Kinematic Evolution of a Transcurrent Fault Propagating Through Consecutive Volcanic Cones: a Case of Rheology and Separation

Kinematisk utveckling av en strike-slip-förkastning propagerande genom på varandra följande vulkaniska koner: en studie i reologi och separation

Jaime Eduardo Cadeias de Araújo Moreira de Almeida
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Abstract

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Jaime Almeida

The main objective of this work is to test the effect of two conical-shaped positive topographic obstacles on propagation of a discrete basement dextral strike-slip or transcurrent fault. A set of sandbox analogue (physical) models was constructed, in which two consecutive sand cones were placed progressively closer to each other. Key structural and strain parameters, such as axial strain ratios and angular strain, as well as the width and direction of the basins which formed during deformation were measured and analyzed. This procedure was then repeated with a basal decoupling layer of PDMS beneath each cone, to test the influence of this layer on the deformation.

The results show that, for models without a basal decoupling layer, the distance between the two cones governs the end-stage deformation patterns of the topographic obstacles. The proximity of the topographic obstacles causes an increase of their deformation, i.e., results in higher axial strain ratios and angular strain. This effect is particularly noticeable in the first obstacle, which is affected by a strong clockwise rotation. The basal ductile which partly decouples the basement fault from the cover units nullifies the previous effect (the increase in deformation caused by proximity) and, when present, localizes the deformation by not only producing narrower pull-apart basins within the obstacles but also by increasing their rotation.

Keywords: Strike-slip, transcurrent, obstacles, deformation, rheology, separation

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Resumo

Evolução cinemática de uma falha de desligamento propaganda através de cones vulcânicos consecutivos: um caso de reologia e separação
Jaime Almeida

O objectivo deste trabalho foi o de estabelecer os efeitos de uma única falha de desligamento direito em dois obstáculos cónicos consecutivos, de relevo positivo. Adicionalmente, procura-se estabelecer o efeito que uma camada basal dúctil poderá ter na deformação dos obstáculos.

Como tal, uma série de modelos análogos foram efetuados onde dois cones de areia consecutivos foram colocados sistematicamente mais próximos um do outro. Durante estas experiências, parâmetros chave de natureza estrutural e de strain foram medidos, tais como os rácios de strain axial e angular, bem como a direção e largura das bacias formadas. Este procedimento foi repetido com uma camada basal de silicone (PDMS) colocada por baixo dos obstáculos. Os resultados mostram que, para modelos sem a camada de silicone basal, a distância de separação dos cones tem uma influência muito forte no produto final da deformação nos cones. A proximidade dos obstáculos causa um aumento da deformação (ex. valores mais elevados de strain angular e strain axial) em ambos os obstáculos. Este efeito é particularmente visível no primeiro obstáculo, sendo este afetado por uma rotação no sentido dos ponteiros do relógio mais elevada que o segundo.

Por fim, verifica-se que a presença da camada basal dúctil nulifica o efeito anterior e, quando presente, focaliza a deformação, não só criando bacias de pull-apart mais estreitas mas também causando uma maior rotação nos obstáculos.

Palavras-chave: Desligamento, transcurrência, obstáculos, deformação, reologia, separação

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Populärvetenskaplig sammanfattning

Kinematisk utveckling av en strike-slip-förkastning propagerande genom på varandra följande vulkaniska koner: en studie i reologi och separation
Jaime Almeida


Resultaten visar att avståndet mellan de två konerna bestämmer hur den slutgiltiga deformationen av hindrena ser ut för modeller där konerna är i direkttillkommnad med underlaget. Ju närmre de topografiska hindrena är desto kraftigare blir deformationen, dvs dess närhet till varandra resulterar i högre stress såväl längs med som vinkelrätt mot förkastningen. Effekten är tydligast i det första hindret som påverkas av en kraftig rotation med sols. Vid närvaron av PDMS kopplas de topografiska hindren delvis bort från den underliggande simulerade berggrunden vilket upphäver effekten av avstånd mellan de topografiska hindren. När PDMS är närvarande blir pull-apart-försökningarna som bildas inne i hinder småare och deras rotation ökar. (Översättning: Holger Jacobson)

Nyckelord: Strike-slip-förkastning, transcurrent, hinder, deformation, separation, reologi

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1. Introduction

Strike-slip fault zones, or shear zones, are one of the most common features of the lithospheric deformation. They are considered to be heterogeneous deformation bands (Fossen, 2010) and can vary in size from microscopic scale, e.g. shear-cleavage systems (Passchier and Trouw, 2005), to plate boundary systems, e.g. San Andreas Fault (Wallace, 1990) or the Gloria Fault Zone (Argus et al., 1989; Rosas et al., 2014).

During the past century, countless different types of analogue models of strike-slip deformation have been performed, stemming from the simple Riedel shearing experiments. Although plenty strike-slip deformation models have been performed (Sylvester, 1988; Richard, Naylor and Koopman, 1995; Dauteuil and Mart, 1998; Schrank, 2009; Dooley and Schreurs, 2012), very few focus on the mechanics of obstacle interference. Previous works on this topic cover the interference of the Gloria Fault Zone on the Tore-Madeira Rise (e.g. Rosas et al. 2014) or the deformation of a single symmetrical volcano (e.g. Norini & Lagmay 2015).

This particular study uses a single large strike-slip on two identical consecutive volcanic cones, modeling the influence that the presence of one cone has on the deformation of the other and vice-versa. Additionally, the same influence will also modeled in order to constrain the impact that a rheological anomaly, here represented by a basal ductile layer may have on the system. The main objective will be to attempt to observe a systematic difference between models with a ductile layer and models without. Such difference would prove without doubt that an interaction between the two obstacles exists.

To that extent, two identical sand cones were placed at systematically closer distances to each other above a single discontinuity created by the separation of the two sidewalls. This procedure is then repeated with a thin basal layer of silicone placed beneath the extent of the two cones. This method is further described in section 4.1 – Experimental procedure.

This work mostly focuses on oceanic lithospheric analogues namely oceanic islands with well-developed volcanic cones, allowing for not only avoiding modeling of highly complex reworked continental lithosphere but also the use of a single material (dry quartz sand) to reproduce the modelling area. Oceanic lithosphere, from a deformation point of view, has little variety in the types of response to the stresses that are imposed to it. Vertically, it is composed by mostly identical brittle basalt with occasional zones of ductile basalt, formed by thermally active zones. By contrast, the continental lithosphere has very different types of responses to deformation, ranging from weak sediments to very tough granites. As such, this work focus mainly on oceanic lithosphere, allowing for the use of only two different materials, sand (simulating the brittle portions) and silicone (simulating the ductile areas). It is worth noting that all models are simplifications of natural complexity. In this case, the small vertical variation of oceanic lithosphere lithologies are simulated by a single material.
2. Materials and methods

This work was conducted using analogue modeling. This method consists of a simplification of the complex natural behaviors within a laboratory by means of simple and at-hand materials, such as sand or silicone putties. This translates into a very easy way to model that does not entail highly complex numerical simulations and elevated computing power. For the present work, it was chosen as a simple way to study the deformation dynamics in a complex situation.

Experiments were performed using dry quartz sand or dry quartz sand and silicone putty (polydimethylsiloxane or PDMS for short). Dry quartz sand is a classical material used for simulating brittle upper lithosphere compositions and oceanic lithosphere in several works over the past century and is considered to deform according to the Coulomb-Mohr failure criterion. The second material (PDMS) is also a classical material used for simulating thermally active upper lithosphere, lower lithosphere or any sort of material that flows with high degrees of viscosity.

In order to ensure a close similarity to nature, the model was scaled following the principles expanded upon in Hubbert (1937). The “scaling” of a model is performed by creating ratios between the model properties and the properties of a natural example. These ratios are interdependent and, as such, require balancing to be considered accurate. Finally, some ratios can be impossible to determinate due to a lack of information or modelling abilities (such as the use of a motor or centrifuge).

To that effect, three possibilities exist for scaling, with increasing complexity and accuracy:

a) Geometric scaling, where the lengths and basic properties of the model (density, mass, viscosity) are scaled to a possible natural example;

b) Kinematic scaling, where all previous properties and the velocities of the model are scaled to a possible natural example;

c) Dynamic scaling, where all previous properties and all forces involved in the deformation are scaled to a possible natural example.

Since the models performed in this work are hand-driven (i.e. moved by hand) it was impossible to accurately scale the velocity of displacement with a natural example. Additionally, since the models were not run using a proper gravitational scaling, it would be impossible for them to be dynamically scaled. As such, this is a geometrically scaled exploratory work that lays the ground for further improvements.

This relationship between model and natural analogue was calculated using the properties for the materials used that were measured during the experimental work for the Tectonics course (taken in Uppsala University) as well as my own constrains for the model, such as the height and density of the natural example.

