spring from Unzen volcano (Japan) after its 1990 eruption [Notsu et al., 2001]. Starting from 2007, however, the CO2 content dropped to an average value of 83.9%, representing the low-level mantle-derived gas activity of the “inactive period.” Some other gas components, such as He, H2, and N2/O2 from Julong hot spring, also increased anomalously during the “active period” (Figures 4c and 4d). Compared to their values of less than 10 ppm before 2002, the contents of He and H2 reached 700 ppm and 2750 ppm, respectively, in 2004. Moreover, the N2/O2 ratio reached its maximum of 14.94 in May 2002, in contrast to the background ratio of 3.73 for the “inactive period” (Figure 4d) [Ohba et al., 2008]. All of these geochemical anomalies are evidence of magmatic unrest beneath Changbaishan volcano during the “active period,” even though the details of the unrest cannot be discerned.

4. Discussion and Conclusion

[18] Our continuous monitoring of Changbaishan volcano since 1999 has produced a 12-year-long time series of activity associated with magmatic unrest. The time series can be divided into three periods based on seismicity, ground deformation, and gas geochemistry. During the active period of 2002–2006, the number of earthquakes increased by as much as two orders of magnitude, accompanied by earthquake swarms and harmonic events. Ground deformation measurements revealed inflation centered at 2–6 km beneath the volcano’s summit. Meanwhile, the contents of the major gas components CO2, H2, He, and N2/O2 and isotopic 3He/4He were significant higher during the active period than the inactive periods. The depth distribution of earthquake swarms and simulated inflation source based on GPS and leveling data suggest the existence of a shallow magma chamber at a depth about 5 km, in which magma refilled a shallow chamber beneath the volcano. We speculate that continuous magma refilling may have increased the pressure within the magma chamber. Such pressure increase allowed the deep magma from the mantle to penetrate further into the magma system, resulting in increased seismicity, ground deformation and hydrothermal activity. It is thus conceivable that such magma unrest may have played an important role in all the abnormal phenomena detected during the “active period.”

[19] Changbaishan volcano has remained “inactive” since 2006, however several abnormal signals were observed in recent years that require special attention. In 2009, precise leveling measurements along both the north and west slopes of the volcano revealed a change of ground deformation mode from inflation to deflation (Figures 3e and 3f). The water temperature of Julong hot spring suddenly rose to 77.7°C, about 3°C higher than in 2010, which has persisted to the present (Figure 4e). An unusually high 3He/4He ratio of 6.68 from Hubin hot spring was also observed in 2011 (Figure 4b). Taken together, all these phenomena might indicate the beginning of a new “active period.” The episodic unrests probably caused by the pulse of mantle magma intruding the upper crust, have been observed at many volcanoes [e.g., Deurisin et al., 2006; Newman et al., 2012], such as Eyjafjallajökull, in Iceland [Barði, 2012]. As long term precursors, the episodic unrests detected by seismic monitoring, geodetic measurements and gas geochemistry around the Eyjafjallajökull volcano in 1994 and 1999–2000 finally culminated in eruption in 2010. Therefore, the magma unrest process around the Tianchi caldera from 2002 to 2006 may be considered as a long term precursor of the potential eruptive activity of Changbaishan volcano, even though an eruption is not imminent, and thus deserves attention.

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