Estimating Dike Propagation Distance During Global Contraction With Analogues and Frictional Faulting Theory

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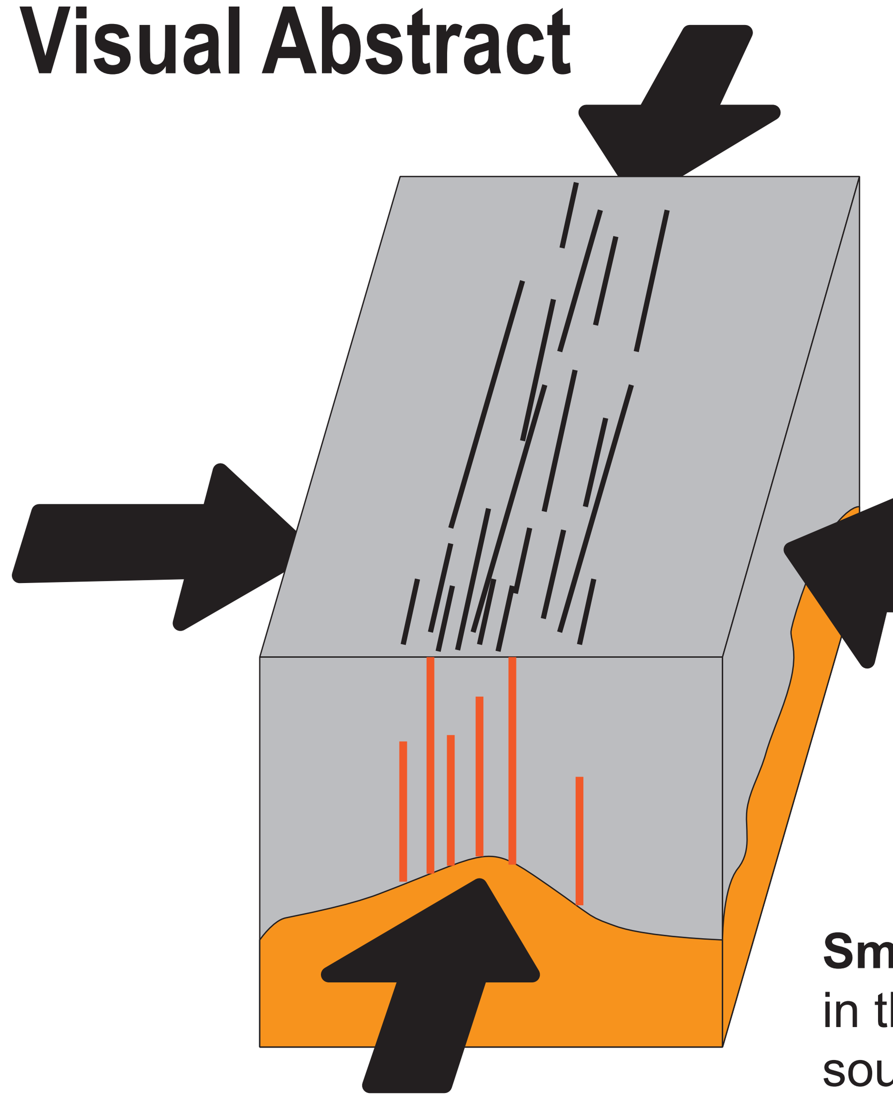
Making sense of effusive volcanism in an overall horizontally compressive stress regime