For this type of model, i.e., without using a centrifuge, the acceleration ratio ($A^*$) is considered to be 1 as the gravity acceleration is identical for the model ($g_m$) and nature ($g_n$):
\[ A^* = \frac{a_m}{a_n} = \frac{g_m}{g_n} = 1 \]  

(1)

For the calculation of the length ratio \( (L^*) \), it was considered that the 3.4 cm of sand used for the model would simulate a 7km high volcano on the ocean floor (similar to an ocean island):

\[ L^* = \frac{l_m}{l_n} = \frac{3.4}{7 \times 10^5} = 4.86 \times 10^{-6} \]  

(2)

The density ratio \( (\rho^*) \) was attained by simply dividing the calculated density of the dry sand (1700 kg/m\(^3\)) by the density of normal oceanic lithosphere (2900 kg/m\(^3\)):

\[ \rho^* = \frac{\rho_m}{\rho_n} = \frac{1700}{2900} = 0.59 \]  

(3)

Using these empirical values, the mass ratio \( (M^*) \) is derived:

\[ \rho^* = \frac{M^*}{L^*^3} \quad (=) \quad M^* = \rho^* \times L^*^3 \quad (=) \quad M^* = 6.72 \times 10^{-17} \]  

(4)

When calculating the Ramberg number for this setup (Ramberg, 1981), it was verified that the model would be close to being dynamically scaled (equations 5-6) as both values were fairly close to each other, within the same order of magnitude. The lack of a velocity scaling makes it impossible to be dynamically scaled, rendering this measurement quite dubious.

\[ R_{model} = \frac{\rho_{model} \times L_{model} \times g_{model}}{\sigma_{model}} = 1054.4 \]  

(5)

\[ R_{nature} = \frac{\rho_{nature} \times L_{nature} \times g_{nature}}{\sigma_{nature}} = 663.8 \]  

(6)

These properties are summarized in Table 1.
Table 1. Material properties and scaling for the sandbox model.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Dry quartz sand</th>
<th>Natural analogue</th>
<th>Ratio: Model/Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (%)</td>
<td>&gt;99.0% SiO₂</td>
<td>Oceanic lithosphere</td>
<td>-</td>
</tr>
<tr>
<td>Grain shape</td>
<td>Well-rounded</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1700</td>
<td>2900</td>
<td>ρ* = 0.59</td>
</tr>
<tr>
<td>Angle of internal friction (°)</td>
<td>30-36</td>
<td>Variable</td>
<td>-</td>
</tr>
<tr>
<td>Cohesion, c₀ (Pa)</td>
<td>Negligible</td>
<td>6.60x10^6</td>
<td>-</td>
</tr>
<tr>
<td>Mass (Kg)</td>
<td>-</td>
<td>-</td>
<td>M* = 6.72x10^{16}</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>3.4</td>
<td>7.00x10^5</td>
<td>L* = 4.86x10^{-6}</td>
</tr>
</tbody>
</table>

The last parameters required to scale are the viscosity/density of the basal PDMS layer, when such a layer is present. Since the density of the PDMS is fixed, due to an impossibility to accurately change the density without affecting the other fundamental properties (namely viscosity), the ratio is used to calculate the correct density for a natural analogue.

As such, using equation 3, the value calculated for the density of the natural analogue (e.g. a thermally active zone beneath the volcanic cone caused by lithospheric upwellings) was 2273.4 kg/m³. For such a density, using information from previous studies conducted (Turcotte and Schubert, 2002), I chose 4x10^{20} Pa/s as a value of viscosity for a thermally active zone.

These properties are summarized in Table 2.

Table 2. Material properties and scaling for the model containing a silicone layer.

<table>
<thead>
<tr>
<th>Material properties</th>
<th>PDMS</th>
<th>Natural analogue</th>
<th>Ratio: Model/Nature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (%)</td>
<td>Polydimethylsiloxane</td>
<td>Thermally active oceanic lithosphere</td>
<td>-</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1333</td>
<td>2273.4</td>
<td>ρ* = 0.59</td>
</tr>
<tr>
<td>Viscosity (Pa/s)</td>
<td>5.84x10^4</td>
<td>4x10^{20}</td>
<td>η* = 1.46x10^{-16}</td>
</tr>
<tr>
<td>Mass (Kg)</td>
<td>-</td>
<td>-</td>
<td>M* = 6.72x10^{-16}</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>3.4</td>
<td>7.00x10^{5}</td>
<td>L* = 4.86x10^{-6}</td>
</tr>
</tbody>
</table>
3. Apparatus

Figure 1. Apparatus used for the models. The central line indicates the separation of the plastic sheet used to create the deformation zone.

The apparatus used to conduct these experiments consisted of a set of twin wooden walls in a C-shape (Figure 1). In order to allow for the formation of a single shear zone, two plastic sheets were attached to the walls. These are represented by the bottom part in the image above. Their separation is marked by the thin dotted line across the separation of the two walls. The corners of these walls were reinforced with small wooden cubes to prevent damage to the box during the experiments (not shown in the picture).

Any sand leakage is prevented by an additional wooden board at the edge of the each wall and a small internal plastic sheet that covers the interval between the walls.

4. Procedure

4.1 Experimental procedure

This work consisted in a series of different experimental stages as follows:

a) First stage, consisting in a set of experiments to test the apparatus and constrain its limitations as well as the repeatability of the experiments;

b) Second stage, consisting of a set of experiments where two identical obstacles are placed systematically closer above a sand-only cake;

c) Third stage, identical to the second stage but a basal PDMS layer is placed beneath the obstacles;
For the first stage of the experiment, the apparatus was filled with dry quartz sand with a thickness of 3 cm and flattened using a scraper. The first experiment was conducted without any obstacle to assess the apparatus’ capability to deform the sand package without being significantly damaged.

Next, still during the first stage, different obstacle configurations were tested to evaluate not only validity of the models but also the ability to create obstacles with identical volume/height in each experimental stage. These were built using a crane containing a small plastic cup with a stopping mechanism). This allowed for an accurate repetition of the obstacle size and width.

As such, obstacles of different height ranging from 2.5 to 3.0 cm were tested. Additionally, obstacles were built as either single centered cones or twin cones spaced at least 20 cm from each other, when measured from their peaks (see Figure 2).

![Figure 2. Cross-section along the plate separation. The placement of the basal layer is also visible.](image)

A second experimental stage consisted in systematically diminishing the spacing between two centered cones with 3.4 cm of height (an example is seen in Figure 3). The initial distance was 25 cm being reduced by 5 cm with each experiment until a spacing of 10 cm was achieved. Afterwards, the spacing was reduced to 8, 6 and 3 cm. A final experiment consisted of a larger cone with 4 cm of height simulating a merge of the volcanic cones.
During stage 2, the final offset was of 7 cm. For every 0.5 centimeter of incremental offset a top-view picture was taken.

For the final stage of the experimental procedure, a PDMS layer with a thickness of 0.5 cm was placed at the base beneath the two cones to simulate a thermally active state. This setup is illustrated in Figures 2 and 4. The cones were placed at a distance of 25 cm, followed by 15, 10 and 6 cm.

During stages 2 and 3, for each centimeter of incremental offset a 3D scan was taken using the ScanStudio™ software available at the HRTL. This software connects to a three dimensional (3D) scanner (seen in Figure 3) and scans the top surface of the model using a laser system. The topographical information is then imported to the software, converting it into a Cartesian (xyz) coordinate system. This is then exported and can be used in other software such as Move™ or MATLAB™.

Table 3. Summary of the different experimental stages.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Purpose</th>
<th>Materials</th>
<th>Total displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Testing</td>
<td>Dry quartz sand</td>
<td>Variable</td>
</tr>
<tr>
<td>2</td>
<td>Brittle interference</td>
<td>Dry quartz sand</td>
<td>5 cm</td>
</tr>
<tr>
<td>3</td>
<td>Ductile interference</td>
<td>Dry quartz sand + PDMS</td>
<td>5 cm</td>
</tr>
</tbody>
</table>

Figure 3. Experimental setup for stage 2 experiments. The device present is the 3D scanner.

Figure 4. Location and boundaries of the basal PDMS layer
4.2 Photographic analysis

The first step in the analysis was to subdivide the shear zone into three possible domains to allow for a higher efficiency. As such, the following domains are defined (Figure 5):

a) The left domain, which encompasses all markers located to the left of the centre of the left obstacle;

b) The central domain, which encompasses all markers located between the centres of the two obstacles;

c) The right domain, which encompasses all markers located to the right of the centre of the right obstacle.

Figure 5. Explanation of the domain division of the model. Each domain is defined to contain a portion of an obstacle as well as a part of the shear zone.

Within these domains, as well as within the obstacles, the visible structures were marked by use of an appropriate software (Figure 6).

As per the objective of analyzing the importance of the separation of the obstacles as an influence on interference between them, the following parameters were measured systematically:

a) The width of the collapsed area on both obstacles, defined by the distance between the two outermost faults (see Figure 6);

b) The direction of the collapsed area, again for both obstacles, defined by the angle that area makes with the main shear direction (see Figure 6);

c) The strain ratio and angular strain of the obstacles, the first defined as the ratio between the long and short axis of the obstacles; the latter as the orientation of the long axis;

d) Highest strain observable in the left, inner and right domains;

e) Highest angular strain observable in the same areas;
For measurements of angles (strike of faults or orientation of basins) during either stage, the direction of the plate separation boundary was considered as 0°. Positive degrees indicate a shift towards the immobile plate while negative degrees indicate a shift towards the moving plate (Figure 6). Whenever a different method was used, a proper mention will be written and the method explained where needed.

Figure 5. Explanation of some of the measurements taken. The arrows on the left indicate the way the strike, or direction, of the collapsed area was measured.

These measurements were taken for 3cm offset, allowing for a systematic comparison of all parameters as a function of obstacle separations. Lastly, a detailed analysis was performed for a fixed 10cm separation to allow for a study of the evolution of the system, taking measurements for each incremental offset stage.

4.3 MATLAB™ analysis

All functions described in this section are present in Appendix I. The codes can be used by copying and pasting the functions found in the aforementioned appendix.

For the two layered models created during the experimental stages, a more thorough analysis of the kinematic markers was required. For that purpose, sets of MATLAB™ functions were written. These measure the length of each axis of the deformed markers and supply as an output the strain measurements (i.e. strain ratio and angular strain).

The first step in this analysis consists of cropping the top-view photographs of the experiment to contain only the deformation area and some circular markers (view extent of figure 5 when compared with Figure 6). This is then followed by the use of the “reading.m” function. This function consists of a set of instructions that import the picture into MATLAB™’s variable set and supplies it with a simple (x,y) coordinate system, with x being parallel to the sense of shear. Moreover, this function also holds the picture so that it can be used in the next stage.

The following step consists of using the “mark.m” which, as the name implies, allows the user to mark points on the picture that was previously imported. This function calls the picture imported and
asks the user to mark a set amount of points and hit “Enter” when finished. The user defines an output file name and defines what will be marked, e.g., `mark('centroid')` indicates that the user will be marking the centers of each deformed ellipse. Once the objectives have been marked, the function will also write the coordinates of each point in a CSV file (Comma Separated Values). As such, this function should be used to mark the centers and 4 vertices of the ellipse, as seen in Figure 7.

