Geoscientific Model Development Discussions

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Reply on RC1

Fernanda Alvarado-Neves et al.

Author comment on "3D geological modelling of igneous intrusions in LoopStructural v1.4.4" by Fernanda Alvarado-Neves et al., Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2022-88-AC1, 2022

Dear Referee #1,

Thank you for the feedback and the suggested references. Please find below our response to your comments:

The paper is messy and should completely be re-organised and re-structured. In the present state, the section titles do not reflect what they content. To start, the introduction does not present the object of interest, the igneous intrusions, and they are hardly presented in the section 3, which mixes in each sub-section theorical description and algorithmic proposals. The algorithm description is dispersed and repeated in several parts of the manuscript: part 2.1, then lines 151- 172 in part 3.1, then 182 to 191, and they are mixed with results presentations in sections 4. Section 6, which is supposed to present a "discussion" presents again some results, supposed to be in section 5. The paper should be re-written and ordered following the classical introduction – methods – results-discussion – conclusion plan, which, in the present case would be easy to follow and sounds. To write their introduction, authors could get inspiration from this reference: Claerbout, J. F. (1991). A scrutiny of the introduction. The Leading Edge, 288–291. And both these references are also advised for paper: Sudarshan Iyengar. (2013, May). How to Write a Great Research Paper. Strunk, W., & White, E. B. (n.d.). The Elements of Style.

In more details, Introduction should here 1) present igneous intrusions, from a geological/descriptive point of view, with figures showing the diversity of encountered shapes, and explaining the processes of formation. Then, 2) clearly explain why these shapes cannot be reproduced easily and automatically by existing geomodelling approaches (going deeper in the geomodelling concepts than just saying "it is hard to do it" : explain why (superposition and lateral continuity principles that constitute a pillar of existing approaches, management of unconformities, etc)). 3) then, present papers that treat similar questions of highly convoluted shapes and explain their limitations considering the author's specific question: I do not know works on igneous intrusions, but there are on salt tectonic features. For ex. the authors cite Clausolles et al., 2019, but hardly in the part 2 (for the SGS parametrization in the ODSIM process (?)) while they are close to the present contribution (salt diapirs modelling with an approach inspired by ODSIM). The authors should explain the differences and demonstrate the originality and plus-value of their own contribution. 4) finish with the plan of the paper. On the contrary, fuzzy focuses are made on "structural frames" in the introduction (lines 25-35) and the section 2.2. In both cases, the link with the present work is hardly understandable and so *many details for fold-frame and fault-frame seem useless to understand the contribution of this paper. Section 2.2 could be removed and lines 25-35 limited to one citation.*

We will restructure the paper following the classical introduction – methods – results-discussion – conclusion. A more thorough description of igneous intrusions and current challenges to model them will be included. Regarding the structural frames, we will clarify the importance of using a structural frame for the approach, and if it seems reasonable to improve the quality of the text, we will remove the details of fold and fault frames.

Vocabulary is not appropriate: "anisotropies" is the general term used by the authors to describe apparently faults and stratigraphic surfaces, and it is not right.

Anisotropies of the host rock has been described by previous authors as major controls on igneous intrusions emplacement, such as Clemens and Mawer (1992), Hogan and Gilbert (1995), Vigneresse et al., (1999), Cruden and Weinberg (2018), Schofield et al., (2012).

Clemens, J. D. and Mawer, C. K.: Granitic magma transport by fracture propagation, 204, 339–360, https://doi.org/10.1016/0040-1951(92)90316-X, 1992

Cruden, A. R. and Weinberg, R. F.: Mechanisms of Magma Transport and Storage in the Lower and Middle Crust—Magma Segregation, Ascent and Emplacement, in: Volcanic and Igneous Plumbing Systems, Elsevier, 13–53, https://doi.org/10.1016/B978-0-12-809749-6.00002-9, 2018

Hogan, J. P. and Gilbert, M. C.: The A-type Mount Scott Granite sheet: Importance of crystal magma traps, J. Geophys. Res. Solid Earth, 100, 15779–15792, https://doi.org/10.1029/94JB03258, 1995.

Schofield, N. J., Brown, D. J., Magee, C., and Stevenson, C. T.: Sill morphology and comparison of brittle and non-brittle emplacement mechanisms, J. Geol. Soc. London., 169, 127–141, https://doi.org/10.1144/0016-76492011-078, 2012.

Vigneresse, J. L., Tikoff, B., and Améglio, L.: Modification of the regional stress field by magma intrusion and formation of tabular granitic plutons, 302, 203–224, https://doi.org/10.1016/S0040-1951(98)00285-6, 1999.

Concerning the method *[which should be presented from a general point of view, not on particular CS]*

We will restructure the description of the methods section so it is presented in a general way and Case Studies will be presented in results.

