Slab buckling as a driver for periodic and rapid (<5 Ma) changes in subduction speed and overriding plate deformation

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1. Rapid changes in plate motion rate

Novel data from marine magnetic anomalies indicate that rapid changes, within < 5 Ma, in plate motion rate can occur in a single plate 1 (Figure1). Variations in plate motion are often associated with major changes in boundary forces or tectonic setting, however these changes either occur gradually on large time-scales or instantaneous and they can not explain oscillations (acceleration & deceleration) in plate motion.

Slab buckling in the mantle transition zone (MTZ) explains the order of magnitude decrease in slab velocity at the surface and in the lower mantle, but it is also expressed in the forward and backward draping slab in the upper mantle. This changes the slab dip at the subduction contact and the morphology and style of subduction due to changes in the force-balance 2

We show that slab buckling can explain short time-scale, quasi-periodic oscillations in plate-motion of both the subducting and overriding plate and that the average subduction speed controls the amplitude and period of these plate motion changes.

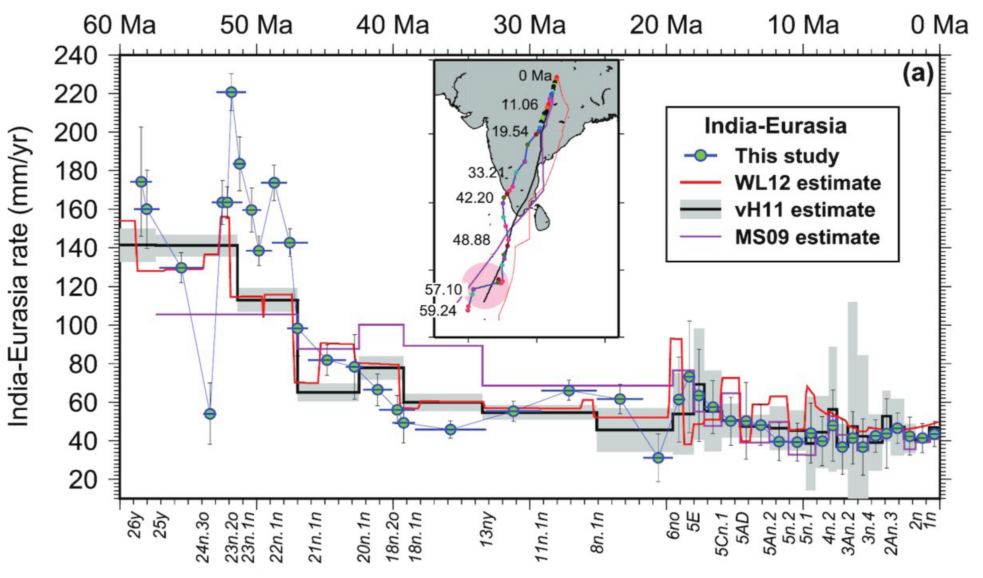

Figure 1: Reconstructed India plate motion rate relative to Eurasia showing the effect of the new high-resolution data (blue circles). With a 50 percent decrease followed by an doubling of plate motion speed within 5 Ma, previously not picked up in plate tectonic reconstructions. Figure from deMets & Merkouriev (2021)1