Before the vertices are marked using the previous function, the function “`centplot.m`” can be called to plot the number of each centroid in order. This function reads the output from the “`mark.m`”. This allows the user a much more systematic approach to the marking stage, avoiding unnecessary errors and frustrations.

![Figure 6. Example of the 4 vertices in 2 deformed ellipses. The two axis indicate why the function "StrAnalysis.m" verifies the length of these to ascertain which one is the longest.](image)

The next function that can be used is the “`vertplot.m`”. This calls once more the output files from the “`mark.m`” function and requests from the user a type of marker. These marker types should be written according the MATLAB™ text properties defined for the plot function. The objective of this function is to mark the different vertices of the ellipse according the user’s specifications.

Finally, the most important function can be called. This function is named “`StrAnalysis.m`” and it calculates and plots the strain ratio for all objects that have been marked. It requests as input all data from each ellipse (centroid, top vertex, bottom vertex, left vertex and right vertex) and calculates with that information two axis for each ellipse, as seen in Figure 7.

The program then verifies which axis is the longest and divides it by the smaller one. This results in a value for the strain ratio of the kinematic marker. Next, this function identifies if the strain is placed within a set of values between 1 and 1.8 with a 0.1 increase interval and plots a different symbol at the center of the ellipse. Lastly, it produces a CSV file containing the coordinates of the centroid, the length of the short and long axis and the value of the strain ratio.

4.4 3D data analysis

During experimental stages two and three, one model was conducted with internal layering. For this case, the obstacle separation was 10 cm, allowing for the study of surface and internal deformation,
as well as their connection. The internal deformation can be defined as any and all structures formed by the deformation of the model beneath the surface.

After running the model to an offset of 5cm, the setup was soaked with a solution of soap and water and allowed to rest and solidify for 24 to 48 hours. Once that period was over, the model was sectioned with an interval of 1cm between slices. These sections were then photographed and uploaded to the Move™ software to create a 3-dimensional rendering of the model.

Once imported to Move™, the first stage of analysis consisted in a digitalization of the surface structural data. This is performed by means of vectorizing the surface faults.

![Figure 7](image.png)

**Figure 7.** Digitized section created using the Move™ software. The white crosses represent the point where the surface faults intersect the cross-section.

The following step consisted in digitizing the sections by marking the coloured horizons and all faults present, taking steps to allow for a surface connection. The result of this step can be observed in Figure 8, a digitized section created using this software.

The next step consisted of connecting the internal faults and creating several faults surfaces, allowing for a clear visualization of the internal and surface deformation. This can be seen in the example Figure that follows (Figure 9).

The final step consists in using the Strain Analysis toolbar to create an output file containing the data for all faults digitized. This file can then be imported into either MATLAB™ or OpenStereo™ to create stereoplots or other types of graphics.
Figure 8. A) Digitized fault lines for surface (white) and internal (blue). B) Interpolated fault line for the faults shown. A portion where the fault is not correctly interpolated requires manual input by the user.

5. Results

5.1 First stage:

For this stage, that aimed to establish the correct setup for stages 2 and 3, the results are:

a) The height of the obstacles should be 3.4 cm (distance from the surface sand and the top edge of the box) to ensure repeatability;

b) The obstacles should be centered using a thread cross (two lines of thread: one along the plate separation and another perpendicular to the previous one) to allow correct and repeatable placement;

c) The cones should be built using a crane system to ensure a systematic size and shape.

This is a simple set of results that derive from the nature of the experimental stage.

5.2 Surface deformation

As stated in section 4 – Procedure, photographs were taken for each 0.5cm of incremental offset. The pictures referenced in this section are placed either inline or at the end of the section. Please refer to the proper locations for a clear understanding of the text.

Regarding the brittle models (i.e. sand only), for obstacle separation larger than 10cm, the first observed structures were the R-shears on the left and right domains paired with the collapse of the right obstacle. The Riedel shears, or R-shears, are sets of faults that are formed before a main shear, with a 15° angle to the main shear direction (Riedel, 1929). An example of these faults is shown in Figure 10, marked by the letter “R”.

The left obstacle shows no evidence of significant collapse until 2cm offset had been achieved (Figure 12). As for the inner domain, a bulging of this area that stems from the two obstacles can be
seen. This structure is limited by a thrust with significant horizontal component on either side (Figure 12).

When the separation was smaller than 10 cm, the collapse of both obstacles occurs after the formation of the R-shears. No evidence can be observed on the inner zone as this has been completely hidden by the obstacles.

An increase in offset leads to the formation of a main shear along the plate separation, regardless of the separation between the obstacles. This is a result of R-shear coalescence on the left and right domains. This is shown in Figure 11, represented by the red colored faults. When all three domains are present, i.e. for an obstacle separation larger than 10 cm, the inner zone shows also R-shear coalescence paired with two oblique faults propagating from both obstacles. These two faults show forward propagation and retropropagation (i.e. propagating in an opposite sense to the motion of the plate) from the edges of the collapsed area (Figure 10).

The incorporation of the basal ductile layer changes this behavior, forming either a single large main shear and collapsing the obstacles before the 2 cm offset mark had been reached for obstacle separations larger than 10 cm. A different occurrence is the formation of a large shear zone bounded by two pairs of oblique faults without a central strike-slip (Figure 13).

Again, for smaller separations we observe the formation of the collapsed areas after the formation of R-shears on the left and right domain. The increase in offset leads to the development of the previously described features (Figure 13). Lastly, although the main shear crosses both obstacles, there is no
formation of a coherent shear zone for obstacle separations smaller than 10cm, i.e. there are “gaps” within the shear system as opposite to what occurs for the sand-only models (Figure 11).

As for the obstacles themselves, they show mostly identical structure development so a single description suffices for both. Additionally, this development suffers little to no change regardless of the proximity of the obstacles.

When the distance between the obstacles is 10 cm or smaller, at a first stage, a single fault with geometry similar to an R-shear is formed across the top of the obstacle (Figure 12, stage 1). With increasing offset, this fault is converted to a pull-apart basin, limited by two symmetrical oblique faults (bounding faults) with significant normal component. Within the basin, several smaller normal faults are formed parallel to the bounding faults (stages 2 and 3 – Figure 12). With time, the edges of these faults are rotated to appear perpendicular to the shear orientation (stages 4 and 5 – Figure 12). This apparent rotation is not observed for obstacle separations larger than 10cm.

Figure 10. Presence of shear gaps when the basal ductile layer is present. These gaps are marked by areas where the nearby transcurrent faults do not connect.
Figure 11. Evolution of the sand-only models for two different obstacle separations. For both cases, the photographs were taken at each centimeter of offset.
Figure 12. Evolution of the PDMS models for two different obstacle separations. For both cases, the photographs were taken at each centimeter of offset.
5.3 Collapsed area

The following sections consist of the results from the second and third experimental stages. For most cases, the values for both will plot in the same graphic to allow a comparison.

When observing the left obstacle for the width of the collapsed area (Figure 14), two very similar patterns are observed for both the presence and absence of a basal silicone layer. When this layer is absent, i.e., for the sand-only model, the width steadily decreases with decreasing separation from 5 cm to 3 cm, for separations between 25 and 10 cm. For separations below 10 cm, the width once more increases to close to 5 cm.

When the layer is incorporated, i.e., the Sand+PDMS model, the pattern is identical, with 2 slight differences. The first is that the lowest width, again for 10 cm separation, is 2.5 cm instead of 3 cm. The second being that an increase after 10 cm seems to require less obstacle separation when this layer is present.

![Figure 13](image)

**Figure 13.** Plot of the width of the collapsed area as a function of obstacle separation, for the left obstacle. Measurements taken for 3 cm offset.

For the same obstacle, when observing the orientation of the collapsed area (Figure 15), two distinct trends are observable. The absence of the basal silicone layer, i.e., the sand-only model, causes a steady decrease in strike with decreasing obstacle separation, from a maximum of 35° to a stable value of 20°.
When the layer is incorporated into the model, i.e., the Sand+PDMS model, a separate trend is observed. For this case, the orientation steadily decreases from a maximum of 40º to a minimum of 12º, a counter-clockwise rotation.

![Figure 14](image1.png)

Figure 14. Plot of the orientation of the collapsed area as a function of obstacle separation, for the left obstacle. Measurements taken for 3 cm offset.

When the right obstacle is observed for the width of the collapsed area (Figure 16), two very similar patterns are once more observed. When the silicone layer is not present, a steady decrease of width from 6.5 cm to 3.1 cm for separations between 20 cm and 10 cm. This is followed by an increase to a stable value around 4 cm.

The incorporation of a silicone layer does not create a significant change in either the pattern or the value of the width. In Figure 16, the two points observed for a separation of 25 cm or the point observed for 20 cm show an anomalous behavior. Either way, these will require further explanation in section 6 – Discussion.

![Figure 15](image2.png)

Figure 15. Plot of the width of the collapsed area as a function of obstacle separation, for the right obstacle. Measurements taken for 3 cm offset.
When the right obstacle is observed for the orientation of the collapsed area (Figure 17), we observe, like for the left obstacle, two distinct trends. The absence of the silicone layer creates a similar pattern as the one observed for the width, with a decrease in angle from 35° to 15° for separation distances between 20 and 10 cm followed by a stability zone of 23-25° for distances smaller than 10 cm.

Like previously, the incorporation of the ductile basal layer causes a shift in trend, causing a steady decrease in the angle from a maximum of 49° to a minimum of 18°. There is no observable stability zone.

![Figure 16](image.png)

**Figure 16.** Plot of the orientation of the collapsed area as a function of obstacle separation, for the right obstacle. Measurements taken for 3 cm offset

### 5.4 Axial strain ratios for the shear zones

Concerning axial strain ratio on the shear zones, the measurements were taken on the most deformed ellipse present on each of the 3 shear areas at an offset of 3 cm. Here the long and short axis were measured and then divided by each other to calculate the axial strain ratio value.

