1 TITLE

2 Volcano-tectonic dynamics of Deception Island (Antarctica): 27 years of GPS
3 observations (1991-2018)

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22 ABSTRACT

23 Deception Island (South Shetland Islands) is one of the most active volcanoes in Antarctica. In
24 the 1988-1989 austral summer, after the most recent eruptive process on the island (1967-1970),
25 monitoring of volcanic activity through geophysical and geodetic techniques was resumed by
26 Spanish and Argentinean scientists. In order to monitor the island's tectonic and volcanic
27 behaviour, a geodetic network was deployed. Currently, this network consists of 15 geodetic
28 benchmarks located around Port Foster, Deception's inner bay open to the sea. Two additional
29 geodetic benchmarks were installed outside Deception Island to be used as reference
30 benchmarks for the differential positioning strategy. Since 1991-1992, geodetic ground-
31 displacement velocities between the successive austral summer Antarctic campaigns have been
32 computed and analyzed.

33 The overall geodynamic behavior of Deception Island within the South Shetland Islands,
34 Antarctic Peninsula and Bransfield Basin regional environment has been analyzed from
35 geodetic ground-displacements. Results obtained demonstrate that Deception and Livingston
36 island have a similar behavior derived from the Bransfield Basin extension and the Phoenix

micro-plate subsidence processes. However, Deception Island is also highly influenced by its volcanic activity.

Deception Island's volcanic behavior between 1991 and 2018 is shown by the velocity field, strain tensors and pressure source evolution obtained from the ground-displacements at the geodetic benchmarks. During this time period, it is possible to identify different inflation and deflation phases separated by transitional (or mixed) stages of extension without uplift and compression without subsidence. The most representative inflation and deflation periods were analyzed in detail, to show how they correlate with high and low seismic activity, respectively. The transitional or mixed stages, seem to be the precursors of the next inflation or deflation phase being the Bransfield basin rifting and NW-SE extension the potential related process.

Finally, we have analyzed the processes that occurred prior to the volcanic unrests of 1999-2000 and 2012-2013. In both cases, an increase in detected seismic activity and/or soil and seawater temperature was observed and a mixed phase of extension without uplift seems to be precursory to the volcanic unrest. The correlation between the inflation processes, identified by ground-displacement of the network geodetic benchmarks, the increase in seismicity and the increment of soil and seawater temperature makes these transitional mixed phases potential precursors of Deception Island's volcanic unrest periods.

KEYWORDS

Volcano geodesy; Deception Island Volcano; GNSS-GPS; volcano-tectonic model 4D; stress-strain model

1. INTRODUCTION

The application of surface deformation in volcano monitoring has evolved from classical geodesic procedures to GNSS-based methodologies (Global Navigation Satellite Systems), in particular GPS (Global Positioning System) (Dzurisin, 2007; Fournier et al., 2010; Segall, 2013; Qin et al., 2018). Horizontal and vertical ground-displacements are obtained from repeated observations through continuous data recording receivers (CGPS) or through episodic measurements (Berrocoso et al., 2016; Dzurisin et al., 2017; Fernández et al., 2017; Gautam et al., 2017). GPS observations are posteriorly analysed to achieve millimetric accuracy in the obtained daily positions (Prates et al., 2013; Cannavò et al., 2015).

Volcano geodesy has evolved beyond the characterization of ground-displacement at several benchmarks, becoming a versatile tool to detect and model volcanic processes occurring, not only on the ground surface, but also in the deep magmatic system (Grapenthin et al., 2010; Sigmundsson et al., 2010; Grapenthin et al., 2013; Pinel et al., 2014; Gudmundsson, 2016; Biggs and Pritchard, 2017; Zhan and Gregg, 2017; Sigmundsson et al., 2018).

This paper focuses on the volcanic activity monitoring of Deception Island, an active volcano located in the South Shetland Islands, near the Antarctic Peninsula. This volcanic island (Figure 1), has registered more than 20 explosive eruptions over the last two centuries, concentrated in three main periods of activity: 1818-1828, 1906-1912 and 1967-1970 (Smellie, 2002). Currently, the island hosts two scientific stations and is highly visited by researchers and

tourists during the austral summer. These two aspects turn the evaluation of its volcanic activity into a very important and necessary topic (Tejedo et al., 2015). Since 1991, and within the limitations of its inhospitable Antarctic environment and scarce human presence, Deception Island is being mainly monitored through the recording of seismic activity (Jiménez et al., 2017; Almendros et al., 2018) and ground-displacements (Prates et al., 2013; Berrocoso et al., 2008). The analysis of the data collected in the successive austral summers has contributed to validate the applied technologies and methods, as well as to evaluate the volcanic activity of Deception within a complex regional tectonic environment (Berrocoso et al., 2016).

2. GEODYNAMIC FRAME

The region defined by the South Shetland Islands archipelago, the Bransfield Basin and the Antarctic Peninsula is characterized by a highly complex tectonic environment driven by the two major tectonic plates converging in this region: the South American and Antarctic Plates (Baraldo, 1999). The boundary between both plates is even more complex due to the interaction of four minor tectonic plates originated by the relative movements of the main plates, i.e. Scotia, South Sandwich, Phoenix and South Shetland plates (Galindo-Zaldívar et al., 2004; Maestro et al., 2007; Solari et al., 2008). The South Shetland archipelago is a volcanic arc, except for Deception and Penguin Islands, attributed to the subduction of the Phoenix microplate under the Antarctic plate (Jin et al., 2009), whose rate has been estimated at 1.0 cm / year (Dietrich et al., 2001; Taylor et al., 2008).

Due to the regional north-eastwards movement of the Antarctic Plate, the South Shetland Trench has an additional left-lateral component that extends to the also left-lateral South Scotia Ridge, the Antarctic-Scotia boundary (Maestro et al., 2007) (figure 1b). This left-lateral component produces NW-SE transform fault systems away from the South Shetland Trench that accommodate the regional compressive, extensive and shear stresses (Maestro et al., 2007). In addition, the subducted Phoenix plate roll-back due to a slow subduction rate produces the Bransfield Basin back-arc NE-SW extension fault system (Galindo-Zaldívar et al., 2004; Maestro et al., 2007; Solari et al., 2008; Berrocoso et al., 2016). Recent geodesic studies have pointed out the existence of two different geodynamic patterns, northeast and southwest of Deception Island, which marks the southern limit of the Bransfield marginal basin spreading (Berrocoso et al., 2016). Furthermore, studies made from aeromagnetic data suggest that the beginning of the expansion took place 1.8 Ma ago, with an average opening speed of the basin of 0.9 cm / year. González-Ferrán (1991) suggested an average rate of 0.25-0.75 cm / year during the last 2 Ma, which totals approximately 15 km.

Along the 500 km long and 60 km wide Bransfield Strait, seismic data identifies activity related to the slow subduction of the Phoenix microplate's young lithosphere, and rifting and active volcanism in the Bransfield basin back-arc (Robertson et al, 2002; Ibáñez et al., 1997). In September 2014, a strong increase in seismic activity was detected near Livingston Island, first aligned NW-SE and then concentrated SE of Livingston, that later spread throughout Deception Island's volcanic edifice, suggesting that the island's unrest had been triggered by the series of events near Livingston Island, on a NW-SE transform fault (Almendros et al., 2018).

Figure 1. a) Map of the Scotia microplate area and the most important plates boundaries. SST = South Shetland Trench; SSB = South Shetland Block; SFZ = Shackleton Fracture Zone; BB = Bransfield Basin; SOM = South Orkney Microcontinent (modified from Jiménez et al., 2018). b)

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180 122 *Map of the Bransfield Strait and the South Shetland Islands showing the main faults of the*
181 123 *region. c) Geological map of Deception Island with recent volcanic activity, OCTF = Outer*
182 124 *Coast Tuff Formation (from Pedrazzi et al., 2018).*

184 125 Deception Island is a horseshoe-shaped composite volcano located in the southern limit of the
185 126 Bransfield Basin back-arc rift, between the Antarctic Peninsula and the South Shetland Islands.
186 127 The normal magnetic polarity of all Deception Island's exposed rocks indicates that these are
187 128 younger than 0.75 Ma (Valencio et al., 1979; Smellie, 2001), and K-Ar data (Keller et al., 1992)
188 129 suggest that most of the subaerial part of the island was built in the last 0.2 Ma. Deception
189 130 Island's volcanic evolution is marked by a caldera collapse, which took place between 8,300
190 131 and 3,980 years BC (Oliva-Urcia et al., 2015; Antoniadou et al., 2018). Post-caldera volcanism
191 132 comprises at least 70 scattered eruptive vents inside the caldera, mainly associated to
192 133 phreatomagmatic eruptions, which deposited pyroclastic sediments over the pre- and syn-
193 134 caldera lava flows and pyroclastic density current deposits (Martí and Baraldo, 1990; Smellie,
194 135 2011; Pedrazzi et al., 2018).

