**Inclination and heterogeneity of layered geological sequences influence dike-induced ground deformation.**

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**ABSTRACT**

Constraints on the amount and pattern of ground deformation induced by dike emplace­ment are important for assessing potential eruptions. The vast majority of ground deforma­tion inversions made for volcano monitoring during volcanic unrest assume that dikes are emplaced in either an elastic half-space (a homogeneous crust) or a crust made of horizontal layers with different mechanical properties. We extend these models by designing a novel set of two-dimensional finite-element method numerical simulations that consider dike-induced surface deformation related to a mechanically heterogeneous crust with inclined layers, thus modeling a common geometry in stratovolcanoes and crustal segments that have been folded by tectonic forces. Our results confirm that layer inclination can produce localized ground deformation that may be as much as 40× higher in terms of deformation magnitude than would be expected in a non-layered model, depending on the angle of inclination and the stiffness of the rock units that host and are adjacent to the dike. Generated asymmetrical deformation patterns produce deformation peaks located as much as 1.4 km away from those expected in non-layered models. These results highlight the necessity of accurately quantify­ing both the mechanical properties and attitude of the geology underlying active volcanoes.

**INTRODUCTION**

Volcanic eruptions can occur when a magma-filled fracture (a dike, sill, or inclined sheet) propagates from a magma source through the crust to the surface (Rivalta et al., 2015, Acocella, 2021). Magma emplacement deforms the crust, resulting in surface uplift or subsidence signals that can be measured and used to infer information about intrusion depth, volume, shape, and orientation and which may be useful for determining potential eruption characteristics (Geshi et al., 2020). However, the vast majority of models used in volcano monitoring to infer the deformation associated with magmatic emplacement assume that the crust is either isotropic (an elastic half-space) (e.g., Okada, 1985; Mantiloni et al., 2020) or mechanically stratified with horizontal layers (Masterlark, 2007; Bazargan and Gudmundsson, 2019, 2020). Both assumptions are likely sim­plifications, especially in areas where volcanoes are built atop highly folded and deformed rocks, such as in cordillera settings (Clunes et al., 2021). In addition to inclined layers underlying a volcano that may dip either outward or inward toward the volcano center, the slopes of the upper parts of many stratovolcanoes are inclined by as much as 42° (Gudmundsson, 2012; Grosse et al., 2014). In both of these situations, it is not reasonable to always assume that dikes propa­gate through solely horizontal layers. It is also now well known that rock layers that constitute a volcano may vary considerably in terms of their mechanical properties (Maccaferri et al., 2010; Drymoni et al., 2020; Heap et al., 2020; Gudmundsson, 2020). Given these observations, it is perhaps likely that most dikes are emplaced in heterogeneous crustal segments with layers that are somewhat inclined, even in extensional settings albeit the layer inclination may be minor or close to horizontal near the surface (e.g., Gud­mundsson, 1983). Therefore, it is necessary to constrain the deformation signals associated with both heterogeneous and inclined layered sequences and compare the differences asso­ciated with commonly used simplified crustal assumptions. There have been attempts to con­strain the crustal stress field (e.g., Gudmunds­son, 2006) and deformation (e.g., Manconi et al., 2007; Masterlark, 2007) associated with magma chamber inflation using either a simple dipping sequence in Iceland (Gudmundsson, 2006) or horizontal heterogeneous layered sequences (Masterlark, 2007). Masterlark (2007) demon­strated using a combination of analytical and finite-element models that the widely used Mogi (1958) model, which considers a point-pressure source embedded in a homogeneous, isotropic segment, can generate substantial displacement prediction errors and significantly inaccurate deformation source parameters if the crustal unit is heterogeneous. In that work, the presence of weak layers in a caldera resulted in a deformation source located >1 km deeper compared to the source depth obtained using the elastic half-space assumption. Bazargan and Gudmundsson (2019, 2020) analyzed both the stresses and dis­placements generated at the surface by dikes and inclined sheets intruding horizontally layered rocks. They showed that the presence of compli­ant layers (with low Young’s modulus) increases the surface deformation expressed during dike or inclined-sheet emplacement and that intrusions meeting layered sequences at lower angle gen­erates larger surface displacements. Although significant progress has been made in volcano monitoring in the past decades (Gudmundsson et al., 2022), we still cannot yet forecast with any certainty when and where a magmatic dike will emplace or erupt. This becomes further complicated in highly deformed crustal settings such as the Andes where the host rock is com­monly formed by rock layers inclined at differ­ent angles, in part because understanding of the role of crustal properties and geometry through which the dikes propagate is lacking. We pres­ent a series of novel two-dimensional numerical models using the finite-element method (FEM) that consider dike-induced ground deformation resulting from a crustal segment hosting contrasting mechanical properties and with variably dipping layers.