Visual Abstract



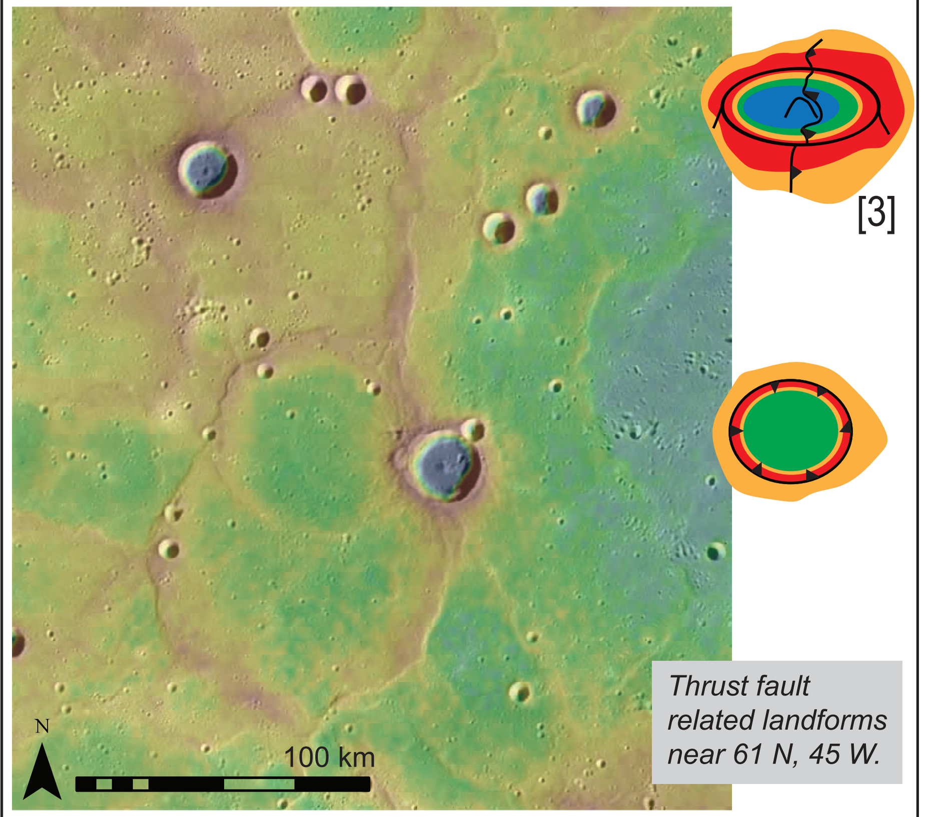
Vertical dikes imply propagation through a stress regime where the **least principal stress is horizontal.**

Thrust faults imply propagation through a stress regime where the **least principal stress is vertical.**

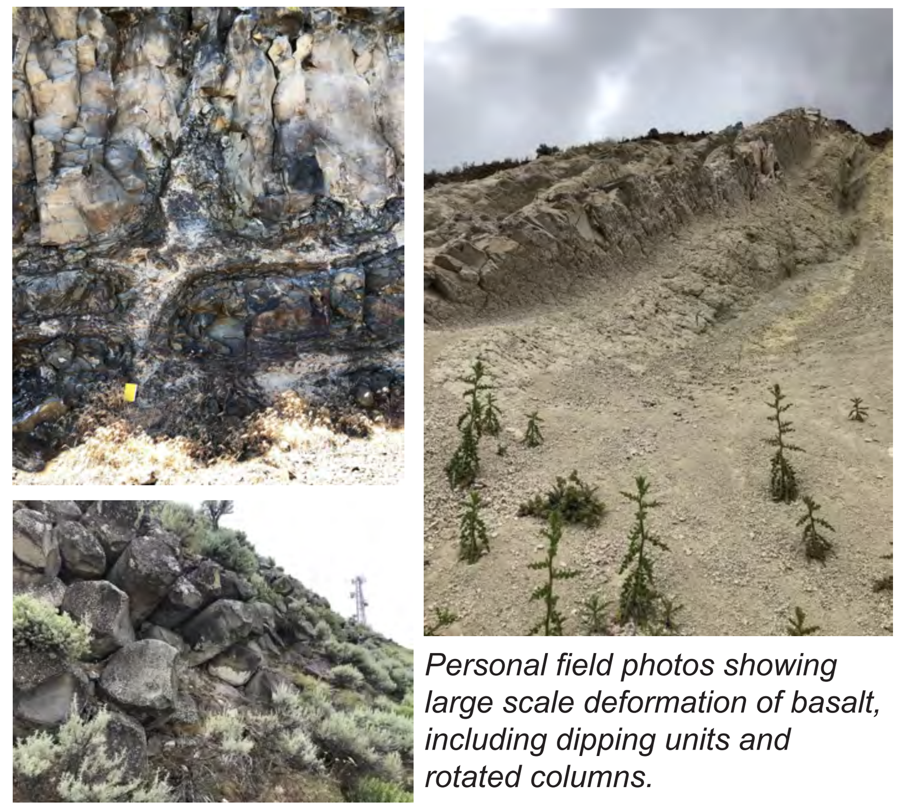
Earth analogues and models [1] show that dikes **can propagate** finite distances in horizontally **compressive stress regimes**.