Regarding your suggestions for the path search algorithm, we will consider removing the shortest path algorithm as the same results can be achieved without this step. We will refer to the suggested references if we keep the description of the shortest path algorithm.

On the "structural frame": Beside the fact that it is presented several times (3.2 and 4), each time incompletely, the necessity of this step is unclear. Demonstrating the interest of these 3 directions by comparing with a more classic approach without this structural frame but an anisotropic 3D variogram (like in Clausolles et al., 2009) would be more convincing. The time and user expertise needed to perform so many steps should be discussed. The way this step is incorporated in the global workflow was unclear to me. I "guess" it replaces the distance field computed in ODSIM, but it is never really said, and it remains unclear why this step is changed.

The structural frame replaces the skeleton of the ODSIM, so the threshold values are distances to the axes of the structural frame. This allows us to simulated distances to constrain the thickness of the intrusion, and distances to constrain the width of the intrusion. The intrusion network (originally built using shortest path algorithm) is essentially a way to generate more value constraints for the Coordinate G of the structural frame, with the particularity that these constraints honour the anisotropies of the host rock involved in the emplacement of the intrusion. These value constraints are points that approximate the location of the roof or floor contact. The structural frame can be also constrained with other field measurements (inflation vector and flow direction vector) that cannot be used by interpolation algorithms (RBF, co-kriging, DSI). The structural frame is also used to parameterise simple conceptual models and adapt them for complex intrusion shapes. For example, with the structural frame, a sill complex with steps and sill fragmentation can be modelled as a one simple parallelepiped within the coordinates of the structural frame. Without the structural frame, the conceptual model would be significantly complex. We will include a figure showing more clearly how we use the structural frame coordinates to parametrise the conceptual models.

Regarding the reviewer’s suggestion about demonstrating the interest of these 3 directions by using an anisotropic 3D, we believe this will not be helpful because the anisotropic variogram does not provide a tool to parameterise the conceptual models. The authors believe the conceptual models are a key part of the workflow since they allow us to incorporate interpretations of the intrusion geometry in a traceable and repeatable way.

On the “ODSIM-inspired” part: The difference between the distance field and the random field is not clear in the text while it is a crucial point for the reader to understand. Distance field does not need to be Euclidean (see Rongier et al). This could be, at least, said, and discussed later in the discussion part. If I guess right and the 1 distance field is replaced by the “structural frame”, this should be better explained and the motivations behind this choice should be given. For the SGS generating the random field, why using an isotropic variogram? especially when asymmetric shapes are searched? Why an infinite range? Does it have any sense from a geostatistical point of view in a SGS? I don’t think so

We will clarify that the simulated random fields represent the difference between the conceptual models and the intrusion contact that is being modelled (we called these ‘residual values’). Two groups of random fields are used: one for the lateral contact (width of the intrusion) and one for the vertical contact (thickness of the intrusion). Isotropic variograms and infinite ranges are used so these random fields (i.e. the difference with the conceptual model) are relatively constant and with no sharp changes throughout the model. Sharp changes in the intrusion geometry such as sills or pluton steps are controlled by the structural frame, and therefore there is no need to achieve this in the simulations. Furthermore, as suggested by the second referee, we will assess the use of an exact interpolation method instead of simulations.

How do you infer the histogram parameters for running the SGS? No demonstration is provided from the data

Why not using Gibbs sampler when you want to fit data? The part about data fitting is quite unclear.

We will include how the histograms are calculated, and we will clarify that the data conditioning is reached using Sequential Gaussian Simulations.

How do you managed data which are not located on the envelope of the intrusion but inside or outside?

How do you manage data that say "no intrusion here"?

Data points that are not located in the intrusion contact are not used but will be considered for further improvements of the method. This will be discussed in the text.

One point of ODSIM is that the SGS generates a random field, and thus, when you mix the distance field with the random one, you obtain several equiprobable realizations: it is stochastic. Here the stochasticity is not presented in the results, only one result is each time presented. And the interest of this stochasticity is not really highlighted.

We will discuss briefly the usefulness of doing stochastic simulations, however, presenting in the text more than one model for each Case Study is outside the scope of this work. Since the simulation outcomes represent the differences with respect to the conceptual model constrained by the data, we expect the coarse scale geometry of the intrusions should not differ significantly, and we will evaluate to include as supplementary material different realizations of the case studies.

Results [they should incorporate the presentation of the CS (not introduced earlier, as the method part should be general) and the results obtained on it]:

Igneous intrusion shapes: only sills are presented while the introduction speaks of sill, plutons, dikes, laccoliths. Several examples should be provided and compared with what is obtained with other methods especially, a conceptual model is presented for pluton, but not really illustrated. If only sill and plutons are considered, this should be clearly stated in the title, abstract and introduction. And this limitation should be discussed and presented as a future work in conclusion.