When the left shear zone is observed for the maximum strain ratio observable (Figure 18), two very distinct trends are observable. The absence of the basal layer results in a somewhat steady and regular increase in strain ratio with decreasing obstacle separation. This trend is particularly regular for separation distances smaller than 10 cm with a linear trend. For distances larger than 10 cm, the pattern shows higher stability with the strain ratios around 1.9.

The incorporation of the basal PDMS layer causes a very marked change in trend. The presence of only 3 points is not very statistically relevant but, however, these show a nearly identical value of strain ratio for 10 and 25 cm, similar to the pattern observed previously. This is followed by an increase in strain ratio for 6 cm separation.
Figure 17. Plot of maximum axial strain ratio for the kinematic markers on the left shear zone as a function of obstacle separation. Measurements taken for 3 cm offset.

When possible, the same measurements were performed on the inner shear zone. This limitation derives from the proximity of the two cones, covering this area. Regarding the maximum strain ratio (Figure 19) two different patterns are visible. For the sand-only model, we observe a stable pattern with values around 1.7 with a small tend towards decreasing values for smaller obstacle separations.

Figure 18. Plot of maximum axial strain ratio for the kinematic markers on the inner shear zone as a function of obstacle separation. Measurements taken for 3 cm offset.

When the basal PDMS layer is present, the pattern is more erratic. The two points for the smallest obstacle separations suggest a decreasing trend in strain ratio for this area, however the measurements taken for 25 cm separation indicate a much lower value in strain ratio. This would therefore indicate a sharp increase in strain ratio followed by a decreasing trend in value with decreasing obstacle separation.
Finally, when the same analysis was performed for the right shear zone (Figure 20), two similar trends are observable. For both presence and absence of the basal layer the maximum strain ratio on the right shear zone steadily increases with a decrease in obstacle separation. The model that contains a basal layer shows a slower rate of increase than the one without.

Figure 19. Plot of maximum axial strain ratio for the kinematic markers on the right shear zone as a function of obstacle separation. Measurements taken for 3 cm offset.

5.5 Angular strain measurements for the shear zones

Figure 20. Illustration of the angular strain measurement. This value was measured as indicated by $\alpha$, the angle between the perpendicular to the sense of shear and the long axis.

Regarding angular strain, the measurements were performed on the same ellipse that was used to measure the axial strain ratio. The angle measured was the strike of the long axis of the ellipse. For this purpose, the orientation of the plate separation was considered to be the 90º line while its perpendicular was considered to be 0º (Figure 21).

The results were plotted as the measurement for the deformed ellipse versus the distance between the obstacles for the 3 cm offset stage (Figure 22).

Regarding the left shear zone (Figure 22), we can observe that for the sand-only model the value for the angular strain is stable, fluctuating around 30º for all obstacle separations. It’s also arguable that
the sand shows a slight decreasing trend with decreasing obstacle separation but overall the value is stable.

When the model contains the basal PDMS layer, the pattern shows a decrease in angular strain with decreasing obstacle separation.

![Figure 21](image1.png)

**Figure 21.** Plot of maximum angular strain for the kinematic markers on the left shear zone as a function of obstacle separation. Measurements taken for 3 cm offset.

For the inner shear zone (Figure 23), two similar trends are observed. For both scenarios, the angular strain increases steadily with decreasing obstacle separation. However, when the basal PDMS layer is present, the angular strain value is reduced by 5-10° when compared to the absence of the layer.

![Figure 22](image2.png)

**Figure 22.** Plot of maximum angular strain for the kinematic markers on the inner shear zone as a function of obstacle separation. Measurements taken for 3 cm offset.

Finally, for the right shear zone (Figure 24), two similar trends are observed, like in previous instances. For this case, the overall trend is an increase in angular strain with decreasing obstacle separation.
When the PDMS layer is present, a double trend might be present, for separation distances below 10 cm. Here we observe a rapid increase in angular strain that follows a slow decrease in angular strain for distances larger than 10 cm. It’s also arguable that the value of 25º for an obstacle separation of 8 cm is an effect of something other than the separation of the obstacles themselves.

![Figure 23. Plot of maximum angular strain for the kinematic markers on the right shear zone as a function of obstacle separation. Measurements taken for 3 cm offset.](image)

**5.6 Strain across the fault line**

When the MATLAB™ scripts described in section 4.2 were applied, one of the outputs created was a large CSV file containing the strain ratio for all the markers present on the experiment for the 3cm offset stage along with the (x,y) coordinates of the said markers.

This file was used to create a set of graphics (Figures 25 and 26) that shows how the strain on the markers compares to the strain of the obstacles present. For these purposes, like stated previously, the model was divided into different domains, similar to the shear zone division:

- d) The left domain;
- e) The central domain;
- f) The right domain;
This division was previously referred and illustrated in Section 4.2, with Figure 6.

**Figure 24.** Axial strain ratio for all markers within 5cm of the plate separation for the sand-only model as well as the obstacles themselves. Measurements for 10 cm obstacle separation.

For the scenario where the basal PDMS layer is absent, i.e., the sand-only model (Figure 25) we can observe three different clusters, marking the left, inner and right domains. The highest strain observable is found in the central and right shear domain, both with higher strain ratio than either cone.

Both obstacles reveal similar high strain ratio, around 1.7, with a slightly higher value for the right obstacle. Nevertheless, both obstacles show higher strain ratio than most markers present.

Additionally, one can observe a higher point density for the left cluster, indicating a more constrained deformation state; while the right cluster indicates a very disperse pattern with more points trending towards higher strain ratio values. Furthermore, despite the low amount of markers within the inner zone these indicate values similar to the other two zones.
From this, we can observe that the strain ratio increases along the fault, showing higher values for the points found after the last obstacle has been crossed.

![Axial strain ratio graph](image)

**Figure 25.** Axial strain ratio for all markers within 5cm of the plate separation for the sand and PDMS model as well as the obstacles themselves. Measurements for 10 cm obstacle separation

When the basal silicone layer is incorporated into the model (Figure 26), the pattern changes slightly in what concerns the markers but shows a much larger difference when these are compared to the obstacles. Once again, the largest strain ratios are observed in the central and right domains, with the highest value being located in the right domain.

Like previously, both obstacles show a very similar strain ratio (the ratio between the long and short axis of the markers), around 1.5, values smaller than the ones observed for the sand-only model. Yet again, the strain ratio value is slightly higher for the right obstacle.

Finally, we observe much higher values for the overall strain ratio when the basal PDMS layer is included with values consistently higher than the highest values observed for the sand-only model.

### 5.7 Internal deformation

#### 5.7.1 Sand-only (10 cm separation between obstacles)

The following sections are the result of an analysis performed with the Move™ software. After observing the procedure defined in a previous section and observing the internal deformation (as defined in section 4.3 – 3D analysis) using the aforementioned software, the following deformation groups can be derived (Figure 27):

1) Group A. Deformation occurring inside the area defined by the edges of the obstacles;

2) Group B. Deformation occurring within the shear zones;
Figure 26. Deformation zones observed for the sand-only model for the final stage of deformation (5cm offset). The white elliptic areas mark the edges of the obstacles. 10 cm obstacle separation.

Within the zone marked as belonging to group A, the deformation is marked by a central strike-slip fault (refer to section 5.2 – Surface deformation for a top-view picture) with a near vertical dip bounded laterally by two conjugate less steep oblique faults with a very marked normal component. These latter faults mark the edge of the collapsed area within the cones, as described in a previous section.

In order to improve on the analysis of the group A deformation zone, this group was further subdivided:

1) Group A_L – Deformation occurring in the left obstacle;
2) Group A_R – Deformation occurring in the right obstacle;

For this analysis, their structural data was imported into OpenStereo™ and used to create a stereoplot (Figure 28). This stereoplot includes all the faults obtained for the two cones while analysing the sections.

For both obstacles (group A_L and A_R), the stress directions should be $\sigma_1$ placed at 45º clockwise rotation from the the N-S line and $\sigma_3$ being perpendicular to the previous one. The intermediate stress component, $\sigma_2$, is vertical for both cases. Both obstacles show a symmetrical pattern with a decrease in dip that is perpendicular to the shear sense. Additionally, both show a significantly higher number of steep dipping faults than shallow dipping faults. It is worth noting that group A_R shows a larger spread in strike than the one observed in group A_L.

On both cases, the faults with a trend toward less steep dip angles are normal faults while the steepest faults observable are strike-slip faults. The normal faults with the smaller dip angle are found on the right obstacle.
Group B deformation zone can be classified by a single large strike-slip fault (refer to section 5.2 – Surface Deformation or Figure 12 for a top view picture) bounded by an shallow dipping oblique fault with strong reverse component. Both faults stem from the plate separation boundary.

5.7.2 Sand with basal PDMS layer

In this section, the internal deformation is again divided into group A (A\textsubscript{L} and A\textsubscript{R}) and group B, please refer to the previous section.

Within the zone belonging to group A (Figure 29), like in the previous model, the deformation is marked by a central strike-slip fault (refer to section 5.2 – Surface Deformation or Figure 12 – Figure 2.
for a top view picture) with a near vertical dip bounded laterally by two conjugate slightly less steeply dipping oblique faults with a very marked normal component. These latter faults mark the edge of the collapsed area within the cones, as described in previous sections.

For both A_L and A_R, the stress directions stress directions should be \( \sigma_1 \) placed at 45° clockwise rotation from the the N-S line and \( \sigma_3 \) being perpendicular to the previous one. The intermediate stress component, \( \sigma_2 \), is vertical for both cases.

![Figure 29](image.png)

**Figure 29.** Comparison of the internal deformation of the obstacles at a 10cm separation.

By contrast, when the PDMS layer is present, both cones show little dispersion away from the steep dipping faulting. Only a very small amount of faults show a dip smaller than 60° as opposed to a very large amount in the precious model (Figure 28 vs Figure 30). The normal faults and strike-slip faults show identical behavior in both obstacles, with elevated symmetry along the main shear direction (E-W line, Figure 30)

Like the previous section, group B deformation zone is classified by a single large strike-slip fault, shown by the long band of strike-slip faults in Figure 29 (refer to section 5.2 – Surface Deformation or Figure 13 for a top view picture) bounded by an shallow dipping oblique fault with strong reverse component. Both faults stem from the plate separation boundary.
5.8 Structural evolution

5.8.1 Strain measures for the left obstacle

This analysis was performed by measuring the long and short axis of the ellipsoids defined by the edge of the obstacle (as seen in Figure 31), followed by the calculation of the strain ratio. Additionally, the strike of the long axis was also measured to compare its evolution over time. For this last measure, 0° is defined by the direction perpendicular to the shear direction (marked by the red line in Figure 31). All results in this section were plotted against the offset, or displacement, between the two plates in the model.

