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Reply to: One neuron versus deep learning in aftershock prediction

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REPLYING TO Mignan, A. & Broccardo, M. *Nature* https://doi.org/10.1038/s41586-019-1582-8 (2019)

Before commenting on the interesting philosophical issues raised by Mignan and Broccardo[1], I note that the authors were able to reproduce the results presented in our paper[2] (available at https://github.com/phoebemrdevries/Learning-aftershock-location-patterns). In the accompanying Comment[1], the authors make two conceptual points: (1) a model with fewer parameters can explain the same feature to label mapping just as well as the neural network presented in our paper[2] and (2) quantities such as the average fault slip and the distance from the mainshock are precise and useful predictors that can be used instead of the elastic stresses that we used.

The fact that a neural network result can be closely approximated by a simpler model (the first point of Mignan and Broccardo) is a core result of our paper and one that we described in detail. In fact, it is the way in which our findings are interpretable. For example, the entire last paragraph of our paper is dedicated to this result, stating explicitly: "In other words, without any assumptions about receiver plane orientation or geometry, the neural network identified an aftershock location forecast that is strongly correlated with a small number of physical quantities", including the maximum shear stress and the von Mises yield criterion. Similarly, we presented a graphical representation of this central result in figure 2d of our paper[2], where we presented the neural network prediction, and in figure 2b, c, where we showed how the maximum shear stress and the von Mises yield criterion provide close approximations. In the first part of their Comment[1], Mignan and Broccardo recapitulate this central result of our paper by constructing a single-node network that yields an AUC score approximately equal to that obtained by the neural network in our study[2] or the von Mises yield criterion alone (which, when filtered through a sigmoid, is a single-node network). The perspective presented in our paper is that it was interesting to discover that a neural network learned a simple, non-exotic combination of stresses that provided considerably improved precision.

Whereas point (1) is a restatement of a central result from our paper, point (2) represents a philosophical departure. In particular, they show that two parameters, the average mainshock fault slip and the fault–aftershock distance, are also precise and interpretable predictors of aftershock locations, serving as a parsimonious phenomenological model. We used an alternative, physics-focused approach to focus on physical parameters that appear in the equations for frictional fault failure (normal and shear stresses) and fracture (difference in principle stresses). Our approach ensures that the labels are consistent with the conservation of both mass and linear momentum. In other words, we included prior information about the physics of solid Earth by developing labels that were consistent with elastic-stress transfer. Because stresses decay with distance from a mainshock, the direct use of distance as a proxy for locally resolved stresses may be an effective approximation for operational aftershock forecasting of the type considered by Mignan and Broccardo. I thank the authors for replicating our results and for their insightful Comment.

1. Mignan, M. & Broccardo, M. One neuron versus deep learning in aftershock prediction. *Nature* https://doi.org/10.1038/s41586-019-1582-8 (2019).
2. DeVries, P. M. H., Viégas, F., Wattenberg, M. & Meade, B. J. Deep learning of aftershock patterns following large earthquakes. *Nature* **560**, 632–634 (2018).

Author contributions B.J.M. conceived the idea and wrote the manuscript. The other authors of the original study[2] were not involved in the preparation of this Reply.

Competing interests The author declares no competing interests.

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