Smooth Plains emplacement could happen in the context of **global contraction** with magma sources between **3 and 27 km.**

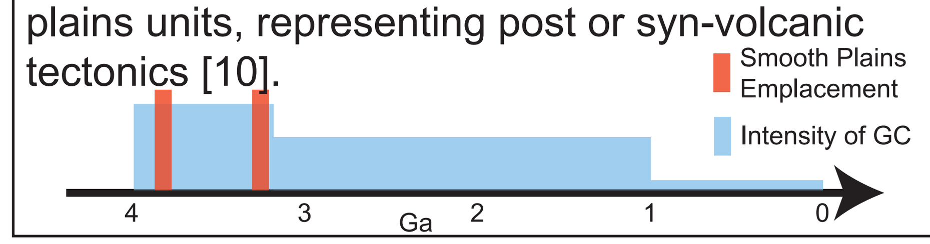
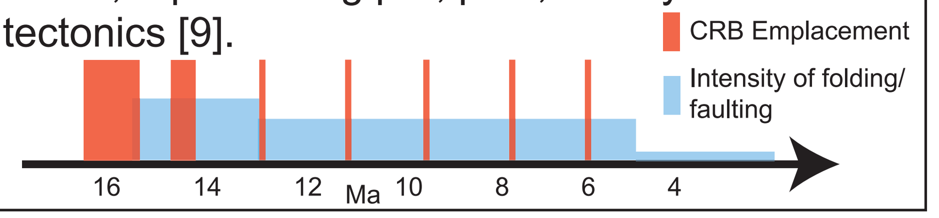
Earth Analogue



Thrust fault related landforms near 61 N, 45 W.



Personal field photos showing large scale deformation of basalt, including dipping units and rotated columns.

Volcanically emplaced units with mafic presumed basaltic composition [4].	Volcanically emplaced units with varying basaltic compositions.
Emplacement through multiple epsidodes of effusive volcanism over a geologically "short" period of time (100 Ma) [5, 11].	Emplacement through multiple epsidodes of effusive volcanism from 16.8 Ma - 5 Ma [6].
Effusive deposits are relatively thick (~ 0-2 km) and laterally extensive (5.59 x 10^6 km^2) [5,7].	Effusive deposits are relatively thick (~4km) and laterally extensive (200,000 km^2) [8].
Thrust fault related landforms propagate through plains units, representing post or syn-volcanic tectonics [10]. 	Thrust faults and folds propagate through CRBs, representing pre, post, and syn-volcanic tectonics [9]. 