![Diagram of Original and Deformed ellipsoids](image)

**Figure 30.** Explanation of the measurement of the axial strain ratio and strike of the long axis for the obstacles.

When observed as a function of displacement (offset), for an obstacle separation of 10cm (Figure 32), the left obstacle shows an identical pattern for both setups, i.e., a steady increase of strain ratio with increased offset, as expected. A small difference is generally seen between the presence and absence of the PDMS layer, as the absence seems to lead to a slightly higher amount of strain ratio in the obstacle. A more pronounced strain ratio increase is observable between 4.5cm and 5cm offset for both models.
When considering the evolution of the strike of the long axis, the materialization of the maximum strain axis, over time (Figure 33), for an obstacle separation of 10cm, a similar pattern is once again observed for both setups. For the present parameter, an overall increase in the rotation of the maximum strain axis is observed with increased offset, as expected.

**Figure 31.** Plot of axial strain ratio as a function of offset for the left obstacle. Measurements taken for 10 cm obstacle separation.

A large difference in value is observable between the presence and absence of the basal PDMS layer. The presence of the layer reduces the angle by of 10º, indicating that the obstacle is less deformed when the layer is present.

**Figure 32.** Plot of strike of the long axis as a function of offset for the left obstacle. Measurements taken for 10 cm obstacle separation.
When at a separation of 25cm, the left obstacle (Figure 34) shows two similar trends for the absence or presence of the basal PDMS layer. For this case, both scenarios are described by a steady increase in strain ratio with a slightly higher value for the model with the basal layer. The last two points indicate that for 5cm offset there is a much higher strain ratio for the obstacle with a basal layer.

Figure 33. Plot of axial strain ratio as a function of offset for the left obstacle. Measurements taken for 25 cm obstacle separation.

When observing the strike of the long axis of the left obstacle (Figure 35), for a separation of 25cm, two distinct trends are observable for the presence and absence of the PDMS layer. For the sand-only model an increase in strike is observed for offsets between 1 and 3.5cm, from 40 to 50º, indicating a shift towards the shear direction. For any offset above 3.5cm, the value is stable around 50º.

When the basal layer is present beneath the obstacle the trend shows a steady increase in strike for offset values between 1 and 4 cm, from 35º to 52º. When the offset is higher than 4 the value is stable around 50º, similar to what occurred in the sand-only model.

Figure 34. Plot of strike of the long axis as a function of offset for the left obstacle. Measurements taken for 25 cm obstacle separation.
5.8.2 Strain measures for the right obstacle

An identical analysis was performed for the right obstacle, using the same principles as the ones in the previous section. When the right obstacle is observed, for an obstacle separation of 10cm (Figure 36), the strain ratio defines a pattern very similar to one observed in the previous obstacle. There is a steady difference in the value for the strain ratio for the two setups.

![Figure 35](image)

**Figure 35.** Plot of axial strain ratio as a function of offset for the right obstacle. Measurements taken for 10 cm obstacle separation.

Like previously, the presence of a basal PDMS layer causes a slightly smaller strain ratio for the obstacle in question. Similar to the first parameter, for an obstacle separation of 10cm, the strike of the long axis on the right obstacle (Figure 37) shows a very similar pattern to the one observed for the left obstacle. Once again, the strike steadily increases for both setups with a large difference in value between the two. The presence of the basal PDMS layer causes a decrease of at least 15º in the strike of the long axis, indicating like before that this layer reduces the deformation of the obstacle.

![Figure 36](image)

**Figure 36.** Plot of the strike of the long axis, for a separation of 10cm, for the right obstacle plotted versus the offset.
Like for the left obstacle, the same analysis was performed for an obstacle separation of 25 cm to allow for a comparison between the two deformation states.

When observing the strain ratio of the obstacle for a 25 cm separation (Figure 38), two distinct trends are visible. For the sand-only model, the pattern is a steady increase in strain ratio over the increase of offset to a maximum of 1.75.

When the basal layer is present, we observe an increase of value with increasing offset. By contrast with the previous model, the increase is much faster and towards higher values reaching a maximum of 2.1.

![Graph](image)

**Figure 37.** Plot of axial strain ratio as a function of offset for the right obstacle. Measurements taken for 25 cm obstacle separation.

Finally, when the strike of the long axis of the obstacle is observed for 25 cm separation (Figure 39) two different trends are again visible. Like the previous parameter, the two trends are similar yet the presence of the PDMS layer causes a much faster increase in strike, i.e., a quicker shift towards the shear direction.
To conduct this analysis, systematic measures were performed to check the distance between the outermost faults of the collapsed area of the obstacles.

When this structure is monitored as a function of offset, for the left obstacle (Figure 40), a systematic difference is observed between the presence and absence of a basal PDMS layer. For models with basal layer, the collapsed area is systematically narrower by at least 0.5 cm for all offsets.

An overall increase in width is observed for both setups. Additionally, a sudden increase width is observed between 2.5 and 3 cm offset for the model with a basal PDMS layer.
When observing the right obstacle for the same structure (Figure 41), a similar pattern is observed, albeit with a much smaller difference between the presence and absence of the basal layer.

When observing the width of the collapsed area for the left obstacle for a higher separation (Figure 42), two very distinct trends are observable. For the sand-only model we observe a steady increase in width with increasing offset, from a minimum of 3 cm to a maximum of 6.5 cm.

For the model containing the basal layer, the width increases much slower from a minimum of 6.8 to a maximum of 8.3 cm. Additionally, the first collapse of the obstacle produces a much wider zone, a possible indication of a larger deformation zone.

**Figure 40.** Plot of width of the collapsed area as a function of offset for the right obstacle. Measurements taken for 10 cm obstacle separation.

**Figure 41.** Plot of width of the collapsed area as a function of offset for the left obstacle. Measurements taken for 25 cm obstacle separation.
5.8.4 Orientation of the collapsed area

For this measure, this orientation is compared to the shear orientation that, for the effect, will be considered as 0°. Additionally, positive degrees will indicate a shift towards the fixed plate, i.e. a clockwise rotation (refer to Figure 5 in section 4.2).

When one observes the evolution of the orientation of the collapsed area for the left obstacle (Figure 43), for an obstacle separation of 10cm, an interesting pattern is observed for the models without a basal. The pattern consists of an initial increase of angle followed by a sharp decrease from 3.0 to 3.5cm offset, indicating a clockwise rotation of the fault. With increasing offset, the angle once again steadily increases. The models with a basal layer show a slight decrease in angle followed by a slight increase, with low variation with increasing offset.

Like previously, there is a consistent difference in value between the two setups. For the present case, the presence of a PDMS layer causes a decrease in strike of at least 4°, i.e., the fault rotates less towards the shear plane.

A similar analysis for the right obstacle, for an obstacle separation of 10cm (Figure 44), indicates different behaviours for the two scenarios. When the basal PDMS layer is present, the orientation of the collapsed area shows a sTable angle around 15° followed by a counter-clockwise rotation for offsets larger than 4 cm.

![Figure 42. Plot of orientation of the collapsed area as a function of offset for the left obstacle. Measurements taken for 10 cm obstacle separation.](image)
By contrast, the absence of this layer causes a significant increase in orientation from 14° to 18°, indicating a tendency to deviate away from the main shear orientation.

![Figure 43](image.png)  
**Figure 43.** Plot of orientation of the collapsed area as a function of offset for the right obstacle. Measurements taken for 10 cm obstacle separation.

If we observe once more the left obstacle (Figure 45), for a separation of 25 cm, two distinct trends are, like previously, visible. For the sand-only model, for offsets between 2 and 3 cm we can observe a steady increase in strike, from 25° to 35°. For an offset higher than 3 cm the value stabilizes around 22°.

The model containing the basal layer shows a different trend, with a steady increase in strike from 36° to 48° for offsets between 2 and 5 cm before experiencing a large decrease in strike for the 5 cm offset.

![Figure 44](image.png)  
**Figure 44.** Plot of orientation of the collapsed area as a function of offset for the left obstacle. Measurements taken for 25 cm obstacle separation.
Finally, if we observe the right obstacle for 25 cm separation (Figure 46), two different trends are visible. The sand-only model shows a steady decrease in strike from 32º to 20º for offsets between 2 and 3.5 cm followed by an increase for offsets higher than 3.5 cm. For an offset of 5 cm the strike once again decreases, to a value of 21º.

On the other hand, the model with the basal PDMS layer shows a steady increase of strike for offsets between 2 and 4 cm, increasing from 40º to 50º. For an offset of 5 cm the strike decreases abruptly to a value of 28º.

![Figure 45. Plot of orientation of the collapsed area as a function of offset for the right obstacle. Measurements taken for 25 cm obstacle separation.](image)

### 6. Discussion

No attempt to constrain the influence of a single large scale strike-slip system on two consecutive obstacles has yet been performed, although previous studies have been done only considering a single volcano affected by a basal strike-slip systems (Norini and Lagmay, 2005; Mathieu et al., 2011). In the present work besides using two aligned coned-shaped obstacles, we use as variables both the distance between these and their prescribed rheology (presence vs. absence of a basal silicone slab beneath the cones).

The results of this study confirm that the presence of a ductile layer beneath brittle volcanic cones causes a measurable change in the state of deformation. Below, I focus on evaluating a possible influence between both obstacles, at different distances, with a basal ductile layer or a brittle medium.

#### 6.1 Structural considerations

As this is a work mainly based on structural geology, it is required to take a closer look at the structures formed and their connections to the overall evolution of the system.

