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Remote sensing and petrological observations on the 2012–2013 fissure eruption at Tolbachik volcano, Kamchatka: Implications for reconstruction of the eruption chronology

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ABSTRACT

We present a reconstruction of the chronological sequence of events that took place during the first days of the 2012–2013 Tolbachik fissure eruption using petrological data and remote sensing methods. We were forced to use this approach because bad weather conditions did not allow direct observations during the first two days of the eruption. We interpreted infrared images from the scanning radiometer VIIRS Suomi NPP and correlated the output with the results of the geochemical study, including comparison of the ash, deposited at the period from 27 to 29 November, with the samples of lava and bombs erupted from the Menyailov and Naboko vents. We argue that the compositional change observed in the eruption products (the decrease of SiO_2 concentration and K_2O/MgO ratio, increase of MgO concentration and Mg#) started approximately 24 h after the eruption began. At this time the center of activity moved to the southern part of the fissure, where the Naboko group of vents was formed; therefore, this timeframe also characterizes the timing of the Naboko vent opening. The Naboko group of vents remained active until the end of eruption in September 2013.

1. Introduction

Tolbachinsky Dol (TD) is located at the northern part of the Kamchatka island arc system and belongs to the Klyuchevskoy group of volcanoes (Churikova et al., 2015). It comprises lava flows and pyroclastic deposits produced by numerous scoria cones formed along the regional linear fault zone about 70 km long. At its northern end Tolbachinsky Dol crosses Ostry and Plosky Tolbachik stratovolcanoes. About 80% of the TD eruptive centers are concentrated along the narrow axial part of this regional fault zone. In the Holocene, more than 60 eruptions took place in TD (Fig. 1, Fedotov, 1983; Fedotov et al., 1984). Historical eruptions produced Krasny and Zvezda scoria cones (1740 CE), the 1941 CE cone, and the Northern and Southern Breakthroughs of the 1975–76 Tolbachik Fissure eruption (Fedotov, 1983; Fedotov et al., 1984; Inbar et al., 2011). On 27 November 2012, after minor precursory seismicity (Senyukov et al., 2015; Kugaenko et al., 2015; Kugaenko et al., 2014) a new eruption began on the southern slope of Plosky Tolbachik stratovolcano. At the beginning, a 6 km long submeridional fissure was formed; its opening was accompanied by intense lava effusion. Later, explosive and effusive activity was concentrated at two centers: Menyailov vent at the northern part of the fissure, and Naboko vent at the southern part of the fissure. The lava discharge rate during the first two days was ~440 m^3/s, and by 29 November 2012 lava flows covered an area of 14.46 km^2 (Dvigalo et al., 2014). By 30 November the activity of the Menyailov group of vents ceased. From this point until the end of eruption in September 2013, the activity was concentrated at the Naboko group of vents. Unfortunately, on 27–28 November 2012 a strong snowstorm above Kamchatka prevented direct observation of the beginning of the eruption; thus no visual observations exist to confirm the exact time of the beginning of the Naboko vents' activity. Here we make an attempt to reconstruct the eruption chronology during the period of 27–30 November, using satellite and petrological data.

2. Data and methods

2.1. Satellite data

Based on seismic data, the 2012–2013 Tolbachik fissure eruption (FTE) started at 05:15 UTC 27 November 2012 (Senyukov et al., 2015). Cloud cover and a snowstorm at this time made visual ground-based and satellite-based observations impossible. Satellite images did not record ash clouds. Only 11 h later (at 16:30 UTC 27 November 2012) an AIRS satellite image showed an SO_2-bearing cloud (according to the data of Support to Aviation Control Service http://sacs.aeronomie.be; Brenot et al., 2014), which was located about 800 km to the north of the eruption site. Most likely, this cloud corresponds to the first explosive phase of the fissure opening at the Menyailov vent. After

