SENSITIVITY OF SLAB SINKING TIMES TO MANTLE VISCOSITY AND SLAB BUOYANCY

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1. INTRODUCTION

- Mechanisms controlling the breakup and amalgamation of supercontinents are not well understood
- Lithosphere, subducting slabs, deep mantle structures, and upwellings are all important for the spatial and temporal evolution of supercontinents (fig.1)

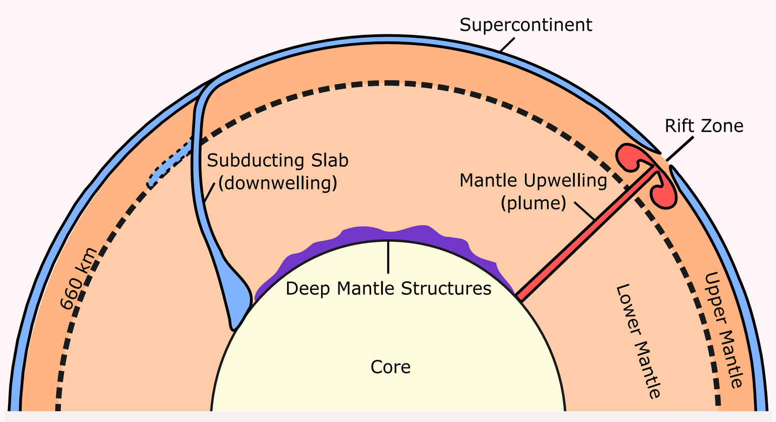

Fig.1: Schematic representation a mantle convection 'cycle', comprising key mantle structures associated with supercontinents.

- We aim to constrain the timescales on which subducting slabs reach the lower mantle
- We consider if each supercontinent cycle can be considered in isolation, or rather with inherited structures from previous cycles.

2. METHODS

We utilise the 3D mantle convection code ,TERRA (Baumgardner, 1985), to conduct a sensitivity analysis of slab sinking times to variable plate buoyancies and mantle viscosities. Buoyancy here is considered with respect to plate size and composition. We present 9 incompressible models with an average radial grid resolution of ~90 km which are driven at the surface by 1Ga of plate motion history (Merdith et al., 2021), based on the following variables:

2.1 PLATE SIZE

Plate size (defined here by the length of global subduction zones (SZ; fig.2)) has important implications for the thermal and density structure of a downwelling slab.

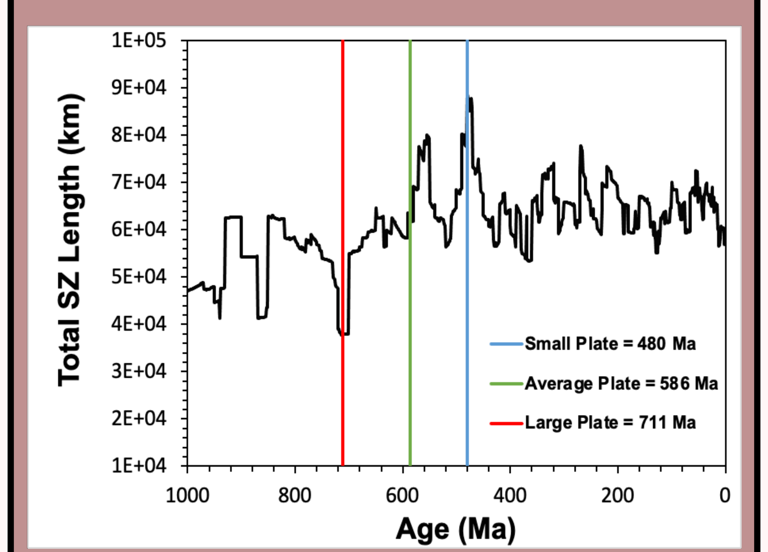

Fig.2: Total subduction trench length for each plate stage of the Merdith et al (2021) reconstruction.

We test the extent of these implications by running models with large, average, and small plate sizes, with each plate stage being run continuously for the duration of the model.

2.2 PLATE COMPOSITION

- We vary the density contrast between basaltic & harzburgite in the lower mantle by 1-3%
- As such we can compare the implications of thermal vs compositional buoyancy of slabs.

2.3 MANTLE VISCOSITY

We test 4 different viscosity structures through the mantle (fig.3), each with an average viscosity on the order of 10^{23} Pa.s (M1-8).