Starting with the collapsed area, this can be viewed as a rhombic releasing bend or pull-apart basin (Sylvester, 1988), created by a clockwise rotation of the dextral strike-system. This is a result of the fault following the path of least resistance (e.g. Rosas et al. 2014), created by non-coaxial
deformation of the obstacle. In this case, the instantaneous direction of compression is at 45º to the shear zone (σ₁ – Figure 47) while the progressive direction of compression rotates towards being perpendicular to the shear. This causes an extension that is perpendicular to that direction, creating a “weak zone” that rotates with increasing offset. This rhombic system is bordered by R-shears on each side (Mathieu et al., 2011) with increasingly narrower grabens between them, a classic feature in collapsing cones (Norini and Lagmay, 2005).

The second most important feature is, the main shear itself. The first structures observed here, as described in the results section, are the R-shears (Riedel, 1929; Dooley and Schreurs, 2012) formed at around 10º to the main shear direction. For obstacles separated by less than 10cm, these form before the collapsed areas within the obstacles. This is due to the obstacles behaving less and less like individual cones and shifting towards a larger single obstacle. This increases the resistance of the obstacle to deformation and, as such, hinders the development of the collapsed areas.

Such an effect occurs regardless of the prescribed rheology of the cones, since ductile layers are placed only beneath the obstacles. This is an indication that this ductile basal layer has an influence that is less important than the distance between the two obstacles at the start of the deformation. This factor is further discussed in the subsequent sections.

The increased proximity of the PDMS layers beneath the cones tends to cause an overlap of the cones, therefore, hiding the formation of these shears within the inner shear zone (central domain, as defined in section 4.2). This factor is the main reason why the measurements taken for this domain show only a few values.

The main shear is formed by the coalescence of the R-shears and is bounded by two conjugate faults that can vary between a set of oblique faults with a marked inverse component or two oblique faults with a marked normal component. These sets of faults (central strike-slip and lateral oblique faults) are a classical expression of strike-slip deformation called flower-structures that can be divided into two extreme groups (Figure 48) (Sylvester, 1988):

a) Positive flower-structures or palm-tree structures, where the central strike-slip is bounded by oblique faults with an reverse component;

b) Negative flower-structures or tulip structures, where the central strike-slip is bounded by oblique faults with a normal component;
Along the strike of the main shear, the shear zones outside an obstacle are characterized by positive flower structures (group B deformation – Section 5.7) and the shear zones occurring inside an obstacle are characterized by negative flower structures (group A deformation – Section 5.7), as seen in Figures 27 and 29 – Section 5.7. These shifts are caused by systematic changes from transpressive to transtensive to transpressive deformation when the faults cut across and then exit each of the obstacles.

The positive flower structures, usually an indicator of transpressive forces, are formed by the compression existent in the dextral system. This is inherent to the deformation mechanism and is a result of the dilation effect of the sand. This effect causes an expansion of around 5% and leads to compressive structures in most natural and artificial systems (Guerroue, Le and Cobbold, 2006).

The negative flower structures, a sign of transtensive forces, were created as a consequence of the change in topography along the length of the fault. In other words, when the same fault crosses from a flat surface to a zone represented by a topographical high it causes this area to collapse (Sylvester, 1988). The collapse of the internal area of the obstacle causes the formation of conjugate normal faults along the walls, merging with the single central strike-slip at depth. These conjugate faults are curved, yet symmetrical, showing identical changes in dip and strike on both sides of the central fault. This is a consequence of the conic shape of the obstacle (Lagmay et al., 2000; Norini and Lagmay, 2005).

These are considerably narrower when the basal ductile layer is present, due to the localization of the deformation, as explained in Figure 49. This phenomenon is counter-intuitive and seems to contradict the established literature. In order to explain it, it is required to observe the properties of this basal layer. This viscous layer deforms plastically, accommodating the deformation gradually instead of transmitting it. The ability to accommodate deformation is strongly dependant of the ratio between the thickness of the ductile layer and the thickness of overlying sand (Keppler, Rosas and Nagel, 2013).
A thinner layer (when compared to the overlying sand) has a higher resistance to deformation and, as such, causes narrower deformation bands (Keppler, Rosas and Nagel, 2013). This in turn leads to smaller spacing between the surface faulting and, in consequence, to narrower pull-apart basins (Figure 49).

Finally, when one observes the interactions between the two obstacles it is visible that two possible connections exist:

a) A connection along the main shear zone, parallel to the plate separation, for separations larger than 10cm;

b) A connection along a single transfer fault between two of the faults of the collapsed areas;

Examples of these connections can be seen in Figure 12 for an offset of 3cm.

![Theoretical scenario](image1.png) ![Model](image2.png)

**Figure 49.** Comparison between a theoretical transfer fault and the one observed in the models conducted.

The first is of no consequence to this work as it is not a transfer of the deformation but a case of two isolated obstacles without any influence on each other. The second connection is an actual stress transferal between the obstacles as it shows a connection between two similar structures by means of a strike-slip fault, akin to what occurs in transfer faults in nature (see Figure 50 for a comparison).

This second transfer is fully formed at an offset of 3cm for the sand models and 4cm for the models with a basal PDMS layer. This additional 1cm needed to form the transfer fault (as seen in the photographic sequence presented in Figure 13) is caused by the viscosity of the basal layer. This property causes the PDMS to deform strongly on its base and weakly on the top, resulting in a delay of the surface deformation. In other words, as stated previously viscous rheology localizes the strain, accommodating stress locally rather than propagating it (Rosas et al., 2014).

At a first stage (Figure 12, stage 2), this transfer fault forms between the two closest faults of the two obstacles, the central strike-slip of the right obstacle and the fixed side bounding fault on the right obstacle for the sand-only models. This is due to the formation of a central elliptical structure on the left obstacle, perpendicular to the main extensional direction, hindering the formation of the main central fault. This structure is formed by rotation of the outer faults, creating a central zone that hinders the propagation of the main shear zone and, by consequence, of the transfer fault.
When the basal layer was present, the connection was formed across the central strike-slips. This was a result of the localization of the deformation caused by the PDMS (Rosas et al., 2014). This layer changes the plate separation vertically by 0.5 cm, causing the deformation to be focused. This effect is illustrated in Figure 49.

The localized deformation favors the development of the central faults, creating a narrower, well-marked central strike-slip zone, allowing it to connect earlier with the adjacent obstacle. This can be seen in Figure 13 for an offset of 4 cm for instance.

6.2 The influence of obstacle separation on the geometry

This section focuses on the differences caused in the deformation of the obstacles as they are placed closer or farther away from each other.

For most parameters measured on the obstacles as a function of obstacle separation, there is little difference between the presence and absence of a basal ductile layer. This is an indication that the obstacle separation has a stronger influence than the presence of the basal layer on the overall deformation of the system. For measurements of width and direction of the collapsed area, a decreasing obstacle separation leads to a narrower space for deformation (as mentioned above) and causes these values to decrease with decreasing separation. Conversely, the increase in obstacle separation causes more space to deform for the markers outside of the obstacles, leading them to increase their axial strain ratios. Regardless, there are some interesting results that require further explanation.

A point that requires explanation is the apparently smaller width of the collapsed area (Figure 14 – Section 5.3) for the largest separation for the right obstacle. For both scenarios, with and without a basal ductile layer, the right obstacle shows a narrower collapsed area for the widest separation, when observing the other values measured for this obstacle and the left obstacle (Figures 14 and 16 – section 5.3). For the sand-only model, a possible explanation could be the early development of the main Y-shear while no such explanation is possible for the model with the basal ductile layer. Another possible explanation, and more likely, is that this effect is a consequence of a proximity to the walls of the box, i.e., a border effect and should be disregarded.

Overall, it seems that the obstacle separation overshadows the effects caused by a basal ductile layer. This change in separation largely affects the area available for the obstacles to deform and, as such, mostly diminishes the possibility for the structures to rotate or widen.

6.3 Geometric changes as a function of offset

For fixed obstacle separations of 10 cm and 25 cm, several different types of trends were observed for the models with and without a basal ductile layer. This section analyze the implications of the different trends.
For the left obstacle, when considering either obstacle separation values (i.e. 10 or 25 cm), the width is considerably larger when a basal layer is not present, indicating a localization of the deformation above the PDMS layer. This is the effect explained in the previous section (Figure 49).

By contrast, the right obstacle shows a narrower band of width variation with a slightly larger width for the model with the basal layer (Figure 41 – Section 5.8.3). This is an indication that the deformation is distributed and a possibility that the right edge of this obstacle is escaping the edge of the basal layer at some point (Figure 51), allowing an increase in the width of the area. This escape is favored by the lateral expansion of the obstacle and preferred direction for collapses (Lagmay et al., 2000). Both obstacles suffer this lateral expansion and collapses, however, unlike the left obstacle, this one has no other obstacle to hinder the process. As such, it can easily rotate and collapse past the edge of the basal layer.

Regarding the direction of this area, i.e. the angle this area makes with the main shear direction (Figures 43 to 46, section 5.8.4), very distinct patterns are observable for both obstacles for the different obstacle separations described previously (10 and 25 cm of separation). These are discussed in the following sections:

6.3.1 Left obstacle (10 cm obstacle separation)
Considering the left obstacle, when separated 10 cm from the right obstacle, we observed different patterns for the two main scenarios, i.e., with and without a basal PDMS layer. The drop in angle, i.e., an anticlockwise rotation towards the main shear direction observed in the sand-only scenario, can be explained by the overlapping of the two halves of the obstacles, causing the inner faults to veer towards each other and connect as a single larger basin and main shear zone. This effect causes the original basin orientation to be hidden by the new arrangement of the faults in the new basin. The subsequent increase is a result of the continuous rotation of the collapsed area according to the main stress directions (see Figure 47, section 6.1).
The PDMS scenario shows a decrease in angle for low offset values (below 3 cm) caused by the formation of the basin and adjustment of the outer faults to the rotation of the obstacle. The increase after 3 cm of offset is caused by the same effect as before, i.e., new distribution of faults bordering the now conjoined basins of the obstacles.