197 136 The fault systems in Deception Island reflect the regional trends (Baraldo, 1999; Pérez-López et
198 137 al., 2007; Maestro et al., 2007). Indeed, the craters of some phreatomagmatic eruptions were
199 138 generated from these fissures, as in the Crater Lake 1842 eruptive process (Smellie, 2001)
200 139 (figure 1c). Also, Deception Island's elliptic shape developed under the combined influence of a
201 140 NW-SE back-arc basin and a NE-SW transtensional regime, consequence of the slab roll-back
202 141 and the left-lateral component along the South Shetland Trench, respectively (Lopes et al.,
203 142 2014). However, in the last years, the NE-SW compression rate has inferred to be higher than
204 143 the NW-SE extension rate in Deception Island (Berrocoso et al., 2012; Prates et al., 2013).

207 144 Historical volcanism at Deception Island, classified as VEI (Volcanic Explosivity Index) 2-3,
208 145 has involved small to moderate-volume monogenetic eruptions (<0.1 km³) with eruptive
209 146 columns up to 10 km height (Pedrazzi et al., 2018). The most recent eruptions date from 1842,
210 147 1912, 1917, 1967, 1969 and 1970 (Baker et al., 1975; Roobol, 1982; Smellie, 2002). During the
211 148 explosive eruptions occurred in 1967, 1969 and 1970, ash fall and lahars destroyed the Chilean
212 149 and British scientific bases, and significantly changed the island geomorphology (Bartolini et
213 150 al., 2014; Pedrazzi et al., 2014; Torrecillas et al., 2012). During this period, a large volume of
214 151 ash was emitted and deposited in the neighbouring islands, as can be seen in the Johnson
215 152 Glacier on Livingston Island (Geyer et al., 2017).

218 153 At the surface, the main indications of current volcanic activity are the existence of fumarolic
219 154 areas at Fumarole and Whalers Bay with gas emissions reaching 100°C and 70°C, respectively;
220 155 100°C hot soil in Cerro Caliente; and 45°C and 65°C thermal springs in Pendulum Cove and
221 156 Whalers Bay, respectively (Berrocoso et al., 2018). A remarkable seismic activity is also
222 157 registered in the island, most of these events being shallow, with low energy content and
223 158 magnitudes ranging from 1-2 (Carmona et al., 2012). Recent geomagnetic, gravimetric and
224 159 seismic refraction studies support also the existence of magma underneath Deception's flooded
225 160 caldera extending from 2 km to at least 5 km depth (Somoza et al., 2004; Muñoz-Martín et al.,
226 161 2005; Ben-Zvi et al., 2009; Zandomenighi et al., 2009; Pedrera et al., 2012; Catalan et al., 2014;
227 162 Prudencio et al., 2015). Recent petrological and geochemical data combined with detailed
228 163 Pressure-Temperature (P-T) estimates, and fractional crystallization modelling also support this
229 164 idea (Geyer et al., 2019).

During the recent volcanic unrest detected in 1991-1992 and 1998-1999, several volcano-tectonic (VT) earthquakes were felt and volcanic tremor was recorded (Ibáñez et al., 2000; Ibáñez et al., 2003). In 2012-2013, the increase in soil and seawater temperature was followed by an increment of the seismic activity and a period of volcano inflation inferred by ground-displacement data (Berrocoso et al., 2018).

3. GEODETIC NETWORK AND DATA PROCESSING

The GPS geodetic network deployed on Deception Island, named REGID (Geodetic Network for geodynamic studies in Deception Island, in Spanish *Red Geodésica para estudios geodinámicos de Isla Decepción*), comprises 15 geodetic benchmarks distributed around Port Foster (Figure 2). In order to evaluate and distinguish the volcano-tectonic activity at Deception Island from the South Shetland former volcanic arc (Figure 2), an additional geodetic benchmark was deployed on Livingston Island. Despite Livingston's geodetic benchmark experiencing relocations in 2009/2010 and 2011/2012, distanced no more than 50 m, their observations were properly tied (BEJC, BEJ1 and BEJ2). Throughout the diverse austral summer campaigns, the network has evolved and been improved by newer GPS instruments (lower energy consumption and weight, greater storage capacity) and remote access to data and status via WIFI transmission.

The REGID network deployment began during the 1989-1990 campaign, and was constructed throughout three different phases. The first one started in the 1989-1990 campaign and ended during the 1995-1996 one. In this initial phase, four geodesic benchmarks were built on Deception Island (figure 2): BARG (Argentina Deception Base), FUMA (Fumarole Bay), PEND (Pendulum Cove) and BALL (Whalers Bay). The BEJC benchmark near the Juan Carlos I Base on Livingston Island was constructed also during this first phase. During this period, the geodetic benchmark BARG was considered the reference benchmark of the network. The 1991-1992 volcanic crisis located offshore of Fumarole bay motivated the island reference benchmark relocation. During the 1995-96 campaign, a new benchmark, BEGC, was built close to the Gabriel de Castilla Base, and has been considered since then the reference benchmark of Deception Island's geodetic network.

During the 1998-1999 campaign, the largest volcanic crisis occurred since the 1967-1970 eruptive process (García et al., 2002). Correspondingly, during the 1999-2000 campaign, a reobservation of the initial REGID network was carried out, and an updated deformation model corresponding to this seismovolcanic crisis was obtained (Berrocoso et al., 2006a; Berrocoso et al., 2006b; Berrocoso et al., 2008). Thus, in order to cover the entire inner ring of the island, the geodetic network was densified during the second newly built phase that started with the 2001-2002 campaign. The newly built benchmarks were: COLA (Colatinas), GEOD (Soto Crater), UCA1 (Obsidian Valley), TELE (Telephone Bay), BOMB (Bomb Field), CR70 (Craters of the 1970 eruption) and GLAN (Glaciar Negro) (Fernández-Ros et al., 2007) (See figure 1c). The establishment of these benchmarks provided the required consistency to define the deformation models and the necessary framework for applying other complementary geodetic techniques such as levelling or gravimetric measurements.

During the 2006-2007, 2007-2008 and 2009-2010 campaigns, PUCO (Punta Collins), CECA (Cerro Caliente) and STNE (Stonethrow Ridge) benchmarks were set up, respectively. Due to the remodelling of the Juan Carlos I Base on Livingston Island, the BEJ1 benchmark was built

in the 2009-2010 campaign, remaining operative until the 2014-2015 campaign. Eventually, BEJ2 was built during the 2011-2012 campaign, remaining operative until today. The construction of the above-mentioned benchmarks is considered the third phase of the establishment of the network (Table 1).

Nowadays, the REGID network has a radial coverage around Port Foster. All benchmarks are 20 cm height and are located at the top of an approximately 1 m deep concrete base, which is fastened to the permafrost by metal bars (Fig. 3a). In order to correctly ensure the GPS antenna centre and precisely determined positions relative to the benchmark at each campaign, we have designed an accurately-measured system based on a 5 cm stainless steel screw for the benchmark and a prolongation of nearly 13 cm length where the antenna is attached (Fig. 3b). For the antenna orientation, washers with a thickness of 1 mm are added until the orientation to the north is reached.