**NUMERICAL MODEL SETUP**

The FEM software COMSOL Multiphysics 5.4 (https://www.comsol.com/release/5.4) was used to analyze dike-induced surface displace­ments in a layered crustal segment comprising either horizontal or inclined layers (Figs. 1A and 1B). The dimensions of the layered crustal segment hosting the dike were 20 km wide × 20 km deep, tested as being sufficient to avoid boundary effects (Figs. S1 and S2 in the Supplemental Material1). The dike was mod­eled as an elliptical cavity of 1 m thickness, and its geometry and location in the model domain was varied by changing both the dike length and emplacement depth between 1, 2, and 4 km. The crustal segment hosting the dike was modeled as a linear-elastic solid because the primary inter­est was the influence of elastic properties on ground deformation. The inclined layers, with contrasting elastic properties (Young’s modulus ratios), were made to dip by 10°, 25°, and 45°. Both the upper and lower layers were assigned alternating Young’s modulus of either 1, 10, or 100 GPa such that four stiffness ratios were examined between the different models, 100:1, 10:1, 1:10, 1:100, where the first number relates to the layer hosting the dike (Young’s modu­lus *E*1) and the second to the layer above the dike (*E*2). These stiffness values were chosen to encompass a wide range of rocks, such as compliant pyroclastic rocks and stiff lava flows (Gudmundsson, 2011). To compare our results with the more common modeling protocol, we also tested a horizontally layered sequence using the aforementioned contrasting elastic proper­ties and a non-layered crustal segment with only one Young’s modulus of 50 GPa. The only boundary load in the model comes from an inter­nal magmatic overpressure (*P*o) of 5 MPa. The upper boundary of the model is a free surface, and it is along this surface that the horizontal and vertical displacements were measured. The other boundaries of the model are fixed, indi­cated by crosses in Figures 1A and 1B, so as to avoid rigid-body translation and rotation. The dipping layers are always located in the right-side of the crustal segment starting at the center of the domain, above the dike tip. More informa­tion about the modeling setup is provided in the Supplemental Material.

**VERTICAL GROUND DISPLACEMENTS**

Figure 2 presents profiles of vertical ground displacement (*u*z) induced by a 2-km-long dike with its upper tip emplaced at 2 km depth. Results from other models are provided in Figures S4–S19. In both the non-layered and horizontally layered models, *u*z is symmetri­cally distributed and peaks between ∼2.4 km and ∼4.8 km on either side of the dike (Fig. 2). The vertical ground displacement becomes asymmetrically distributed when the inclined layers are modeled, and the magnitude of ver­tical deformation becomes greater with lower Young’s modulus ratios (Figs. 2B and 2D).

When the layer hosting the dike is stiffer than the inclined layer, the vertical displacements are greatest in the layer above the dike (Figs. 2A and 2C). Conversely, when the layer hosting the dike is more compliant than the upper layer, *u*z is greatest in the layer hosting the dike (Figs. 2B and 2D). In this case when the inclined layer is stiff, the asymmetric deformation is more pro­nounced when the stiffness contrast is great­est (i.e., 1:100 rather than 1:10). Under these conditions, the maximum peak of *u*z is located as much as 1.4 km (in the 45° model) farther away from the dike than compared with the non-layered model. However, the opposite is found when the inclined layer is compliant such that the larger stiffness contrast (100:1) demon­strates a more symmetrical deformation pattern than the lower stiffness contrast (10:1). When the upper layer is compliant, the amount of *u*z increases with layer inclination. For example, in the 10:1 case (Fig. 2C), for the upper layer dipping at 45° the maximum *u*z is 19 cm, at 25° is 16.3 cm, and at 10° is 13.5 cm. The opposite pattern is observed when the upper layer is stiff, such that the amount of *u*z decreases with layer inclination. For example, in the 1:10 case with the layer dipping at 10° the maximum vertical displacement is 83 cm, at 25° is 51 cm, and at 45° is 29 cm (Fig. 2D).