As for the considerable difference between the actual direction angle values observed in Figure 43 (section 5.8.4) between the two scenarios, these are explainable by the viscous effect of the basal layer on the surface deformation. This effect is caused by the strain rate differential between the zones closer and further away from the plate separation boundary. To elaborate, when a basal silicone layer is present, the strain rate is higher for the portions of the layer closest to the plate separation boundary (proximal zones) and smaller for portions located at some distance (distal zones). This in turn results in a faster rotation for the proximal zone and slower for the distal zone, culminating in a collapsed area that is less deviated from the main shear direction (Figure 52).

![Figure 51. Explanation of the effect of the PDMS on the shear velocity and rotation of the collapsed areas.](image)

### 6.3.2 Left obstacle (25cm obstacle separation):

For a larger obstacle separation, we observe on the left obstacle (Figure 45, section 5.8.4) a higher overall direction angle for the model with the basal ductile layer. This is, again, an effect of viscosity of the PDMS on the development of the shear zone.

### 6.3.3 Right obstacle (10 cm obstacle separation)

While observing the direction of the collapsed area in the right obstacle, when separated from the left obstacle by 10cm (Figure 44, section 5.8.4) two distinct patterns were observed. For the model with the basal silicone layer, we observed a sTable zone followed by a decrease in direction angle, i.e. anticlockwise rotation, while a steady increase was observed for the sand-only model.

The first case can be explained with the viscosity of the basal layer. Similar to previous sections, the zones closest to the plate separation boundary are affected by higher strain rates. The higher plate
motion in the proximal zones causes an anticlockwise rotation of the collapsed area, veering towards the main shear direction. The sudden decrease in orientation after 4 cm is caused by the new fault configuration in this obstacle after connection to the previous one.

By contrast, the clockwise rotation observed for the sand-only model is a result of the opening of the pull-apart basin following the main extensional direction shown in the beginning of this section (Figure 47). The low angular values observed might be a consequence of the small dimension of the obstacle. To confirm this hypothesis, it would require further studies with varying obstacle size.

6.3.4 Right obstacle (25 cm obstacle separation)

At an obstacle separation of 25 cm (Figure 46, section 5.8.4), the right obstacle showed two distinct patterns for the presence and absence of the basal ductile layer. When the basal layer was present, we observed a clockwise rotation of the collapsed area, away from the main shear direction. This is an unintuitive result that derives from the escape of the obstacle from the basal ductile layer. This allowed it to rotate with significant ease and deviate from the main shear direction.

The sand-only model, by contrast, shows a steady anticlockwise rotation of the collapsed area caused by a rotation of the obstacle itself towards the main shear direction followed by a stable zone at around 20-25º. This is caused by an early development of the main shear zone connecting the two obstacles. This structure was formed after 3.5 cm of offset (see Figure 12) and caused the collapsed zone to rotate in order to allow for a total connection of the shear.

6.3.5 Strain evolution

The axial strain ratio and angular strain are indications of the state of deformation of an obstacle. In addition, they can be controlled by means of theoretical lines (Ramsay and Graham, 1970) allowing for a clear detection of changes and their reason.
Regarding the first mentioned parameter, the axial strain ratio, both obstacles show similar patterns. The models with a basal ductile layer show very similar axial strain ratios regardless of the distance between the obstacles, as seen in Figure 53. A slightly higher axial strain ratio is observed for the right obstacle when placed 10 cm apart from the left obstacle, both with basal ductile layers, indicating that the presence of the left obstacle is enhancing the motion of the right one.

Figure 52. Plot of axial strain ratio versus total offset during the experimental runs for a model with a basal ductile layer: (Left) left obstacle. (Right) right obstacle. The dots represent the experiments performed with obstacles separated by 10 cm while the lines represent the models with obstacles separated by 25 cm. The equation indicates a linear fit for the obstacles separated by 10 cm.

Figure 53. Plot of axial strain ratio versus total offset during the experimental runs for a model without a basal ductile layer: (Left) left obstacle. (Right) right obstacle. The dots represent the experiments performed with obstacles separated by 10 cm while the lines represent the models with obstacles separated by 25 cm. The equation indicates a linear fit for the obstacles separated by 10 cm.

These results mainly show:

1) For the presence of a ductile layer:
   a. Strain ratio is approximately the same, regardless of the separation distance between the obstacles;
   b. Strain ratio is identical for both obstacles.
2) For the absence of a ductile layer:
   a. Strain ratio is higher on the right obstacle, regardless of separation;
   b. Strain ratio is higher for a lower separation (of 10 cm).

This combination of factors shows that this layer controls the deformation whenever it is present beneath the obstacles, allowing for only a slight input by the obstacle separation as this layer renders this effect nearly negligible.

The obstacle separation however is the key factor behind the deformation for the sand-only models (Figure 54), where both obstacles show a clear increase in axial strain ratio when placed next to another obstacle. Thus, the presence of a second obstacle in close proximity to a first causes a higher degree of deformation to occur on both, with an even higher difference occurring for the right obstacle.

The case is not the same when observing the angular strain (i.e. direction of the long axis of the deformed obstacle – maximum strain direction) on the same obstacles (Figures 33 and 37, sections 5.8.1 and 5.8.2). Two identical patterns are visible for the models with and without the basal ductile layer but a significant difference is observed between the two scenarios. When the basal layer is present, the angular strain on the obstacles is severely reduced by an average of 20-25°. This is a case, like for the direction of the collapsed area, of the effects of different strain rates for proximal and distal areas of the silicone layer. As such, like explained before, the outer edges of the obstacle move slower than the inner areas when this layer is present, resulting in a much lower angular strain in the overlying obstacles. Some minor deviations from the overall increasing trend in value can be attributed to collapses of the outer areas of the obstacle.

When the obstacles are farther away from each other, the trends in strain ratio and angular strain show less variety. Here, there is little to no difference between the models with and without a basal ductile layer for both parameters. This is an indication that the influence of a basal layer is amplified by the proximity of the two obstacles or that there is no influence when the layer is only beneath the obstacles and not connecting between them. Additionally, it’s also probable that for higher separations between the obstacles the topographical effect is the most important. This effect can be described as the difference in the deformation caused by a change in topography when compared to a flat surface. This means that despite the presence of the basal layer, the volume of sand above the surface is responsible for the control of the deformation.
To make the previous statement clearer, I’ve compared my results to the theoretical baseline established in Ramsay and Graham (1970), created for a flat surface and passive markers. To allow for this comparison, firstly the measurements taken had to be transformed in order to follow the explanation supplied in the aforementioned article (Figure 55). This comparison allows a verification of the passive and active behavior of the obstacles, as well as the influence of their proximity and presence of a basal decoupling layer.

Since the measurements performed during this work for the axial strain ratio were done based on 0º being perpendicular to the main shear direction, these had to be subtracted from 90º to obey the $\Theta$ parameter in Figure 55. In these experiments, $\gamma$ was interpreted as the offset between the moving and fixed plate (interpreted to be the shear strain observable in the obstacles), in centimeters while $\Theta$ was defined as the counterclockwise angle between the long axis of the obstacle and the direction of the shear.

On Figures 56 and 57, the theoretical line from Ramsay & Graham (1970) plots $\Theta$ as a function of $\gamma$. As such, the calculation of this line first entailed a calculation of $\gamma$ as a function of $\Psi$ (Figure 55):

\[ \gamma = \tan(\Psi) \]

Afterwards, the value for $\Theta$ was equally derived from the value of $\Psi$, following the principles of the aforementioned article:

\[ \tan(2\theta) = \frac{2}{\gamma} \]

\[ \theta = \frac{1}{2} \cdot \arctan \left( \frac{2}{\tan(\Psi)} \right) \]
Once more, we observe little to no difference between the presence and absence of a basal ductile layer for the obstacles separated by 25cm. In Figure 56, Θ shows little variation for all scenarios. This is an indication that the bulk of the deformation is controlled by the topographical effect of the obstacle itself, i.e. all obstacles are behaving like active markers regardless of the presence of a basal ductile layer. A slight deviation observed in the model with a basal ductile layer may indicate an increased rheological control for an offset larger than 4 cm on the right obstacle. This may be a consequence of the yield of the basal silicone layer beneath this obstacle or an outlier caused by border effects.

Figure 55. Plot of the Θ angle versus increasing offset (cm) during experimental runs. Comparison with the theoretical line for the left and right obstacles with 10 cm separation. In the legend, S stands for Sand while S+P stands for Sand and a PDMS layer.

Conversely, when separated by only 10 cm (Figure 57), it is observable that the topographical effect is not as marked for the sand-only models. When the basal layer is not present, these obstacles follow closely the theoretical line (Ramsay and Graham, 1970) and seem to behave a single passive
marker, with a slight topographical influence marked by the larger than 5° difference for \( Y > 2.5 \). The behavior observed for \( Y < 2.5 \) for these models is a consequence of the obstacles behaving as passive markers for small amounts of offset. The increased offset causes them to fault, resulting in heterogeneous deformation and, as such, to behave increasingly as active markers and deviate from the theoretical line.

The model with the basal ductile layer follows the patterns observed for the obstacles separated by 25cm. This is a consequence of the active behavior of the ductile layer, causing each obstacle or set of obstacles to behave as single active markers, responding with a combined topographical and rheological effect.

To summarize, the axial strain ratio is strongly affected by the presence of the basal ductile layer to the point of almost masking any influence of the separation between the obstacles. When the basal ductile layer is absent, the axial strain ratio is strongly influenced by the proximity of the two obstacles, indicating that their deformation is enhanced when in close proximity. The angular strain is controlled strongly by the proximity of the obstacles while the presence of a basal ductile layer seems to nullify the effect of proximity.

### 6.4 Comparison with a natural example

For the present study, as well as with other modelling studies, the comparison with a possible natural analogue is of critical importance. To that extent, the results obtained from this study will be compared with some of naturally occurring systems to access the similarity between them.