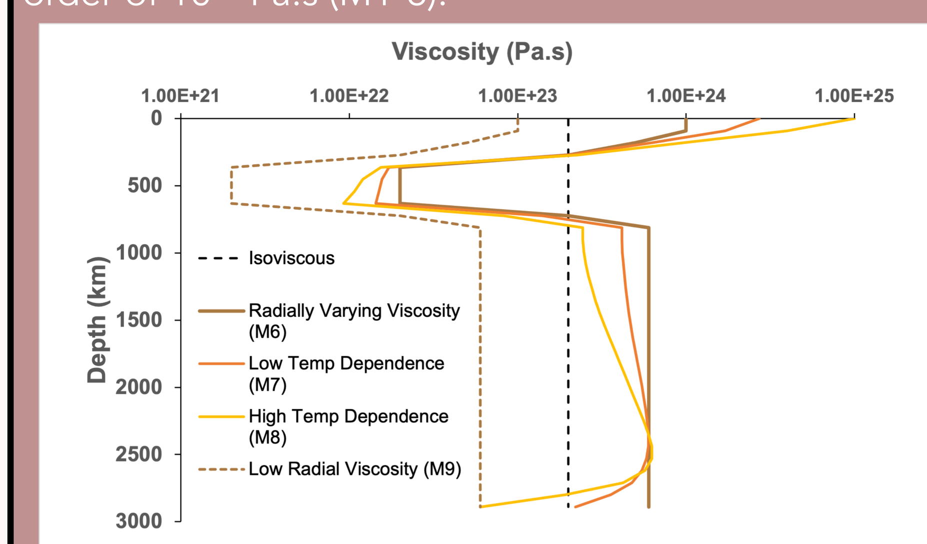

Fig.3: Layer averaged viscosity profiles.

Additionally, we test a radial viscosity profile with an average viscosity of 10^{22} Pa.S (M9).

This sensitivity analysis comprises the following model setups:

Model Number	Plate Size	Density Contrast	Viscosity Profile
1(REF)	Large	3%	Isoviscous
2	Medium	3%	Isoviscous
3	Small	3%	Isoviscous
4	Large	2%	Isoviscous
5	Large	1%	Isoviscous
6	Large	3%	Radial Viscosity
7	Large	3%	Low Temp Dependency
8	Large	3%	High Temp Dependency
9	Large	3%	Low Radial Viscosity
10	Large	3%	Pre-conditioned

Table 1: Model Index.

For model 10, we implement an isoviscous set up which is allowed to mix for 200 Ma with free-slip boundaries to introduce lateral heterogeneity and viscosity variations, prior to applying plates.

To calculate slab sinking times, we define slabs as having a composition of >75% basalt and a negative temperature anomaly of at least 200 K. Slabs are tracked from the first appearance of basalt at a depth of 100 km.