**HORIZONTAL GROUND DISPLACEMENTS**

Figure 3 reports horizontal ground displace­ments (*u*x) of the model domain for the Young’s modulus ratios tested where the position of the center of the dike is again marked at zero. In both the non-layered and horizontally layered models, the *u*x is symmetrically distributed and peaks between 4.4 km and 7 km on either side of the dike. In these results, the component of horizontal displacement is oriented with respect to the center of displacement above the dike, such that negative horizontal displacement sim­ply represents ground movement in the opposite direction with respect to the positive values. In all cases, the overall deformation signal is extensional, such that each side of the model domain above the dike moves away from the other, as expected during dike emplacement. However, when the modeled layers are inclined, the amount of *u*x is different above the area with the inclined layer than the area without the layer and so the extension is asymmetric. This effect is most pronounced when the inclined layer is stiffer than the layer hosting the dike (Figs. 3B and 3D). In this case, the maximum peak offset is located 2.4 km farther away compared to the horizontally layered model for an inclination of 10° and 1.1 km farther away from the non-lay­ered model for an inclination of 45°. When the inclined layer is compliant (Figs. 3A and 3C), the amount of *u*x recorded over the inclined layer increases with layer inclination. For example, in the 10:1 case (Fig. 3C), with the layer dip­ping at 45° the maximum *u*x is 29.1 cm, at 25° is 25.1 cm, and at 10° is 19.9 cm. As observed for vertical ground deformation, the amount of horizontal surface deformation recorded over the inclined layer decreases with layer inclination when the layer above the dike is stiff. This effect is more pronounced when the stiffness ratio is 1:10 as observed in Figure 3D. In this case, the maximum horizontal deformation with the layer dipping at 10° is 42.2 cm, at 25° is 34.6 cm, and at 45° is 25.6 cm.

**DISCUSSION AND CONCLUSION**

Our results indicate that for any study attempting to invert ground deformation mea­surements to determine dike emplacement pro­cesses, it is necessary to constrain, as best as possible, both the mechanical properties of the geological units and their attitudes, especially the amount by which the layers dip. Figure 4 shows the change in vertical and horizontal ground deformation with respect to the non-layered cases recorded for each tested stiffness ratio and layer inclination. The comparison highlights that layer inclination in the stiff-to-compliant setup (high *E*1, low *E*2) is a principal contributor to increasing surface deformation, while in the compliant-to-stiff setup (low *E*1, high *E*2) is a principal contributor to decreas­ing surface displacement. A series of model fits describe the relationship between changes in ground displacement, layer inclination, and stiff­ness ratios. We suggest that when the geology of a volcanic zone is well characterized in terms of the rock mechanical properties and attitudes, it should be possible to derive a similar series of curves so as to be able to estimate the contribu­tion of the component of ground deformation associated specifically with the layered sequence amplification effect reported.

Our numerical results can be explained by considering the area of the different modeled rock layers which in nature are represented as rock volumes. The angle at which each individ­ual unit dips would alter the amount of deform­able available material because the area of the upper layer changes depending on the angle of inclination (Fig. 4C). The displacement amount increases or decreases because the area of the stiff layer reduces or increases with respect to the area of the compliant layer. As we show in our results, the larger the area of the stiff unit, the less the deformation and vice versa, and in these simplistic models it is the angle of inclination of the contact between the units that controls the area. It is then expected, and quantifiable, that the area over which compli­ant or stiff rocks are located would deform more or less as a function of both the rocks’ Young’s modulus and area. In nature, the calculation of layer areas would likely be more complex and involve multiple layers, but the physical processes described here remain. Fur­ther work should aim to fully characterize both the mechanical properties and layer geometries of crustal zones hosting volcanoes in order to delineate their relative influence on recorded surface displacements.