One possible example occurs in the São Jorge Island (Azores) (Figure 58) where the São Jorge Transform (SJT) crosses the entire island. The SJT is a transcurrent dextral fault system that contains a

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**Figure 56.** Comparison with the São Jorge Island example. This area is located close to the geometric centre of the island. The peak to the left is the Pico da Esperança. Satellite image from GoogleEarth™. The model on the right shows the obstacles separated by 10 cm, with a basal layer beneath.
set of volcanic alignments across its span. One of the segments of this fault is the Picos Fault (PF), a
dextral oblique fault with a normal component that crosses the Pico da Esperança and the two peaks in
close proximity (Madeira, 1998; Mendes et al., 2013; Madeira et al., 2015).

This normal component is marked by a set of normal faults along the peaks, as seen in Figure 58.
These are a consequence of the dextral motion combined with the topographic effect of the obstacle size
and, as such, are comparable to the models. A portion of this component is also created by the rifting
occurring along the long axis of the island, running parallel to the SJT and PF.

This island has shown recent volcanic activity (around the 16th century) and is located very close
to the Mid Atlantic Ridge (MAR) being, as such, a thermally active spot. This suggests that the
comparison should be performed with the models containing a basal PDMS layer, a material that can
represent a thermally active zone with a more ductile rheology.

In this example, we can observe that the dextral system creates, similarly to the model, a narrow
collapsed area on the left volcanic cone connected to the right cone by a single dextral fault. The second
cone shows a different configuration than the one observed in the model. This difference can be due to:

a) An interference with a set of left-lateral transcurrent faults located just to the east of this
zone (Madeira et al., 2015);

b) Caused by different internal geometry/different volume of the cone;

c) Strong effect of erosion that affects this island (Madeira et al., 2015).

Despite these differences, this example is most likely a case of interference between two natural
volcanoes placed above a dextral transcurrent system.

One particular shortcoming for this comparison is that since the models did not have an inherent
 crater at the summit, this feature was not simulated. Therefore, additional models containing this feature
would be required to conduct a more accurate comparison.

Another possible shortcoming is that, for the case of the SJT and the PF, is that this fault predates
the formation of the cones (Madeira, 1998), meaning that, at an early stage, these would not act as
obstacles. The natural growth of these volcanic cones steadily increases their volume and mass,
increasing the amount of resistance they can offer to the lateral motion of the fault. This means that if
the model is compared to the recent deformation only, i.e., after the growth of the cones and their
deformation by the fault then these are comparable to the models.

It is worth once more noting, as I did in the Introduction, that models are a simplification of nature
and will never be able to entirely reproduce the complexity of a natural system. In this case, to
summarize, my models are only comparable to present day deformation on these two volcanic cones in
a larger alignment. At this stage of study, no further natural analogues have been found yet further
studies should hopefully show new cases.
7. Conclusions

This work aimed to establish the interference in the deformation of two consecutive obstacles placed above a single strike-slip fault. In addition, it was also a goal to test two different rheological scenarios: a scenario where the obstacles were overlying a basal ductile layer and another this was not present, i.e., presence and absence of a ductile basal zone.

To that extent, I’ve systematically measured key parameters (such as width and direction of the pull-apart basin; axial strain ratio/angular strain of the obstacles, and 3D differences between models with and without a basal ductile layer). These measurements on both obstacles were analyzed to establish a possible interference in the faults developed within them. This objective has been achieved and such an interference was measured and recorded.

Firstly, it was verified that the distance separating the two obstacles controls the spatial availability for them to deform, in other words denies the obstacles the space needed to expand during the deformation. This in turn imposes a strong effect in the overall evolution of the system by forming the narrower and less rotated collapsed areas in the obstacles, increased axial strain ratios. This effect further overshadows the presence of a ductile layer (producing results identical to the models without it) indicating that the distance that separates the obstacles is the key parameter in the end-product of deformation.

By contrast, the evolution of a system is controlled not only by the distance that separates the obstacles but also the presence of a ductile layer. The combination of the differences in axial strain ratio and angular strain for the two obstacles over time shows that the presence of a cone in close proximity increases the deformation on both when a ductile layer is not present. The presence of a basal ductile layer nullifies the effect of proximity and forces the cones to act as a single obstacle, regardless of proximity.

In short, the following points have been verified:

I. The distance between two consecutive obstacles controls the spatial availability for them to deform, leading to narrower collapsed areas, increased axial strain ratios and a decrease in the amount of rotation of the obstacles;

II. The presence of a basal decoupling ductile layer, here assumed to represent a thermally active zone beneath the volcanic cone, nullifies the effects of proximity, causing the obstacles to behave as identical active markers, regardless of the distance between them.

Further research in this topic should focus on establishing the influence of obstacle size in the evolution of the system to establish if smaller or larger obstacles can promote a stronger influence in the final stage of deformation. This possible future study should test the outcomes for:

a) Two obstacles with two different sizes;

b) Two larger obstacles (e.g. twice the volume of the ones used for this work);

c) Two smaller obstacles (e.g. half the volume of the ones used for this work);
This should allow to verify if this effect is universal and unaffected by obstacle size or if it depends on the dimensions of the obstacles. Another improvement that should be made in future works is a measurement of the angular deformation of the grid placed on the model for the incremental offsets.

To conclude, this work has managed to establish that proximity of two obstacles is a key parameter in the end-stage deformation of the obstacles while a decoupling ductile layer causes obstacles to behave as a single one, ignoring the effect of proximity.

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9. References


Appendix I

This appendix contains the coding for the MATLAB™ functions described in section 4.2.

a) Reading.m function:

```matlab
function [] = reading (image_name)

%%
%Image reading. reads and plots the image correctly.

image = imread(image_name); %Reads the image file

imshow (image) %Projects the image
axis image %ensures a correct ratio for image
hold on %Holds the image for the next plotting stage
```

b) Mark.m function:

```matlab
function [ ] = mark(outputname)
%Function to follow the reading script. This will bring up the ginput
%function and write in csv format the position of the vertexes.

hold on %maintaining the previous image open

%Detecting the image and marking the points
[x,y] = ginput;

marker = [x,y];

csvwrite(outputname, marker) %Writes the file down with "outputname"
as a title
end
```

c) Vertplot.m function:

```matlab
function [ ] = vertplot(filename, markertype)
%plots the vertexes obtained from the mark function to allow for
easier
%visualization
%Markertype should be an input for the plot function such as "rx" for
%crosses.

vert = csvread(filename);

hold on
plot(vert(:,1), vert(:,2), markertype)
end
```

d) Centplot.m function:
function []= centplot (centroid_file)

%%
%plots the centroids marked numbered in order.

cent = csvread(centroid_file);

%%
%plotting the centroids with numbering

ID = 1:length(cent);
for i = 1:length(ID)
    text(cent(i,1), cent(i,2), int2str(ID(i)), 'HorizontalAlignment',
        'center', 'VerticalAlignment', 'middle')
end
end

e) StrAnalysis.m function:

function [strain] = StrAnalysis (centroid, top, bottom, left, right)
%Function for analysing data attained from "Mark" function.
%Function written by Jaime Almeida, MSc Student, Uppsala University, 2016.
%Function free to be used as long as the author is cited when so done.
%Any contact should be done at jaime.ed.almeida@gmail.com

%%
%Reading cycle
c = csvread(centroid); %Reading the coordinates for the centroids
t = csvread(top); %Reading the coordinates for the top vertex
b = csvread(bottom); %Reading the coordinates for the bottom vertex
l = csvread(left); %Reading the coordinates for the left vertex
r = csvread(right);

%defining the coordinates from the files read
x = c(:,1);
y = c(:,2);

%%
%Preallocating the variables for easier calculations
axisA = zeros(length(c),1);
axisB = zeros(length(c),1);
long = zeros (length(c),1);
short = zeros (length(c),1);
strain = zeros (length(c),1);

for i = 1:length(c)
    %Strain calculation on the markers
    axisA  = sqrt((l(i,1)-r(:,1)).^2+(l(:,2)-r(:,2)).^2); %Calculates the length of one axis
    axisB  = sqrt((t(i,1)-b(:,1)).^2+(t(:,2)-b(:,2)).^2); %Calculates the length of one axis
if axisA (i) < axisB (i) %verifies if A is the short axis for calculation of the strain ratio
    strain (i) = axisB(i)./axisA(i);
    long (i) = axisB (i); %attributes the value for axisB on this iteration to long axis.
    short (i) = axisA (i); %attributes the value for axisA on this iteration to short axis.
else
    strain (i) = axisA(i)./axisB(i);
    long (i) = axisA (i); %attributes the value for axisA on this iteration to long axis.
    short (i) = axisB (i); %attributes the value for axisB on this iteration to short axis.
end

end

hold on %ensures the picture displayed is held while the plotting occurs

for i = 1:length(strain) %plots the strain ratio depending on its value.
    if strain (i) >= 1 && strain (i) < 1.1
        plot3(x(i),y(i),strain(i), 'bo')
    elseif (strain (i) > 1.1 && strain(i) < 1.2)
        plot3(x(i),y(i),strain(i), 'b+')
    elseif (strain (i) > 1.2 && strain(i) < 1.3)
        plot3(x(i),y(i),strain(i), 'bx')
    elseif (strain (i) > 1.3 && strain(i) < 1.4)
        plot3(x(i),y(i),strain(i), 'yo')
    elseif (strain (i) > 1.4 && strain(i) < 1.5)
        plot3(x(i),y(i),strain(i), 'y+')
    elseif (strain (i) > 1.5 && strain(i) < 1.6)
        plot3(x(i),y(i),strain(i), 'yx')
    elseif (strain (i) > 1.6 && strain(i) < 1.7)
        plot3(x(i),y(i),strain(i), 'ro')
    elseif (strain (i) > 1.7 && strain(i) < 1.8)
        plot3(x(i),y(i),strain(i), 'r+')
    else
        plot3(x(i),y(i),strain(i), 'rx')
    end
end

%%
%output cycle
%Creates a matrix with X,Y coordinates and associated Short axis , Long axis , Strain

out = [x, y, short, long, strain];
csvwrite('StrainAnalysis', out)