3.1 PLATE SIZE

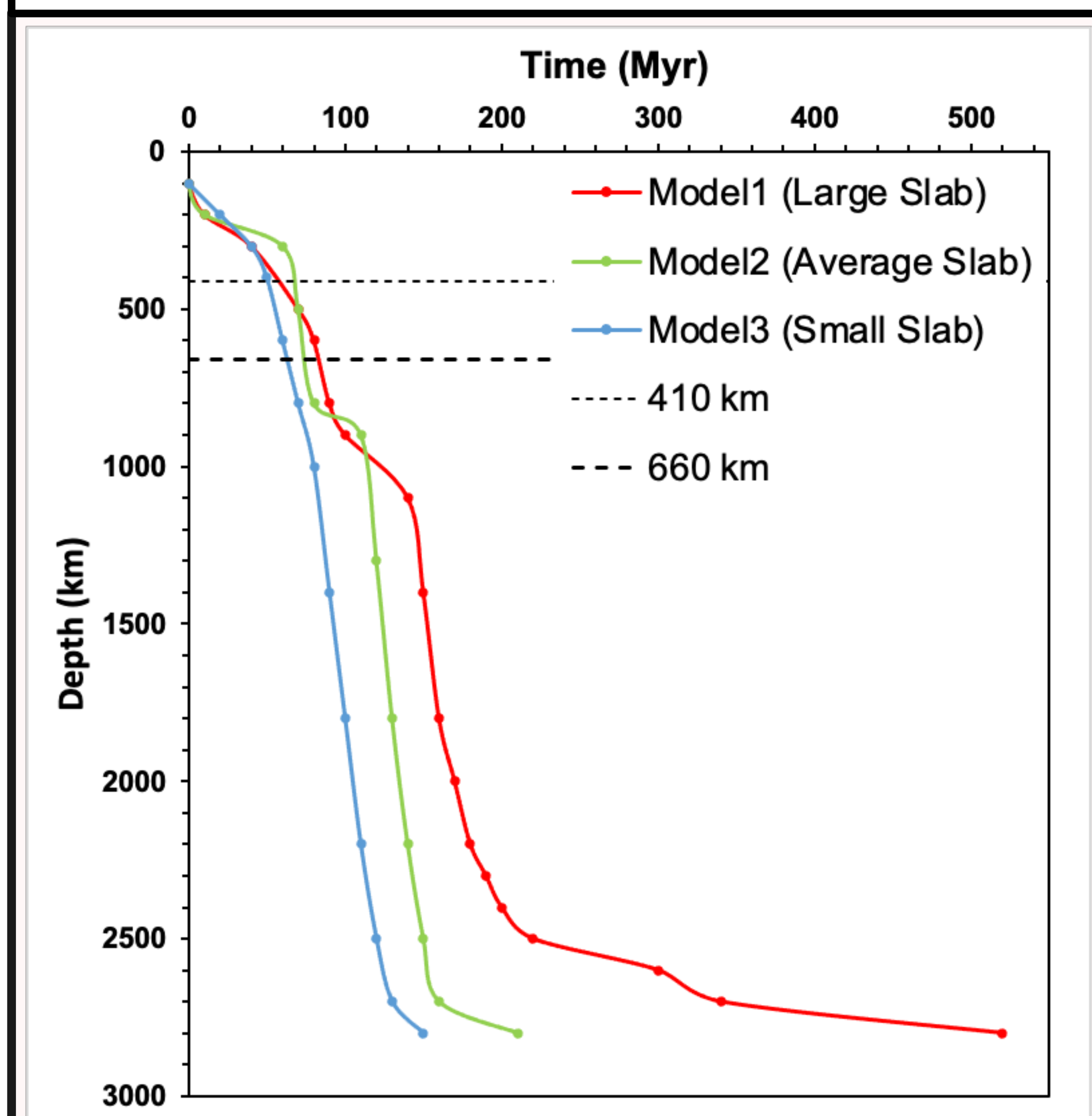

Fig.4: Slab sinking times by plate size.

- Results are associated with signifcant uncertainty (as same slab cannot be tracked across the models), yet sinking times are seemingly dependent on the interplay between density and slab surface area
- Smaller, warmer slabs have lower density than larger, colder slabs yet descend faster through the mantle, suggesting that surface area over which resistive forces act is an important constraint
- Balance between density and surface area is key; slabs with larger surface areas slow beneath the 660 km discontinuity but higher densities allow the slab to pass through
- Larger slabs decelerate in lower mantle as the negative temperature anomaly (& magnitude of negative buoyancy) decreases
- The 'average' slab highlights this interplay, where the steps in sinking history reflect periods where density and resistive forces are seemingly balanced
- Slab dip angle may be an important factor which affects the surface area over which resistive forces act, but currently we cannot control these within TERRA.