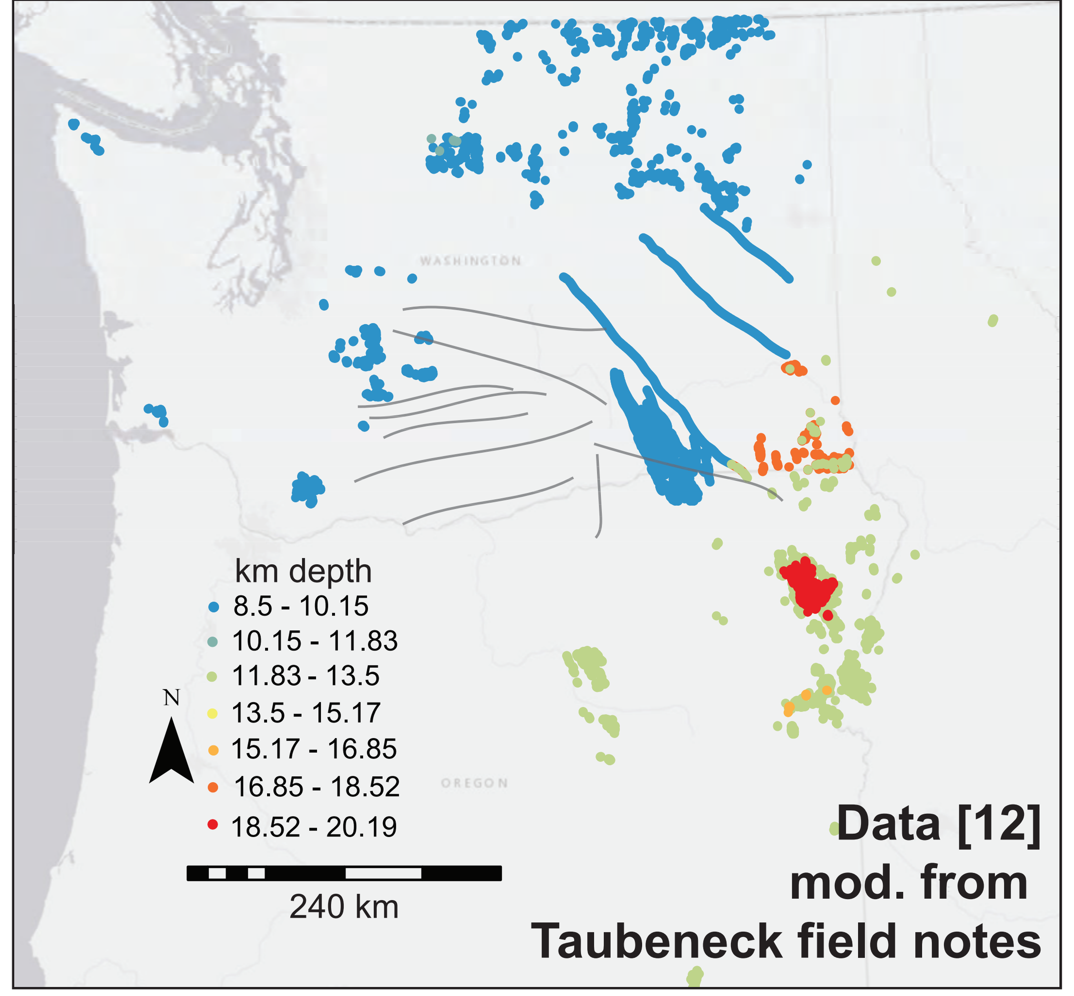
Dike Propagation in Compressive Stress Regimes

Menand et al. [1] modeled the path of dike propagation in a compressive stress regime by increasing the horizontal stresses in gelatin injected with air. They derived an emperical equation for the distance a dike can propagate before rotating over into a sill.

d, distance of propagation before rotation into sill	
Ts, Tensile strength	8 - 14 MPa *3 MPa for heavily fractured basalt [12]
$\Delta\rho$, Density difference	~0.150 kg/m^3
$\Delta\sigma$, Differential Stress	20 - 100's of MPa

$$d \simeq \frac{Ts}{\Delta\rho g} e^{\left[(0.10\pm0.01)\frac{Ts}{\Delta\sigma}\right]}$$

Most dikes can travel ~15 km, the suggested depth from the magma source of the CRBs [12].