Sills and plutons 3D models are presented in the case studies. Presenting these case studies is sufficiently illustrative enough because even though such intrusions differ significantly in nature, the modelling workflow is the same, the main difference being the conceptual model defined for each case. Examples of conceptual models are presented for both sills and plutons in Figure 3. The authors will discuss whether adding conceptual models of laccoliths and dykes will anything significant. If not, we will highlight that their tabular morphologies are similar to sills or tablet-shape plutons.

The case studies should incorporate the demonstration of the variogram and histogram definition from the data

We will include the variogram and histogram definition for case studies.

CS3: why so much data? where should they come from in general cases?

The Case Study 3 has 0.1% of the original contact points dataset. Even though the dataset is dense, the objective of this examples is comparing the results with RBF interpolation. A typical dataset for modelling intrusions is described in the introduction.

ODSIM can generate shapes in the absence of observation points. Here no results are provided in the absence of points indicating the position of the intrusion contour. This should be rectified.

Generating models with no data is beyond the scope of this paper.

One realization, coming from a stochastic process is compared to the solution of a deterministic approach (the RBF-based), and to the "ideal" solution:

stochastic processes do not aim to find "the solution" but a range of realistic solutions *which embraces the possibilities given the non-completeness of data. In that sense, at least several realizations (10-50-100?) should be considered and compared to the "solution". The variability of the realizations should be estimated and in several context of data: the variability should reduce with increasing data. Tt is strange to compare a deterministic solution (RBF) with 1 realisation of as tochastic method which do not use the same input data… You can say that they are usable with different input data, but it is difficult to be objective here.*

The comparison with RBF is performed because RBF is one of the interpolation techniques used to model igneous intrusions in 3D in currently available modelling packages. While the authors understand the reviewer's concern about comparing one solution of a stochastic process with the outcome of a deterministic process, we believe our approach is valid because the whole aim of the stochastic simulation is to better constrain the intrusion contact surface. In the models built using the proposed workflow, the intrusion contact is given by the isovalue 0 of a scalar field. This scalar field is computed so the intrusion contact given by the simulations (*i.e.,* contact = conceptual model – residual distances) is the isovalue 0 of the scalar field. For the purpose of this workflow, the simulations can be replaced by interpolating the residual values (*i.e.,* distances between the data and the conceptual model). This will be implemented and discussed.

The contact data points used for models A, C and D are the same, the only difference is that models C and D also include propagation and inflation vector data, while model A includes planar constraints. The input dataset for Model B has around 5 times the number of data points compared with the other models. This was done to illustrate that RBF can reproduce more realistic geometries (compared to what was mapped in the seismic survey, Figure 9) when dense datasets and gradient constraints are provided. Event though the input data are not exactly the same (because both method do not use the same type of input data), we believe the comparison is fair as models A, C and D use similar amount of value and planar constraints.

Discussion: The influence of variogram and histogram used for the random field generation has been demonstrated crucial (Henrion et al 2008, Clausolles et al 2019). This should be discussed with the help of a small sensitivity analysis, trying various variogram settings.

We believe a sensitivity analysis to assess the influence of the variogram is out of the scope of the paper. We will reference previous works (e.g. Henrion et al., 2010, Clausolles, et al., 2019). As mentioned before, and as suggested by the second referee, we will implement exact interpolation to replace the use of stochastic simulations.

The stochasticity should be discussed and the comparison with RBF should consider the fact that RBF is deterministic. The capacity of the method to reduce uncertainties as the amount of data increase should be discussed. the computing time should be given and discussed. The results concerning the shapes should be discussed as compared to the one proposed in other contexts (eg salt diapirs or karsts anisotropic shapes like in Rongier et al 2014). In particular, the interest of the structural frame compared to the simple introduction of an "standard object" as a skeleton and an adapted distance field (I guess the advantages, but the authors say nothing about it and demonstrate nothing)

We will discuss the stochasticity and comparison with the deterministic approach, the capacity of the method to reduce the uncertainties (however, the quantification of the uncertainties is out of the scope of this paper), the computing time, and the advantages of using structural frames.

Is it possible to combine several types of intrusion in one model?

More than one intrusion can be modelled in one 3D model as independent objects. This is showed in case study 1 and will be stated in the text

Current limitations (considered shapes, grid requirements, …)

Limitation of the method are described in the last paragraph of the discussion section

Regarding the minor comments, these will be addressed to improve the quality of the text.

Code evaluation: Yes, the links are links to the examples. We will fix the link to the LoopStructural python library.