For volcanic activity monitoring purposes, BEGC, FUMA and PEND benchmarks are continuously surveyed during each campaign (Peci et al., 2012). These benchmarks form a wireless connection infrastructure transmitting data to the control centre to be practically analysed in real-time. In 30-minutes sessions, relative distances are evaluated together with the inclination of the plane defined by these three benchmarks (Berrocoso et al., 2012; Prates et al., 2013). To reduce the noise due to broadcasted ephemerides and the fact of processing every 30 minutes, filtering methods are applied (wavelet and/or kalman) (Berrocoso et al., 2006; Berrocoso et al., 2008; Ramírez et al., 2008; Berrocoso et al., 2012; Prates et al., 2013). For the rest of benchmarks composing the REGID network, the observational period is between 5 to 7 days per campaign. In all cases, GPS observations are carried out during the austral summer campaigns, from December to February, therefore minimizing the effect of eventual seasonal biases. Also the GPS data sampling rates progressively increased as GPS equipment improved capabilities. Table 1 shows the observation days of each of the stations in each campaign.

Figure 2. Location of the 15 GPS stations composing the current REGID network. All stations but one are distributed around Port Foster on Deception Island, and the remaining one is located on Livingston Island. Coloured symbols indicate the first campaign for which observational data are available for each benchmark.

Figure 3. REGID network GPS stations monumentation. a) Concrete structure of 1m depth, attached to the permafrost by metal bars. b) System based on a 5 cm stainless steel screw for the benchmark and a high-precision measured prolongation of nearly 13 cm where the antenna attaches.

Table 1. Number of observation days of the stations composing the REGID network in each campaign. The establishment of the network, constructed in three phases, started in the 1989-1990 campaign.

GPS data were analyzed using the scientific software Bernese v5.0 (Dach et al., 2007). Carrier phase double-difference data were used in ionospheric delay free mode. Tropospheric errors were handled by using a combination of the a priori Saastamoinen model (Saastamoinen, 1973) and Neill mapping functions (Niell, 1996). Tropospheric parameters were estimated hourly, and ambiguities were fixed for each baseline, using the ionosphere-free observable with an a priori ionospheric model for determining the wide lane ambiguity (Mervart, 1995). Ocean tide loading displacement corrections were also introduced. Normal equations were computed for each daily

solution. The final solution was achieved by combining the daily normal equations at the mean epoch of each campaign, by using the IGS REPRO2 final orbits (Rebischung et al., 2015) and constraining the movement of the reference benchmarks, PALM at Palmer Station, on Anvers Island, for the realization of the ITRF2008 reference frame (Altamini et al., 2011).

4. GEODYNAMIC ACTIVITY FOR THE LIVINGSTON AND DECEPTION ISLANDS

The final solutions for each benchmark allow establishing their time series in the ITRF2008 reference frame, from which the horizontal and vertical ground-displacement velocities were calculated. On the one hand, the time series for the different Deception Island's benchmarks clearly show the superposition of the island's volcanic activity (figure 4b) and the regional tectonics, also present in the Livingston benchmark time series (figure 4a) (Berrocoso et al., 2006; Berrocoso et al., 2012; Carmona et al., 2012; García et al., 2002; Ibáñez et al., 2000; Ibáñez et al., 2003; Prates et al., 2013). Indeed, the time series analysis for Livingston and Deception Island's benchmarks confirm that both islands are subject to the Phoenix slab roll-back and Bransfield Basin extension process at rate of 1.9 cm / year (Berrocoso et al., 2016). Additionally, both islands have similar mean ground-displacement velocities, about 1.2 cm / year and 1.7 cm / year at Livingston, respectively easting and northing, and 1.4 cm / year and 1.6 cm / year at Deception (BEGC), thus suggesting that they belong to the same tectonic block (Berrocoso et al., 2016). Time series of Deception Island benchmarks are shown in figure A.1.

Figure 4: Time series of BEJC, BEJ1, and BEJ2 benchmarks on Livingston Island (left) and BEGC on Deception Island (right). Easting component is shown in blue diamonds, northing in red squares and height in green triangles. a) The tectonic character of the South Shetland Islands is reflected due to the subduction process of the Phoenix microplate with respect to the Antarctic plate, and to the Bransfield rift expansion process (linear model). b) Volcano-tectonic geodynamic behaviour (non-linear model) of Deception Island (Berrocoso et al., 2016).

The horizontal ground-displacement velocity at Deception benchmarks for their complete time series depicts that Deception benchmarks move away from Livingston with the same orientation as the Bransfield Basin extension NW-SE (figure 5b). This is noticeable once the horizontal ground-displacement velocity of Livingston has been removed, i.e. considering Livingston absent of movement or held fixed. With averaged displacements from magma injection or hydrothermal activity, and apart from the continuous displacement northeast together with the Antarctic plate rotation (figure 5a), there seems to be also a sustained displacement due to the Bransfield Basin extension. This average ground-displacement was inferred to 2 mm / year east and -4 mm / year north approximately (figure 5b).

Figure 5. a) Horizontal and vertical geodynamic deformation models for Livingston (tectonic) and Deception (volcano-tectonic) islands. The average horizontal displacement presents NW orientation and shows a subsidence process due to the Phoenix microplate subduction. b) Long period non-tectonic residual model for Deception Island obtained with respect to Livingston Island stations. The horizontal direction of the stations according to this model is NNW-SSE with SSW orientation.

5. 4D VOLCANIC MODELLING USING THE SURFACE DEFORMATION PARAMETER FOR DECEPTION ISLAND

In order to infer Deception Island's volcano dynamics from 1991 until 2018, the tectonic ground-displacement horizontal velocities from the 15 benchmarks were removed. This has been done considering Livingston's horizontal velocity as purely tectonic and the residual network common horizontal displacement by a common mode filter (Tabei and Amin, 2002; Nguyen et al., 2016).

$$CM = \frac{1}{N} \sum t_N = \frac{1}{N} \sum (d_N - d_R) \quad (1)$$

where d_R is Livingston Island's time series, and N is the number of stations. This filter is subtracted from the time series (eq. 2):

$$t_N = d_N - d_R - CM = d_N - d_R - \frac{1}{N} \sum (d_N - d_R) = d_N - \frac{1}{N} \sum d_N \quad (2)$$

In this way, the reference for the ground-displacement time series is now the centre of motion of the network, from which the horizontal velocities are obtained for each campaign. The average motion of the network subtracted to the time series is 0.9 cm in the east direction and 1.0 cm in the north direction.

The analysis of ground-displacement velocities at the 15 benchmarks deployed at Deception Island allows to detect its volcano dynamics from 1991 until 2018 based also on velocity field, strain tensors and pressure source evolution. The latter is determined applying the Mogi model (Mogi, 1958) justified due to the disposition of the benchmarks relative to Port Foster center, and their typical radial ground-displacements towards and away from the bay's center. The Mogi model assumes that the surface deformation is caused by a spherical source located under the volcanic edifice and exerting an ascending hydrostatic pressure towards the surface. This model considers the Earth's crust to behave elastically at the time of eruption. Mogi model's parameters were computed by Simulated Annealing optimization algorithm (Masterlark et al., 2016) based on a control parameter analogous to the temperature, decreasing or increasing according to a crystallization scheme.

5.1. VELOCITY DISPLACEMENT MODELS, STRESS AND STRAIN MODELS AND LOCATION OF PRESSURE SOURCES (1991-2018)

A sequence of alternating inflation and deflation processes can be identified in ~ 6-year periods (figure 4b). Since we have yearly data recorded during the austral summer period, clear inflation maxima occurred in 2006, between the austral summers of 2005/2006 and 2006/2007 (figure 6h), in 2013 (figure 6o) and 2014 (figure 6p), while clear deflations maxima occurred in 2002 (figure 6d) and 2003 (figure 6e), in 2008 (figure 6j) and 2009 (figure 6k), and 2015 (figure 6q) and 2016 (figure 6r).

Figure 6. Deception Island displacement models from the 1991-1992 to the 2017-2018 campaign. Horizontal displacements are shown in red, and vertical in blue. The # graph indicates the characteristics shown in the multi-screen graphs. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to the 2017-2018 campaign. There are two

differentiated behaviours: inflation - uplift (a, b, g, h, o and p) and deflation - subsidence (c, d, j, k, m, q, r). In addition, transitional processes are detected in the graphs e, i, l and n.