Data [12] mod. from Taubeneck field notes

Mercury Analogue

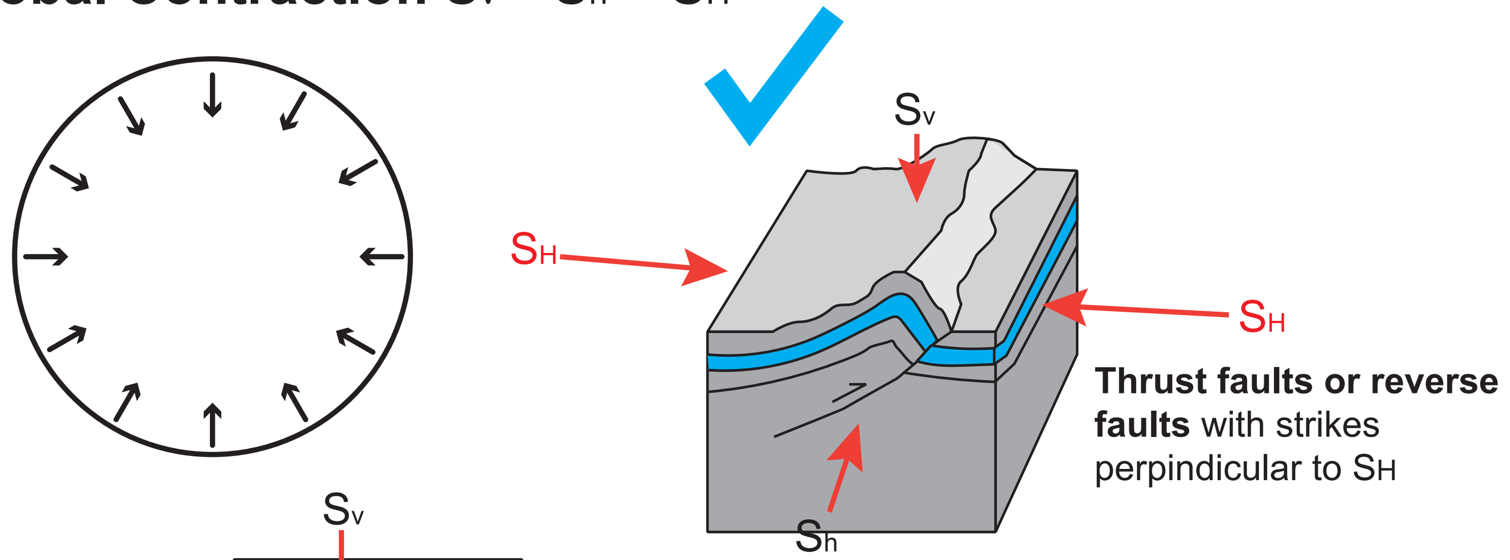
Using the same equation, and differential stresses of 2.1Sv, dikes on Mercury are capable of propagating:

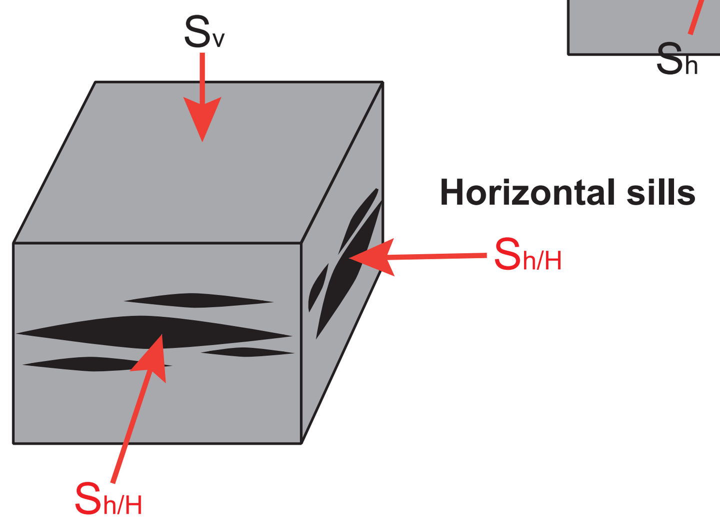
- ~27 km when the bedrock is mostly intact.
- ~3.5 km when the bedrock is heavily fractured.

The smooth plains can be emplaced during global contraction.