Our models have shown that the combination of mechanical heterogeneity (e.g., Masterlark, 2007) and layer inclination can substantially alter dike-induced ground deformation signals, which can become highly asymmetric and as much as 40× different than if assuming a homogeneous elastic half-space model. The asymmet­ric ground deformation profiles demonstrated are similar to those generated in other numerical and analogue models of inclined-sheet emplace­ment (e.g., Kavanagh et al., 2018; Bazargan and Gudmundsson, 2020). This suggests that it is equally important to consider the geometry of the rock units into which a magmatic intru­sion emplaces as well as the intrusion geom­etry because similar deformation signals could be generated by vertical or inclined intrusions depending on the presence of an inclined and stratified layered sequence. While in our models the ground surface is flat, further complexities may arise when introducing both topography (e.g., Trasatti et al., 2003; Johnson et al., 2019) with layer inclination, and so this should be further investigated. Other studies (e.g., Magee et al., 2017; Poppe et al., 2019) have shown that deformation can be partly accommodated by fractures surrounding magmatic intrusions, which also influence surface deformation sig­nals. We do not consider such dislocations or inelastic deformations, but combined with the data presented here, they further highlight the need to accurately characterize crustal structure to correctly determine intrusive processes. Fur­thermore, Masterlark (2007) suggested that dif­ferences in Poisson’s ratio between layers can alter deformation signals by as much as 40%, and so combining such properties into inclined layer models may also be of value. Ultimately, to test such models, more must be known about the stratigraphy underlying volcanoes and the varia­tion in mechanical properties of the geological units (e.g., Kendrick et al., 2021). Our mod­els could be tested using analogue techniques (e.g., Kavanagh et al., 2018), and a dedicated volcano deformation study combining these data with ground displacement measurements is paramount.

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Diagrama

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**Figure 1. (A) Finite-element method model setup for various layer inclinations tested (*L*—dike length; *T***D**—dike thickness; *D*—upper dike tip depth; *P***o**—magmatic overpressure; θ—layer inclination; *E***1**, *E***2**—layer Young’s modulus). Crosses mark fixed boundaries. (B) Horizontally mechanical layered model setup. (C) Example of model mesh with layers inclined at 25°. (D, E) Field photographs of dikes emplaced in dipping rock units from Santorini volcano (Greece) and the Andes (Chile), respectively. B and C are not to scale.**

Gráfico, Gráfico de líneas

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**Figure 2. Vertical ground displacement (*u***z**) variations relative to lateral distance from the dike tip for each layer inclination (θ) and stiffness ratio (*E***1**:*E***2**, where *E***1 **is Young’s modulus of the layer hosting the dike and *E***2 **is that of the layer above the dike) tested.**

Gráfico

Descripción generada automáticamente

**Figure 3. Horizontal ground displacement (*u***x**) variations relative to lateral distance from the dike tip for each layer inclination (θ) and stiffness ratio (*E***1**:*E***2**, where *E***1 **is Young’s modulus of the layer hosting the dike and *E***2 **is that of the layer above the dike) tested.**

Interfaz de usuario gráfica, Gráfico, Aplicación

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**Figure 4. (A, B) Changes in vertical (Δ*u***z**) and horizontal (Δ*u***x**) displacement in percentages with respect to the non-layered model for each layer inclination (θ) and stiffness ratio (*E***1**:*E***2**, where *E***1 **is Young’s modulus of the layer hosting the dike and *E***2 **is that of the layer above the dike) tested. Model fits for each data set are shown allowing comparison between θ and Δ*u***z **or Δ*u***x**. Each individual model fit presents *R***2 **> 0.95. (C) Diagrams showing the area ratio in percentages between the modeled crustal segments for different angles of inclination.**