Figure 7. Deformation tensors main axes from the 1991-1992 to the 2017-2018 campaign. Positive (in red) and negative (in blue) values indicate extension or compression (in $\mu\text{Strain} / \text{year}$) in the given direction, respectively. The # graph indicates the characteristics shown in the multi-screen graphs. The expansion processes (a, b, h, l, o, p and s), and the compression processes (c, d, j, k, m, q and r) are observed. Two periods are distinguished: the period before the 1998 crisis (a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign.

Figure 6 shows a multi-screen with the horizontal and vertical displacement models for Deception Island from the 1991-1992 to the 2017-2018 campaign. The # graph indicates the characteristics shown in the multi-screen graphs. Two periods are distinguished: the first one from the 1991-1992 campaign to the 1999-2000 campaign (Fig. 6 a and b); and a second period from the 1999-2000 campaign until 2017-2018 (Fig. 6 c to s). The first period includes the inflation-uplift model corresponding to the 1998 volcanic crisis, which will be explained in detail later. The second period is characterized by the temporal continuity of the obtained models. Two differentiated processes are observed in both components: inflation or deflation in the horizontal, and uplift or subsidence in the vertical. These models suggest that the deflation processes coincide with those of subsidence (Fig. 6 c, d, j, k, m, q, r), while the inflation processes correspond to processes of uplift (Fig. 6 g, h, o, p).

In between, there were unclear transition mixed processes. The horizontal ground-displacement velocities in transition mixed processes tend to coincide with those inferred by removing Livingston horizontal ground-displacement velocity (figure 5b), therefore without a considerable magma injection or hydrothermal activity, leaving only the ground-displacement due to the Bransfield Basin extension.

Some transition mixed processes preceded inflation processes (figures 6 e, i, l and n). In these processes UCA1, TELE, BOMB and CR70 have smaller ground-displacement magnitudes suggesting the existence of two different blocks, with an average of 1.2 cm / year and 0.7 cm / year for the horizontal ground-displacement, respectively. However, such behaviour did not precede deflation processes, with exception to 2011, where the inflation process did not continue, shifting to deflation, which also did not continue.

Those benchmarks closer to Neptune's Bellows, Port Foster narrow passage to the sea, GLAN, BALL and PUCO, mostly present different horizontal ground-displacement velocities compared to the rest of benchmarks (figure 6 g, h, j, k, l, m, o, p, q, r and s) suggesting a third block separating the centre of the caldera and the southeast sector.

Applying Mogi's model to the ground-displacement data between campaigns, the location of the pressure source and its evolution was estimated. This method converges in those periods in which the volcanic ground-displacement is clear. Mogi's pressure source evolution was computed in periods corresponding to figures 6 a, b, h, j, o, p, q and r, which pressure source parameters are presented in table 2. These parameters are based on horizontal and vertical ground deformation. The coefficient of determination R^2 is shown to evaluate the goodness of fit. The best result is obtained for the 1996-2000 model, during the 1998 crisis, which the coefficient R^2 has a value of 0.94, and the horizontal and vertical displacements are higher.

Table 2. Mogi source parameters for the significant processes: 1995-1996, 1999-2000, 2006-2007, 2013-2014 and 2014-2015 inflation-uplift; 2008-2009, 2015-2016 and 2016-2017 deflation-subsidence. This table shows the source location (latitude-longitude), depth, volume change of the estimated pressure source (DV), and the coefficient of determination R2 to evaluate the goodness of fit.

Strain tensors were also computed from the velocity field interpolated from the horizontal ground-displacement velocities of the individual benchmarks, to a regular mesh of 10 x 10 points. Outside the area covered by the mesh, horizontal ground-displacements, without the Antarctic plate rotation, were considered null, constraining the volcanic ground-deformation to the mesh interior. The interpolation was weighted by the inverse of the distance to a geodetic benchmark. Figure 7 shows the main axes of the deformation tensors from the 1991-1992 campaign until 2017-2018. Deformation tensors clearly depict extensional (Figures 7a, b, h, l, o, p and s) and compressional processes (Figures 7c, d, j, k, m, q and r).

Further details on the vertical ground-displacement, superficial dilatation (inflation-deflation), maximum shear deformation module and maximum modulus of geodetic deformation are shown in the supplementary material.

5.2. GEODYNAMIC MODELLING OF THE 1998 VOLCANIC CRISIS: 1991-1996 AND 1996-2000 MODELS

Figure 8. Displacement and stress-strain maps of 1991/1992 with respect to 1995/1996 (Figure 1a-f), and 1995/1996 with respect to 1999/2000 (Figure 2a-f): a) horizontal displacement, horizontal displacement velocity field (in cm / year), and location of the Mogi source and its estimated depth; b) stress and strain tensors main axes. Extension and compression (in $\mu\text{Strain} / \text{year}$) in the given direction are expressed by positive (red) and negative (blue) values, respectively; c) vertical displacement (in cm / year); contour map with the horizontal dilatation values (d) and maximum shear deformation modulus (e) given both in $\mu\text{Strain} / \text{year}$. The same scale is considered for all campaigns; f) horizontal dilatation contour map considering the maximum and minimum values for each campaign.

During the 1991-1992 campaign there was a notable increase in seismic activity, with 900 registered events and four earthquakes. Gravimetric and magnetic anomalies suggest the volcano reactivation was due to a 2 km-deep magmatic injection in the Fumarole Bay area (Ibáñez et al., 1997). These evidences weaken by the end of January 1992. Seismovolcanic activity significantly increased at the beginning of 1999. This crisis included volcano-tectonic (VT) and long-period (LP) events, most of them recorded between Fumarole Bay and Telephone Bay (Ibáñez et al., 2003). BEGC, BARG and FUMA stations showed a displacement to the southwest, with an absolute maximum of 6.8 cm in PEND. At the same time, those stations located at the eastern side of the island recorded eastward movements (PEND to the northeast and BALL to the southeast) suggesting that the inflation process occurs according to the Hero Fracture alignment, perpendicular to the Bransfield extension axis (Berrocoso et al., 2006b). Taking into account the 1999 crisis, and the consequent apparent change in the geodynamics of the island, the location of the pressure source at halfway between Fumarole bay and Pendulum cove is estimated at a depth of 3.7 km.

Analysis of multi sensor data led to the conclusion that there was a volcanic inflation process with evident seismic activity increase, changes in the gas composition, and gravimetric and geomagnetic anomalies (Berrocoso et al., 2006b). It was interpreted that the reactivation was due to a magma intrusion (at 500 m depth) which produced the volcano-tectonic earthquakes. The long-period events and tremors could be the result of the interaction between the shallow aquifers in the island and the intrusion of incandescent material. These events could be considered as a significant evolution of the volcanic activity, indicating a change from stationary to dynamic conditions in the geothermal process present on Deception Island. According to the relation between the frequency of events and the liberated energy, this process was not finished when the 1998-1999 campaign ended. The most affected area was Fumarole Bay.

Figures 6a and b show the displacement models obtained between the 1991-1992 and 1995-1996 campaigns, and between the 1995-1996 and 1999-2000, respectively. An horizontal absolute deformation rate of 2.6 cm / year, and 2.0 cm / year in BARG and FUMA stations, respectively; as well as 2.2 cm / year and 1.5 cm / year in BALL and PEND stations. A subsidence process was observed around the island, with values of 1.2 cm / year and 2.5 cm / year for BARG and FUMA, and 2.8 cm / year and 3.7 cm / year for PEND and BALL, respectively. Figure 6b shows horizontal deformation of 6.0 cm / year, 4.6 cm / year and 3.6 cm / year in BEGC, BARG and FUMA stations respectively, and 6.8 cm / year and 4.8 cm / year for PEND and BALL. An uplift process is observed with values of 7.7 cm / year, 5.6 cm / year and 2.9 cm / year for BEGC, FUMA and BARG respectively, and 6.7 cm / year and 4.4 cm / year for PEND and BALL respectively.