Stress Context

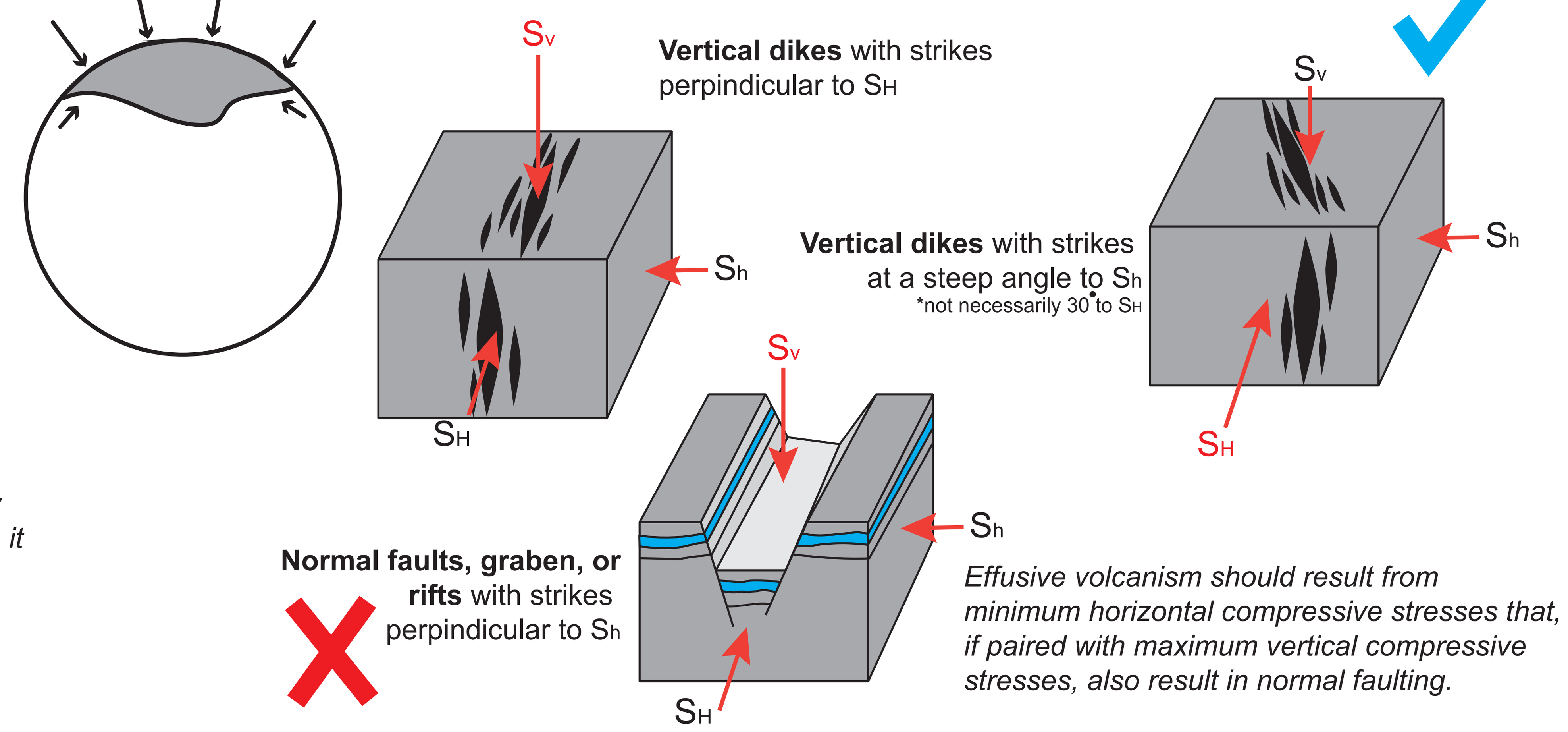
Global Contraction $S_v < S_h < S_H$





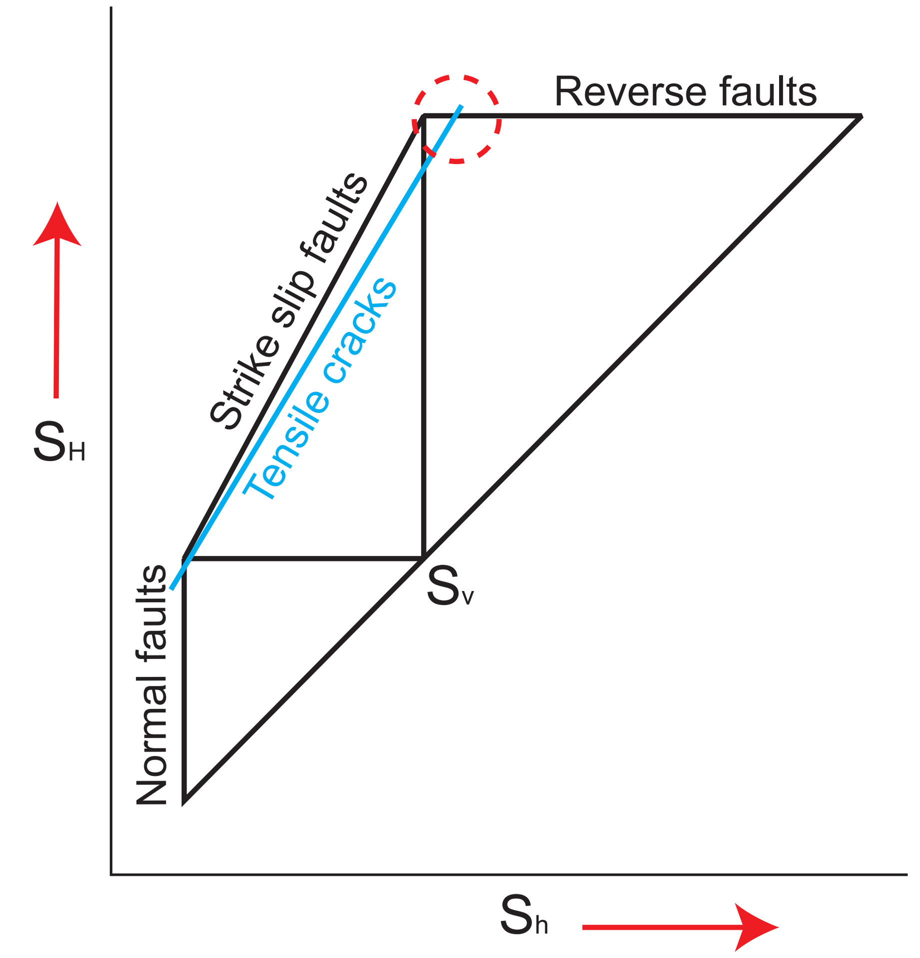
Global contraction should result in horizontally compressive stresses that limit vertical dike propagation, effectively closing off pathways for magma to make it to the surface.