3.2 PLATE COMPOSITION

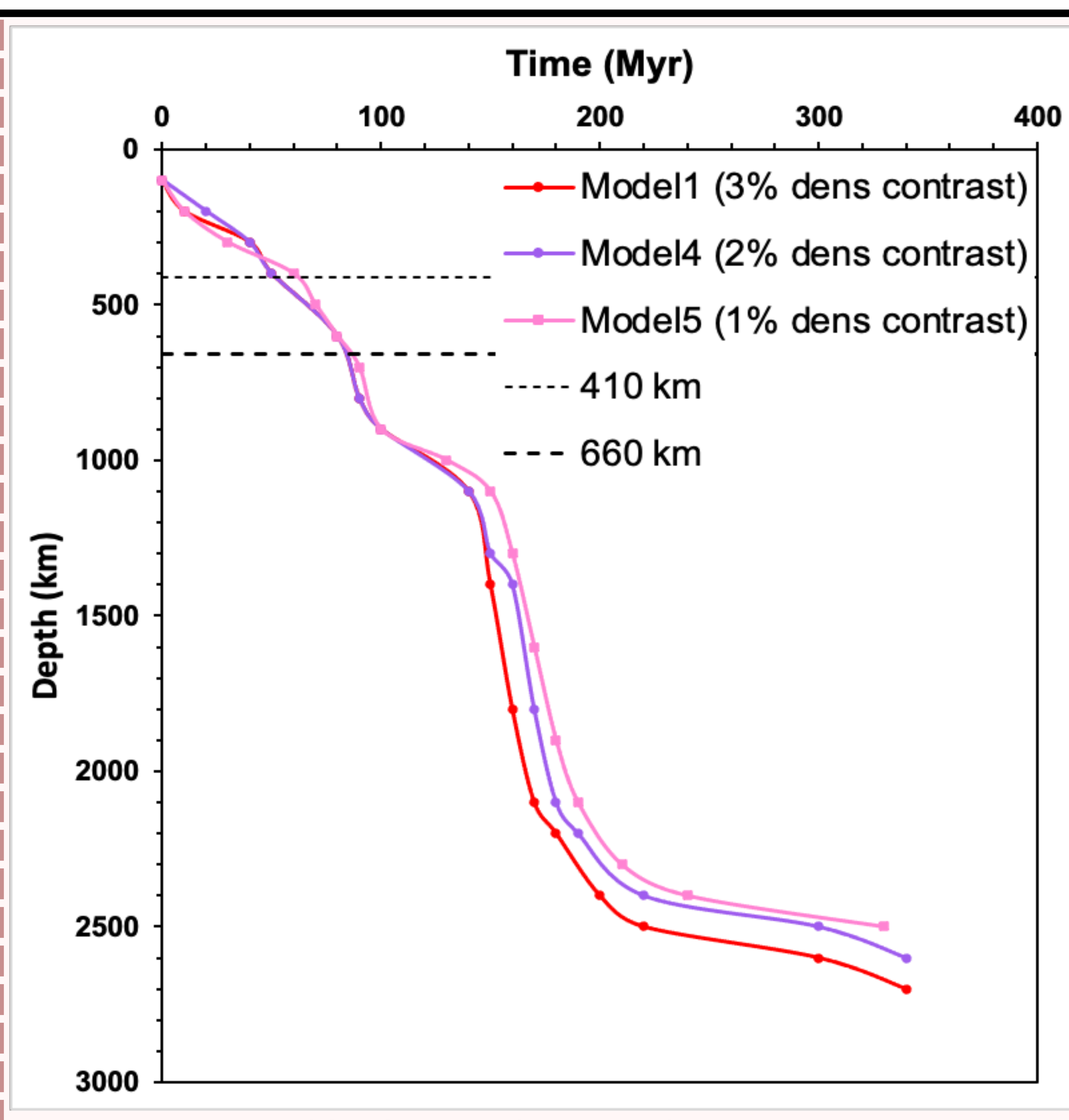

Fig.5: Slab sinking times by varying plate composition.

- Less dense slabs decelerate at a shallower depth in the mantle than denser slabs given the weaker buoyancy contrast between the slabs and the mantle
- Slabs slow down as they approach the CMB, with significant deceleration between 160-200 Myr
- Whilst the cold slab material survives for 330-340 Myr in all models, the depths which they attain decrease proportional to the decrease in density contrast
- Implications of density contrast on slab sinking times are less significant than those of plate size, though composition may ultimately determine the final depth a slab can attain
- Suggests that thermal structure of the plate has a greater affect on the slab sinking history than the composition.