From 1991-1992 until 1995-1996, the average radial ground-displacement was ~2.1 cm / year, and the average subsidence ~2.6 cm / year, reflecting a transition mixed phase (figure 6a). From 1995-1996 until 1999-2000, the average radial ground-displacement was ~5.2 cm / year and average uplift was ~5.5 cm / year, higher than those recorded in the previous period, showing the most significant inflation process registered until now (figure 6b). Ground-displacements acted as a volcanic activity precursor, detecting a transition mixed phase in the period 1992-1996, which culminates in the 1998 seismovolcanic unrest and the 1996-2000 inflation process.

Figure 8 shows the displacement, stress and strain maps of these models. Both models (Figures 8.1 and 8.2) show the inflation-uplift process. The estimated vector field is similar in direction and way in both models, but higher in module in figure 8.2a (2.1 cm / year in 8.1a compared to 5.2 cm / year in 8.2a). Mogi pressure source location evolves from the north sector of Port Foster, at a depth of approximately 6.7 km to the central sector, at a depth of 3.7 km, similar to what was obtained in Berrocoso et al., 2006b. Strain tensors show extension of about 8.5 μ strain / year in 1992-1996 (figure 8.1d) and 26 μ strain / year in 1996-2000 (figure 8.2d). Similar increase is observed in shear-strain, 3.6 to 5.2 μ strain / year in 1992-1996 (figure 8.1e), and 10.8 to 13.2 μ strain / year in 1996-2000 (figure 8.2e).

5.3. REPRESENTATIVE MODELS OF INFLATION PROCESSES (2005-2007) AND DEFLATION (2007-2009)

Figure 9. Displacement and stress-strain maps of the models 2005/2006 with respect to 2006/2007 (Fig. 1a-f), and 2007/2008 with respect to 2008/2009 (Fig. 2a-f). Similar description

to figure 8. Figures 1 show an inflation-uplift process, and figures 2 show a deflation-subsidence process.

Since the 1998 volcanic crisis, several types of processes have occurred on the island. An inflation phase occurred between the 2005-2006 and 2006-2007 campaigns (figure 9.1), followed by a deflation period between the 2007-2008 and 2008-2009 campaigns (figure 9.2). The inflation process showed ground-displacements with an average radial extension of 2.5 cm / year, while the deflation process showed an average radial compression of 1.8cm / year. The measured uplift was higher in the eastern and central part of the island with a maximum of 3.2 cm / year (figure 9.1). The following subsidence was higher in the north and southeast with a maximum of 5.6 cm / year (figure 9.2).

During the inflation phase, the calculated Mogi pressure source is located at halfway between Fumarole bay and Pendulum cove at 5.3 km depth (figure 9.1). However, when deflating better fits are obtained for a pressure source located further south at 7.8 km depth. Strain tensors were consistent with inflation (figure 9.1) and deflation (figure 9.2). The maximum shear strain (9.1e and 9.2e) show higher deformation in the southeastern part of the island, with maximum values of 4.8 μ strain / year and 7.2 μ strain / year respectively. In the horizontal extension contour maps considering the maximum and minimum values of each campaign (Figures 9.1f and 9.2f) opposite processes are observed in the two models. In Figure 9.1f, highest extension values are observed in the central and northwestern area, with a maximum value of 16.8 μ strain / year in those areas. Conversely, in the same region, the highest compression is located in figure 9.2f, of -11.2 μ strain / year.

5.4. INFLATION AND DEFLATION PROCESSES: 2012 TO 2018

Figure 10. Displacement and stress-strain maps for the sequence 2012-2013 to 2017-2018. 1) horizontal displacement, horizontal displacement velocity field expressed in cm / year, and the Mogi source location and depth estimation; 2) stress and strain tensors main axes, showing positive values indicating extension in the given direction in red, and negative values in blue, indicating compression in the given direction, expressed in μ Strain / year; 3) vertical displacement contour map given in cm / year; contour map with the horizontal dilatation values (4) and the maximum shear deformation modulus (5) given in μ Strain / year, considering the same scale for all the campaigns; 6) horizontal dilatation contour map considering the maximum and minimum values for each campaign.

Between July and November 2012 an important thermal anomaly was detected in the DECMAR tide gauge. This situation coincided with an inflation process in the island (Berrocoso et al., 2018). There was also an increment in seismicity, both in volcano-tectonic (VT) and long-period (LP) events, in the 2012-2013 campaign compared to the previous one (Almendros et al., 2015). The detected increase in seawater temperature, also observed in soil temperature, suggests a rapid and almost simultaneous increase in geothermal activity with the onset of caldera inflation and a greater number of seismic events observed in the following austral summer (Berrocoso et al., 2018).

The inflation process initiated in the 2012-2013 campaign and remained until the 2014-2015 campaign (Berrocoso et al., 2018). Following the 2014-2015 campaign the inflation process changed to deflation remaining during the next two campaigns. In 2017, a transitional mixed

phase was depicted with extension and a very small uplift. The extension process observable in figures 10a and 10b, had an average radial extension of 1.8 cm / year and 1.9 cm / year, respectively. The compression process represented in figures 10c and 10d, had an average radial compression of 2.3 cm / year and 1.9 cm / year, respectively. The transition mixed phase is seen in figure 10e, with an average radial extension of 1.3 cm / year radial. The Mogi source associated to the deflation processes is located in the center of the caldera at about 3.1 km depth. In the inflation processes the source is estimated at different depths, at 1.4 km (Figure 9a) or 5 km (Figure 10b). In figure 10e, convergence has not been obtained in the Mogi model.

In Figure 10, column 10.2 shows the main axes of the strain tensors. Positive values indicating extension in the given direction are shown in red (graphs 10 a, b, e). Negative values in blue indicate compression in the given direction, in $\mu\text{Strain} / \text{year}$ (graphs 10c and d). The third column shows the vertical displacement contour map given in cm / year, showing the same scale for all the campaigns. Figures 10 a, b and e show uplift in the vertical deformation, with a maximum deformation of 2.4 cm / year, 2.6 cm / year and 0.4 cm / year respectively, while figures 10c and d have a subsidence of 2.4 cm / year.

Figure 10, columns 10.4 and 10.6 show contour maps with horizontal strain values given in $\mu\text{Strain} / \text{year}$, considering the same scale for all campaigns, and considering the maximum and minimum values of each campaign, respectively. In figure 10, graphs 10.4 a, b and e show extension, and graphs 10.4 c and d show compression. Figure 9, column 9.6 shows higher extension in the central part of the caldera in graphs 10.6 a, b and e corresponding to inflation processes, with maximum values 11.6, 11.2 and 7.2 $\mu\text{Strain} / \text{year}$ in that region respectively. In the deflation processes, the highest inflation is observed in the island outer area, graphs 10.6 c and d, with maximum values of -9.6 and -6.0 $\mu\text{Strain} / \text{year}$ respectively. The maximum shear strain module given in $\mu\text{Strain} / \text{year}$ is presented in the fifth column. Higher shear strain is seen in Figure 10.5 a and c, with the highest values of these models being 7.2 and 5.6 $\mu\text{Strain} / \text{year}$. In the graphs 10.5 b, d and e the maximum shear strain is 2.8, 4.0 and 3.2 $\mu\text{Strain} / \text{year}$ respectively.

6. DISCUSSION

The ground-deformation velocities from 1991-1992 to 2017-2018 have two distinct periods: the period that includes the 1998 crisis and the continuous time series of yearly solutions from the 1999-2000 until 2017-2018 campaign. Ground-displacement velocities obtained in this first period show the inflation process that occurred on the island in the 1998 unrest, following the alignment of the Hero Fracture, perpendicular to the Bransfield Strait extension axis. Deformation models derived from the continuous time series, from 1999-2000 to 2017-2018, show two different behaviors in the horizontal and vertical components; inflation or deflation processes in the first, and uplift or subsidence in the second. The presented models suggest a coincidence in time of deflation and subsidence processes, while the inflation processes would coincide with uplift processes. In addition to these differentiated behaviors, transition processes also occur.

From 1999-2000 until 2003-2004 deflection is identified. This deflection period occurs after the 1998-1999 inflation and volcanic unrest. There is a change in the ground-displacement trend compared to the previous campaigns, during which the dominant extension was NE-SW, orthogonal to the Bransfield Basin NW-SE opening.