Effusive Volcanism $S_h < S_H < S_v$ or possibly $S_h < S_v < S_H$



Effusive volcanism should result from minimum horizontal compressive stresses that, if paired with maximum vertical compressive stresses, also result in normal faulting.

"Zobackogram" [2] and Frictional Faulting Theory



This diagram plots the equations from FFT as lines. These equations are true when structures are observed. For example, if we neglect pore pressure:

$$\frac{S_H}{S_v} = \left(\sqrt{\mu^2 + 1} + \mu\right)^2$$

holds true when thrust or reverse faults are observed. If $\mu = 0.6$, then $S_H = 3.1S_v$ and the differential stress is $2.1S_v$.

If tensile cracks are observed,

$S_H = 3S_h - 2\,P_p$ or $S_H = 3S_h$

Observations then imply that:
$S_H >> S_h > S_v$
so dikes must be propagating in a compressive stress regime.

References

[1] Menand, T., Daniels, K.A., Benghiat, P. (2010). Dyke propagation and sill formation in a compressive tectonic environment. JGR Solid Earth, 115, B08201.
[2] Zoback, M.D. (2016). Reservoir Geomechanics. Cambridge University Press, New York, NY.
[3] Klimczak, C., Byrne, P.K., Celâl Şengör, A.M., Solomon, S.C. (2019). Principles of structural geology on rocky planets. Canadian Journal of Earth Sciences, 56, 1437-1457.
[4] Head, J.W. et al. (2011). Flood Volcanism in the Northern High Latitudes of Mercury Revealed by MESSENGER. Science, 333, 1211997.
[5] Ostrach, L.R. et al. (2015). Extent, age, and resurfacing history of the northern smooth plains on Mercury from MESSENGER observations. Icarus, 250, 602-622.
[6] Kasbohm, J., Schoene, B. (2018). Rapid eruption of the Columbia River flood basalt and correlation with the mid-Miocene climate optimum. Science Advances, 4, eaat8223.
[7] Denevi, B.W. et al. (2013). The distribution and origin of smooth plains on Mercury. JGR Planets, 118, 891-907.
[8] Reidel, S.P, Camp, V.E., Tolan, T.L., Martin, B.S. (2013). The Columbia River Flood Basalt Province. GSA Special Publications, 1-45.
[9] Kelsey, H. et al. (2017). The Story of a Yakima Fold and How It Informs Late Neogene and Quaternary Backarc Deformation in the Cascadia Subduction Zone, Manastash Anticline, Washington, USA. Tectonics, 36, 2085-2107.
[10] Crane, K., Klimczak, C. (2017). Timing and rate of global contraction on Mercury. GRL, 44, 3058-3089.
[11] Byrne, P.K. et al. (2016). Widespread effusive volcanism on Mercury likely ended by about 3.5 Ga. GRL. 43, 7408-7416.
[12] Morris, M.C., Karlstrom, L., Nasholds, M.W.M., Wolff, J.A. (2020). Geosphere 16, 1082-1106.