3.3 MANTLE VISCOSITY

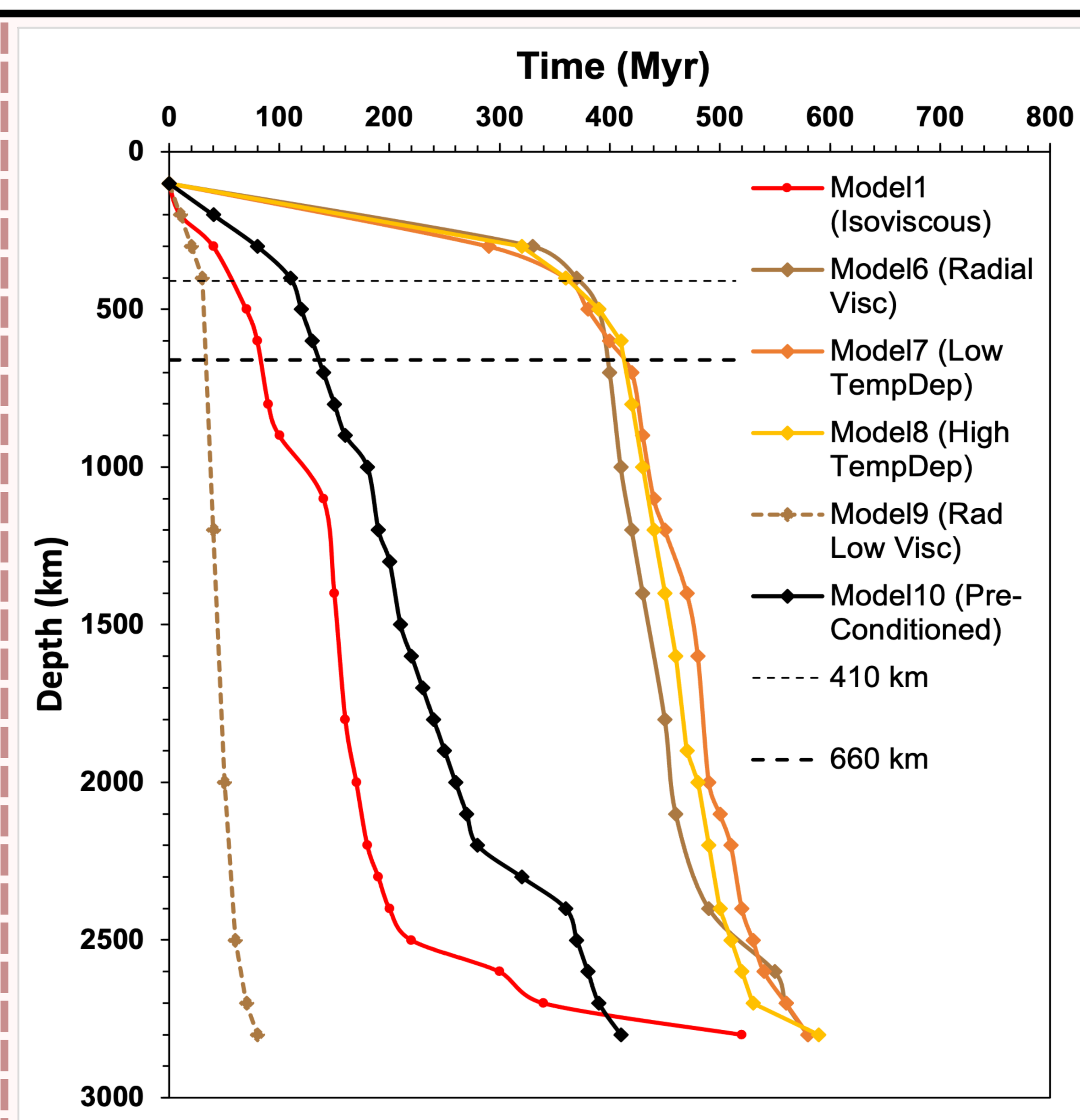

Fig.6: Slab sinking times through contrasting mantle viscosity set-ups.

- The crucial difference between the isoviscous and non-isoviscous set ups is the offset between sinking times in the upper mantle due to the high viscosities (and rapid sinking in M9)
- In M6-8 (see supp. material), the slabs initially spread across the upper mantle, then descend as thick blobs which then sink rapidly, whereas the lower viscosities in M9 mean that basalt breaks up and sinks as a chain of blobs rather than a coherent slab
- M10 exhibits the slowest velocities in the lower mantle, suggesting that lateral variations in viscosity may be signficant, but to a lesser extent than significant radial variation
- From tomography and earthquake data, we know that slabs sink rapidly through the upper mantle in the present day so M6-8 are not representative of modern tectonics
- At the resolution of these models, both high and low end member viscosities may be unrealistic of present day Earth-like behaviour, therefore the model results appear extreme
- These results may still give an indication of the mechanisms controlling slab sinking times and potentially the temporal evolution of subduction in a cooling Earth.

5. CONCLUSIONS

- *Slab sinking times are predominantly controlled by thermal processes, specifically the thermal (density) structure of plate at the surface, and the viscosity of the mantle*
- *In our models, the effects of mantle viscosity are most notable in the upper mantle where the sinking velocities are most variable across each case*
- *Slab sinking histories (for isoviscous models) have a general duration of 100-250 Myr with signficant phases of stalling lasting a maximum of 60 Myr between 800-1100 km depth.*
- *This is inkeeping with the suggested subduction durations and presence of a 'slab stagnation zone' proposed by Van der Meer et al, (2018).*

FUTURE WORK

Increase model resolution to average grid spacing of ~25 km to better resolve the geometry of slabs and constrain more accurate sinking profiles

Sample slab geometries at smaller timesteps to resolve the uncertainty around sinking histories in the uppermost mantle.

Compare multiple slabs from the same model to establish the bounds of possible sinking times

6. REFERENCES

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Van der Meer, D.G., Van Hinsbergen, D.J. and Spakman, W., 2018. Atlas of the underworld: Slab remnants in the mantle, their sinking history, and a new outlook on lower mantle viscosity. Tectonophysics, 723, pp.309-448.

7. SUPP. MATERIAL

SCAN QR CODE:

- Animation of each simulation run
- Full initial conditions

ACKNOWLEDGEMENTS

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