After this process, the observed displacements from the 2004-2005 campaign show the shift to an inflation process. This process is caused by the Hero Fracture zone geodynamics, and occurs in the NNW-SSE direction. Then, the island geodynamics changes again to a deflation process from 2007-2008 to 2009-2010. From 2009-2010 until 2012-2013 a transient processes of inflation followed by deflection with 1 year period culminates in detected seawater and soil temperature increases, increment of seismic activity and inflation that starts in the 2012-2013 campaign and continues until 2014-2015. From 2015-2016 until 2017-2018 deflation is identified. In the last campaign analyzed of 2017-2018, a new inflation process started.

The seismic activity of Deception Island has been monitored every austral summer since 1994 (Ibañez et al., 2000, Ibañez et al., 2003a, Carmona et al., 2012, Almendros et al., 2015, Almendros et al., 2018 Jimenez et al., 2018). A detailed description of the seismic activity occurred during the 1992 and 1998 crises was provided by Ibañez et al. (2000, 2003b). Whereas Carmona et al. (2012) and Almendros et al. (2015) presented an analysis of the seismicity registered from 1999 to 2011 and from 2009 to 2015, respectively. Recently, Almendros et al. (2018) showed a study of the volcanic crisis occurred during the 2014-2015 campaign. Throughout the campaigns, two types of seismic events have been detected: volcano-tectonic (VT) and long-period (LP) events. The inflation processes are related to the significant increase in seismic activity, while in the deflation processes a more moderate seismicity is detected.

During the 1991-1992 campaign there was a notable increase of the seismic activity, with a high number of recorded events, suggesting a volcano reactivation due to an injection of magma 2 km deep in the Fumarole Bay area (Ibañez et al., 1997). These evidences weaken at the end of January 1992. The displacements obtained from that period until the following campaign, 1995-1996, reflect this reactivation corresponding to an inflation process in the horizontal component, with an average radial deformation of 2.1 cm / year. In the vertical component a subsidence process is observed, with an average deformation of 2.6 cm / year. This disparity between inflation and subsidence indicates the process of change occurred on the island during that period.

At the beginning of 1999, there was a reactivation of the system characterized by a large number of VT and LP events registered mainly between Fumarole Bay and Telephone Bay (Ibañez et al., 2003a). The deformation observed on the island shows an inflation and uplift process, the most significant of those registered on the island until now. The average radial deformation was 5.2 cm / year in the horizontal component, and 5.5 cm / year in the vertical, values much higher than those recorded in the previous period. This reactivation of the system was due to an intrusion of magma (at 500 m depth) that produced volcano-tectonic earthquakes (Berrocoso et al., 2006b). The long period events could be the result of the interaction between the island shallow aquifers, and the intrusion of incandescent material. During the process continued 1992-1999, deformation acts as a volcanic activity precursor, showing an inflation process in the period 1992-1996, which culminates in the 1998 crisis process.

Since 1999, the level of seismic activity on the island has varied from low to moderate, with occasional peaks of activity during the 2003-2004, 2005-2006 and 2010-2011 campaigns. These peaks of higher seismic activity coincide with inflation processes. We have observed how the volcanic unrest periods are usually detected first by the geodetic network and afterwards by the seismic activity. For example, the inflation process that started in 2009 (figure 6k) and continued in 2010 (Fig. 6l), was not appreciated in the seismic records until the 2010-2011 campaign. The series of LP and VT events recorded in the 2005-2006 and 2006-2007

campaigns (figure 11a), and in the 2007-2008 and 2008-2009 campaigns (figure 11b), together with the respective ground-displacement velocities represent an inflation process (figure 11a), also showing a higher number of LP and VT events than a deflation process (figure 11b).

In the same way, the inflation process occurred in 2013 and 2014, was first detected thanks to the measured ground-displacement and afterwards by the seismic activity, that remained low until the 2012-2013 campaign. In fact, this inflation process started July-2012, registered in seawater and soil temperature increases, which suggested a rapid and almost simultaneous increase in geothermal activity with the onset of caldera inflation and a higher number of seismic events observed in the following austral summer (Berrocoso et al., 2018). Figure 12 shows the number of seismic events recorded between the 2011-2012 to 2014-2015 campaigns, as well as their corresponding ground-displacement velocities. This figure shows a peak of seismic activity in the 2012-2013 campaign, correlated with the beginning of an inflation process detected in ground-displacement. There were 650 LP and 65 VT recorded in one day in the 2012-2013 campaign, compared to the total of 20 LP and 4 VT detected in the previous campaign (Almendros et al., 2015).

In the following campaign, 2013-2014, there was a decrease in the number of recorded seismic events, while the inflation process continued (figure 12b). In the 2014-2015 campaign, the seismic activity is again very high, registering more than 9000 earthquakes of up to 4.6 magnitude located to the SE of Livingston Island for 8 months. This seismic unrest, that later propagated to Deception Island volcanic edifice, had a maximum of 1900 LP and 600 VT events registered in one day during the 2014-2015 campaign, numbers much higher than the previous campaign, with maximums of 300 LP and only 2 VT recorded in one day. The 2014 ground-displacement velocities (figure 12c) show that the inflation process continued, with an average radial displacement of 1.9 cm / year, very similar to the previous year of 1.8 cm / year. This volcanic unrest process was detected in continuous ground-displacements starting two campaigns before observed in the seismic records. While in seismicity the highest activity occurs during the 2014-2015 campaign, in deformation the highest activity begins in the 2012-2013 campaign, continuing until the 2014-2015 campaign. It is concluded that ground-displacement is a volcanic activity precursor, detecting the changes in volcano dynamics most times before the seismic activity begins in Deception Island.

After this last inflation process, a new deflation process begins on the island. This behavior was maintained from the 2014-2015 to 2016-2017 campaign, obtaining very similar ground-displacement values throughout the period. Initially, from 2014-2015 to 2015-2016 (Fig. 6q) there was an average radial ground-displacement of 2.3 cm / year, and 1.9 cm / year of average subsidence. Afterwards, from 2015-2016 to 2017-2018 (Fig. 6r), the radial ground-displacement was lower, of 1.9 cm / year and a subsidence of 1.6 cm / year. In 2017, between the 2016-2017 and 2017-2018 campaigns (figure 6s) there was a change to a new inflation process, with an average radial ground-displacement of 1.3 cm / year, and 0.2 cm / year of uplift.

Figure 11. Displacement and seismicity models registered during the 2005-2006 and 2006-2007 campaigns (a), and during the 2007-2008 and 2008-2009 campaigns (b). The upper part shows the displacement model corresponding to these campaigns, inflation-uplift (a), and deflation-subsidence (b). In the lower part, the events of long period LP (red) and volcano-tectonic events VT (blue) are represented. Seismic data taken from Carmona et al., 2012.

Figure 12. Number of seismic events recorded between the 2011-2012 and 2014-2015 campaigns (d), and their corresponding displacement models (a-c). The long period events LP (red) and volcano-tectonic events VT (blue) are represented. The increase in seismic activity during the 2012-2013 campaign is observed, correlated with the beginning of an inflation and uplift process in the corresponding displacement model (figure a). During the 2013-2014 campaign, there was a decrease in the number of registered seismic events, while the inflation and uplift process in the displacement model continued (figure b). During the 2014-2015 campaign the seismic activity is again very intense, reaching a maximum of 1900 LP events and 600 VT in one day. In the corresponding displacement model (figure c), the inflation process continues from the previous period, with an average radial displacement of 1.9 cm / year. Seismic data taken from Almendros et al., 2015.

Thus, volcanic activity in Deception Island has shown alternating periods of inflation - deflation of about 6 years since 1999 (Berrocoso et al., 2012) and similar periods of increase - decrease of seismic activity (Carmona et al., 2012; Almendros et al., 2018). Within its complex geodynamic environment, the island's volcanic activity is also influenced by the processes of tectonic NW-SE extension occurring in the Bransfield Basin and NE-SW alternating compression and extension and NW-SE shear processes occurring in the fault systems that accommodate the left-lateral component of the South Shetland Trench. These extension processes favor a higher level of hydrothermal activity, producing an increase in fluid temperature and magma degassing, manifested in the inflation processes.