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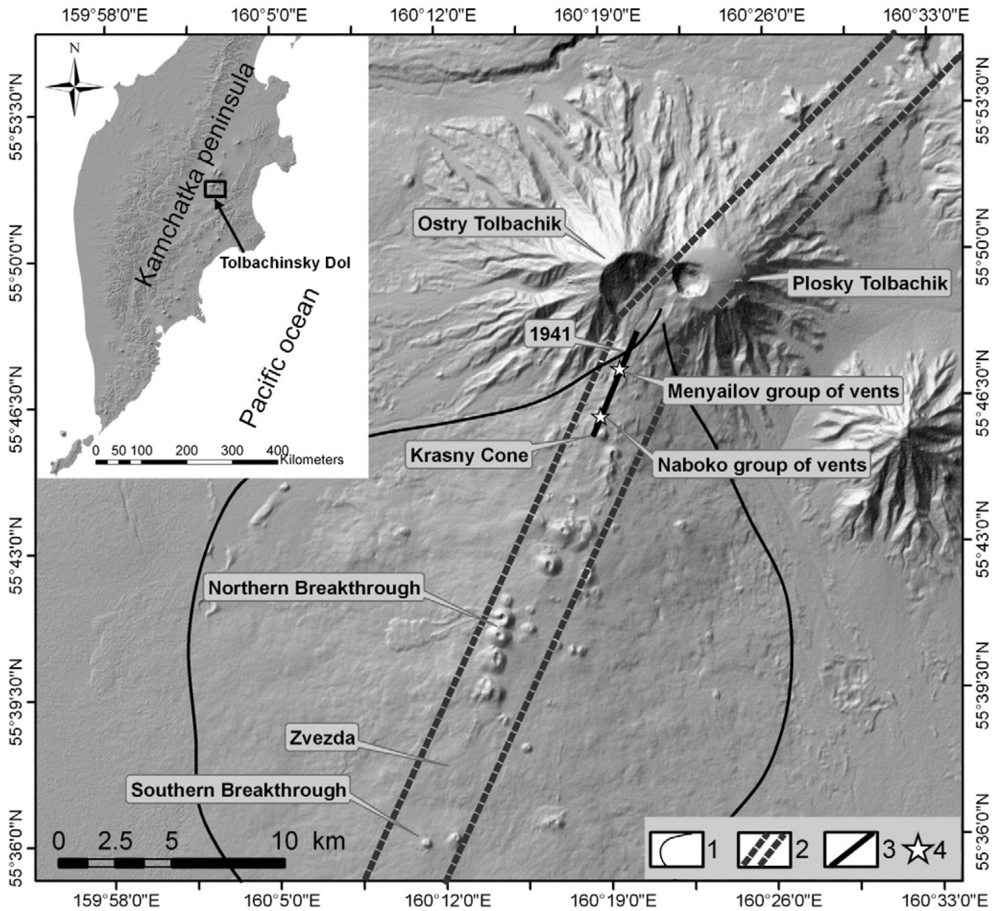

Fig. 1. Schematic map of Tolbachinsky Dol and its location in the Kamchatka arc system. Legend: 1—the boundary of Tolbachinsky Dol; 2—regional linear fault zone; 3—fissure zone of the 2012–2013 Tolbachik fissure eruption; 4—Menyailov group of vents and Naboko group of vents. Centers of the historical eruptions are outlined as follows: Northern and Southern Breakthroughs of the 1975–76 Tolbachik fissure eruption; cinder cone of the 1941 CE eruption; Krasny cinder cone and Zvezda eruptive center (1740 CE). The topographic base is a DEM-derived from SRTM X-band (DLR).

that, the seismic data (Senyukov et al.,2015) indicate a decrease in activity, followed by the strong volcanic tremor at ~08:00 UTC 27 November 2012, possibly caused by the onset of intense lava effusion.

Infrared satellite images of various spatial resolutions are now routinely used for the analyses of lava flows dynamics (Harris et al., 1998; Pieri and Abrams, 2004; Harris, 2013; Wright et al., 2015). High-resolution satellite images (TERRA ASTER, EO-1 ALI), where the lava flows could be viewed in detail, are available for the FTE area only from the beginning of December 2012. For the period from 27 to 30 November 2012, only low-resolution satellite data from MODIS, and AVHRR are available with the spatial resolution for the IR channel of ~1 km/pixel. This kind of resolution is not suitable for the analyses of FTE lava flows. For more detailed analyses of the morphology and edges of the lava flows we used data from the Visible Infrared Imaging Radiometer Suite (VIIRS), which is located on the Suomi NPP satellite and provides global coverage of the Earth's surface every 12 h. One advantage of VIIRS is that it is has two infrared channels with spatial resolution 375 m. VIIRS I4 has a channel for wavelengths between 3.55 and 3.93 μm with a pixel saturation temperature of 367 K; additionally, when pixel saturation is associated with intensive heat flow (large wildfires, lava flows) the pixel's brightness temperature may be set at 208 K (Schroeder et al., 2014). There is also an I5 channel for wavelengths between 10.5 and 12.4 μm and a saturation temperature of 380 K. It has been previously shown that these channels provide good results for the detection and description of active fires and their morphologies (Schroeder et al., 2014). Raw satellite images were obtained through the Comprehensive Large Array-data Stewardship System (http://www.nsof.class.noaa.gov) as Level1 Sensor Data Records (SDR) files.

2.2. Geochemical data

Three samples of ash, produced during the first days of the eruption, were chosen for geochemical analyses; the results were compared with the comprehensive data set of the representative collection of rocks that characterize the composition of lava from the first until the last day of the eruption (Volynets et al., 2015; Volynets et al., 2013). Concentrations of the major and selected trace elements (V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba, Pb) in these three ash samples were analyzed by X-ray fluorescence spectroscopy (XRF) using an Axios MAX vacuum sequential spectrometer (wavelength dispersive) by PANalytical at the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences (IGEM RAS). Descriptions of the sample preparation methods and analytical errors are provided in Volynets et al. (2015).

3. Results

3.1. Satellite data

Fig. 2 shows images from the I4 and I5 channels at brightness temperature (in Kelvin). The first image, showing a thermal anomaly above the eruption area, was made at 15:30 UTC 27 November 2012, but the anomaly is visible only with I4 channel, because clouds prevent