The average ground-displacement from 2000 to 2018 relative to Livingston (figure 5b) shows the Bransfield Basin opening NW-SE continuous effect on ground-displacements of the geodetic benchmarks in Deception.

It is concluded that the island deformation is affected mainly due to the action of the two dominant fractures, one parallel to the Fracture of Hero, and another perpendicular to the previous one and parallel to the Bransfield extension axis. The inflation processes are caused by the Hero Fracture zone geodynamics, according to the NNW-SSE directions. The deflation processes are associated with the island main fracture activity, along the NE-SW direction, coinciding with the Bransfield Strait axis.

7. CONCLUSIONS

Monitoring of Deception Island's through GPS observations has been carried out since 1991-1992 until 2017-2018 thanks to the support offered by the Spanish Antarctic campaigns. For this purpose, a GPS geodetic network has been deployed, which consists of 15 geodetic stations distributed around Deception Island's inner bay, Port Foster (Figure 2). The reference benchmark for the differential GPS data processing was selected in Anvers Island, and to evaluate and remove regional tectonic ground-displacement an additional benchmark was selected in Livingston Island, both not influenced by Deception Island's volcanic activity (Figure 2). The average horizontal displacement of the island is ~1.95 cm / year towards the NE, and an average subsidence of 0.6 cm / year (Figure 5a). Deception Island has the same horizontal geodynamic behavior as Livingston Island (2 cm / year), although subsidence is lower (-0.12 cm / year) due to the volcanic activity of Deception Island (Figure 5a). With respect to the Antarctic Plate, Livingston and Deception islands show a displacement towards

the northwest of 11 mm / year and 8 mm / year, respectively. This behavior is a consequence of the Bransfield Rift expansion and the Phoenix Plate subsidence under the Antarctic Plate.

Deception Island volcanic inflation-deflation processes were shown by the evolution in time of the ground-displacement velocity, areal-strain, shear-strain, pressure source and maximum geodetic deformation models calculated for the period 1991-2018 (Figures 6, 7 and supplementary material). Thus, distinguished phases of inflation and deflation follow each other, separated by transition mixed phases. The inflation and deflation processes correlate with high and low seismic activity, respectively. The horizontal component of the mixed phases, extension without uplift and compression without subsidence, seems to be the precursor of the next phase, clearly differentiated from the inflation or deflation stages. Sometimes, transitional phases correspond to the NW-SE opening process of the Bransfield Basin rift with ground-displacement way from Livingston Island, i.e. towards the southeast (Figure 5b). The pressure sources, calculated using the Mogi model, have been located in the interior of Port Foster at an average depth of 3 km. For inflation processes, the Mogi pressure source is located near the Fumarole-Pendulum alignment. This alignment was identified to separate a central block from another to the north. A third block was also identified separating the central block from another to the south near Neptune's Bellows. These blocks may reflect the influence of main faults aligned NE-SW according to the Bransfield Basin orientation.

Two periods were separately studied: from the 1991-1992 until the 1999-2000 campaign and from the latter to the 2017-2018 campaign, mainly due to the increase in surveyed geodetic benchmarks and to the yearly campaigns possibility. The highest ground-displacement velocities and strain-tensors were detected as a consequence of the volcanic unrest occurred in January 1999 (figure 8.2). Ground-displacement from 1991 / 1992 campaign until 1995 / 1996 (Figure 8.1) show a transition mixed process with extension, although without clear uplift. Together with other examples, this can be interpreted as precursor to the increased seismic activity in December 1991 with felt earthquakes. The correlation with the seismic activity registered in both processes has been verified.

The second period, 1999-2018, initiates with the subsequent volcanic system relaxation that results in a deflation process (figure 6 c, d), followed by alternating inflation and deflation processes. The correlation between seismic activity and geodetic ground-displacement was analyzed in detail showing that in inflation processes there is an increase in seismic activity, while in the deflation there is a decrease. The inflation processes were preceded by a transition mixed phases, as well as deflation processes. This analysis suggests that transition mixed phases will occur before well-defined processes. In 2017 a transition mixed phase with extension, however without well-defined uplift was observed, being precursor to an inflation processes and therefore of significant importance to allow between campaigns forecast of Deception Island volcanic activity (Figure 12).

The correlation between the inflation processes with the increase of seismic activity and with the increase of the soil temperature makes that the previous transitional mixed phases have to be considered as precursor of a possible volcanic crisis of the Deception Island.

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Stations			Location		Number of observation days																	
PHASE I	BEGC	Gabriel de Castilla Base	3	75	83	54	71	73	69	82	66	79	52	84	58	31	74	69	71	76		
	PEND	Pendulum Cove	4	68	74	28	39	72	58	66	60	68	50	76	52	26	71	58	67	69		
	FUMA	Fumarole Bay	5	74	50	29	35	58	62	57	60	73	51	81	53	27	71	66	67	70		
	BARG	Argentinian Base	5	49	25	6	9	7	23	5	4	9	4	7	8	4	17	14	7	5		
	BALL	Whalers Bay	4	36	15	2		5	6	5	4	7	5	7	6	4	9	9	7	5		
	BEJC	Juan Carlos I Base	3	48	50	91	48	48	92	97	87	43										
PHASE II	BOMB	Bomb Field		3	4	3		5	7	4	4	6	4	16	8	4	7	6	10	5		
	COLA	Colatinas		11	8	6		5	9	11	5	5	4	5	7	4	8	6	10	8		
	CR70	Crater 70		13	4	3	9	5	6	6	5	5	4	14	6	7	7	6	7	7		
	GEOD	GEODEC		14	9	4	6	4	8	4	4	5	5	5	8	4	12	15	7	7		
	GLAN	Glaciar Negro		16		1		5	6	11	4	5	5	6	7	3	8	6	5	8		
	UCA1	Obsidian Valley		16	4	5		6	5	19	5	8	4	15	4	6	6	7	8	6		
	TELE	Telephone Bay		6	4	1		6	5	6	5	5	4	5	6	5	6	11	7	7		
PHASE III	GRAV	Gravimétrico						2			15	5	7	28	3	7	16	8	10			
	PUCO	Punta Collins						5	4	5	8	5	6	6	5	8	11	7	5			
	CECA	Cerro Caliente							4	2	8	8	9	33	4	7	29	11	8			
	STNE	Stonethrow Ridge									7	3	5	5	2	8	9	8	4			
	BEJ1	Juan Carlos I Base									40	75	87	59	32	79						
	BEJ2	Juan Carlos I Base											13	31	21	67	35	71	75			
			1999-00	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18		

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1001 Table 1. Number of observation days of the stations of the REGID network in each campaign.
 1002 The establishment of the network began in the 1989-1990 campaign, and three phases are
 1003 considered in its construction.

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Parameters of the Mogi sources					
Models	Longitude	Latitude	Depth (m)	DV (km ³)	R2
1995-1996	-60,642	-62,933	6750	0,0105	0,86
1999-2000	-60,641	-62,951	3776	0,0090	0,94
2006-2007	-60,655	-62,948	5304	0,0088	0,88
2008-2009	-60,639	-62,961	7807	-0,0195	0,72
2013-2014	-60,641	-62,953	1378	0,0012	0,79
2014-2015	-60,648	-62,937	6100	0,0097	0,91
2015-2016	-60,640	-62,957	3115	-0,0029	0,86
2016-2017	-60,639	-62,958	3125	-0,0025	0,88

Table 2. Parameters of the Mogi source for significant processes: 1995-1996, 1999-2000, 2006-2007, 2013-2014 and 2014-2015 inflation-uplift; 2008-2009, 2015-2016 and 2016-2017 deflation-subsidence. This table shows the location of the source (latitude-longitude), the depth, the volume change of the estimated magmatic chamber (DV), and the coefficient of determination R2 to evaluate the goodness of fit.

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1543	1039	APPENDIX
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1545	1040	<i>Figure A.1. Time series of Deception Island benchmarks with error bars. Easting component is</i>
1546	1041	<i>shown in blue diamonds, northing in red squares and height in green triangles. Time series are</i>
1547	1042	<i>plotted in meters, and error bars in tenths of millimeters.</i>
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2005-2006 / 2006-2007

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FUMA

PEND

BALL **BARG** **BOMB** **COLA**

CR70 **GEOD** **GLAN** **TELE**

UCA1

PUCO

CECA

STNE

SUPPLEMENTARY MATERIAL: Vertical displacement, superficial dilatation, maximum shear deformation module and geodetic deformation maximum modulus models from 1991 to 2018 of Deception Island.

The velocity displacement models, location of pressure sources models and stress-strain models from the 1991-1992 to the 2017-2018 campaigns are presented in the main text. Moreover, the most representative processes of this period are analysed in detail: the 1998 volcanic crisis, representative models of inflation-uplift (2005-2007) and deflation-subsidence processes (2007-2009), and the inflation-uplift and deflation-subsidence processes from 2012 to 2018. Below models obtained from estimated deformation parameters are presented. These are vertical displacement, superficial dilatation (inflation-deflation), maximum shear deformation module and geodetic deformation maximum modulus in Deception Island's environment.

Strain and stress tensors are determined from the velocity field estimate, obtained through interpolation processes for the horizontal displacement vectors. For this, a regular mesh of 10 x 10 points has been defined. Null displacements are considered in those points outside the mesh, constraining the existing deformation to the interior of the region covered by the mesh. The established interpolation criterion is based on the distance of the points of the mesh to the observation points. For the network internal points, the closest points with observed data are used, defining triangles. The estimated deformation parameters are vertical displacement, superficial dilatation (inflation-deflation), maximum shear deformation module and geodetic deformation maximum modulus in the Deception environment.

Figure S.1 shows the horizontal velocities field multi-screen, in cm / year, obtained through interpolation processes for the horizontal displacement vectors. Figure S.2 shows the vertical displacement contour maps (in cm / year) from the 1991-1992 to the 2017-2018 campaign. The same scale is considered for all campaigns. Figure S.2b shows the highest elevation, with an average of 5.5 cm / year, as a consequence of the 1998 crisis. The highest subsidence is observed in graph S.2j, of 2.7 cm / year on average, corresponding to a deflation process in the horizontal component, with an average radial deformation of 1.9 cm / year. Figure S.3 considers vertical displacement maximum and minimum values for each campaign, to highlight the contrasts between the different areas of the island.

Figure S.4 shows a multi-screen with the contour maps (in μStrain / year) with the horizontal dilatation values from the 1991-1992 to the 2017-2018 campaign. The same scale is considered for all campaigns. The # graph indicates the characteristics shown in the multi-screen graphs.

The highest dilatation is observed in graph A.4b due to the volcanic crisis of 1998, with values between 24.8 and 27.2 μstrain / year. In addition, the graph S.4h shows high values of horizontal dilatation, between 12.0 and 16.8 μstrain / year, due to the expansion process occurred in that period, but lower than the values in figure S.4b. The minimum expansion values are obtained in S.4 j, q, and r, with an average of -10.2, -11.0 and -8.2 μstrain / year respectively, corresponding to a deflation processes in the horizontal component. Figure S.5 shows contour maps with the horizontal dilatation values considering the maximum and minimum values of each campaign. In the deflation processes (Fig. S.5 j, q, and r) the smallest dilatation is located in the island inside, and the highest values in the exterior, with an average difference of 3 μstrain / year between these regions. Conversely, in inflation processes (Fig. S.5 h, o and p) the highest dilatation is located in island interior, with an average difference of 4

$\mu\text{strain} / \text{year}$ with respect to the island exterior. Figure S.5b, inflation, differs from this norm due to the lack of stations in the north of the island.

Figures S.6 and S.7 show the contour maps with the maximum shear deformation values modulus and the maximum geodetic deformation values respectively, given in $\mu\text{Strain} / \text{year}$. The highest shear values are observed in graph S.6b due to the 1998 volcanic crisis, with a maximum deformation of $13.2 \mu\text{strain} / \text{year}$. From this process and until the 2005-2006 campaign (Fig. S.6g), higher shear deformation is calculated in the island west-southwest area. From the graph S.7h and until the period 2017-2018, the highest shear deformation is located in the island southeast. With respect to the maximum geodetic deformation, the highest deformation is obtained in the 1998 crisis (Fig. S.7b), with values between 18.4 and $20.0 \mu\text{strain} / \text{year}$. After this process, the highest values are observed in the A.7h inflation models (between 8 and $9.6 \mu\text{strain} / \text{year}$) and S.7o (from 5.6 to $8.8 \mu\text{strain} / \text{year}$), and in the S.7k deflation models (2.8 to $5.2 \mu\text{strain} / \text{year}$) and S.7q (between 5.6 and $8.4 \mu\text{strain} / \text{year}$).

Figure S.1. Horizontal displacement models, horizontal velocity field (in cm / year), and location and estimated depth of the Mogi source, from the 1991-1992 to 2017-2018 campaign. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign. The Mogi model converges in those periods in which the volcanic activity is greater, and in which the deformation process is clear. This occurs in the graphs a, b, h, j, o, p, q and r. The parameters of these models are shown in table 2. The # graph indicates the characteristics shown in the multi-screen graphs.

Figure S.2. Vertical displacement contour maps (in cm / year) from the 1991-1992 to the 2017-2018 campaign. The same scale is considered for all campaigns. The # graph indicates the characteristics shown in the multi-screen graphs. Positives values in vertical displacement are shown in red, and negative values in blue. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign. The different behaviours observed for the island, uplift or subsidence in the vertical component, coincide with inflation or deflation processes in the horizontal. Graph b shows the highest elevation, as a consequence of the 1998 crisis. The highest subsidence is observed in j, corresponding to a deflation process in the horizontal component.

Figure S.3. Vertical displacement contour maps (in cm / year) from the 1991-1992 to the 2017-2018 campaign. Each campaign maximum and minimum values are considered. The # graph indicates the characteristics shown in the multi-screen graphs. High values are shown in red and low values in blue. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign.

Figure S.4. Contour maps with the horizontal dilatation values (in $\mu\text{Strain} / \text{year}$) from the 1991-1992 to the 2017-2018 campaign. The same scale is considered for all campaigns. The # graph indicates the characteristics shown in the multi-screen graphs. High values are shown in red and low values in blue. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign. The highest dilatation is observed in b due to the

1998 volcanic crisis. In addition, graph h shows high values of horizontal dilatation due to the inflation process that occurred in that period. The minimum dilatation values are obtained in the graphs j, q, and r corresponding to deflation processes in the horizontal component.

Figure S.5. Contour maps with the horizontal dilatation values (in $\mu\text{Strain} / \text{year}$) from the 1991-1992 to the 2017-2018 campaign. The maximum and minimum values of each campaign are considered. The # graph indicates the characteristics shown in the multi-screen graphs. High values are shown in red and low values in blue. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign. In the deflation processes (j, q, and r) it is observed that the smallest dilatation is located in the interior of the island, and the highest values in the extremes. Conversely, in inflation processes (h, o and p) the highest dilatation is located in the interior of the island. The graph b, inflation, differs from this norm due to the lack of stations in the north of the island.

Figure S.6. Contour maps with the maximum shear deformation modulus values (in $\mu\text{Strain} / \text{year}$) from the 1991-1992 to the 2017-2018 campaign. The # graph indicates the characteristics shown in the multi-screen graphs. High values are shown in pink and low values in white. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign. The highest shear values are shown in graph b, due to the 1998 volcanic crisis. From this process until the 2005-2006 campaign (g), higher shear deformation is obtained in the west-southwest area of the island. From the graph h and until the last campaign, 2017-2018, higher deformation in shear is located in the southeast area of the island.

Figure S.7. Contour maps with the maximum geodetic deformation values (in $\mu\text{Strain} / \text{year}$) from the 1991-1992 to the 2017-2018 campaign. The # graph indicates the characteristics shown in the multi-screen graphs. High values are shown in blue and low values in white. Two periods are distinguished: the period before the 1998 crisis (graphs a and b) corresponding to an inflation-uplift process; and the continuous time series from the 1999-2000 to 2017-2018 campaign. The highest deformation is obtained in the 1998 crisis (b). After this process, the highest values are observed in the graphs h and o (inflation), and k and q (deflation).