2. 2D subduction with free or fixed overriding plate

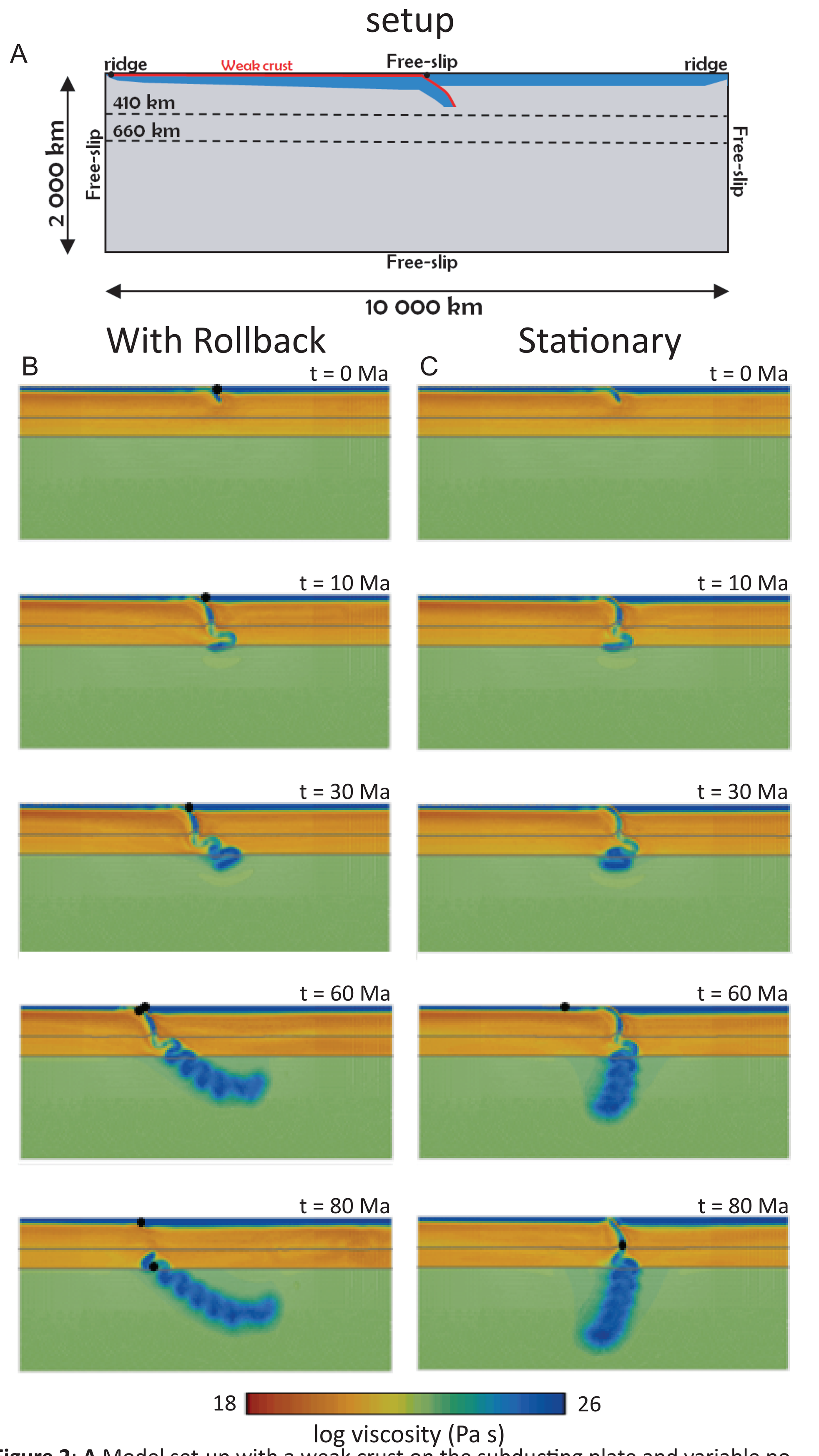

Figure 2: **A** Model set-up with a weak crust on the subducting plate and variable position of the right ridge to start models with rollback or a stationary trench. Other variables changed in the models are the subducting and overiding-plate ages. **B & C** show viscosity snapshots (zoomed-in) of both reference models at different time intervals. Buckling is prominent in both models between the 410 en 660km-discontinuities. Models with rollback have a tilted slab in the lower mantle while stationary trenches create vertical slabs.

In our setup (figure 2A) we give the subducting plate a weak crust to lubricate the subduction interface to create 'free' subduction with no external forcing (after an initial 6 Ma push)3.Furthermore the rheology in our models has been extensively tested 4 We have two sets of models either with rollback (figure 2B) or with a stationary trench (figure 2C) in which we track the motion of the subducting and overriding plates (SP & OP) at the black dots.

Both reference models have similar average subduction velocities, although the model with rollback has much **higher amplitudes** in its oscillations than with a stationary trench (figure 3). The subducting plate in the reference model takes up 100-50 % of the total convergence while the overriding plate's convergence ratio oscillates between 0-50 % (figure 4).

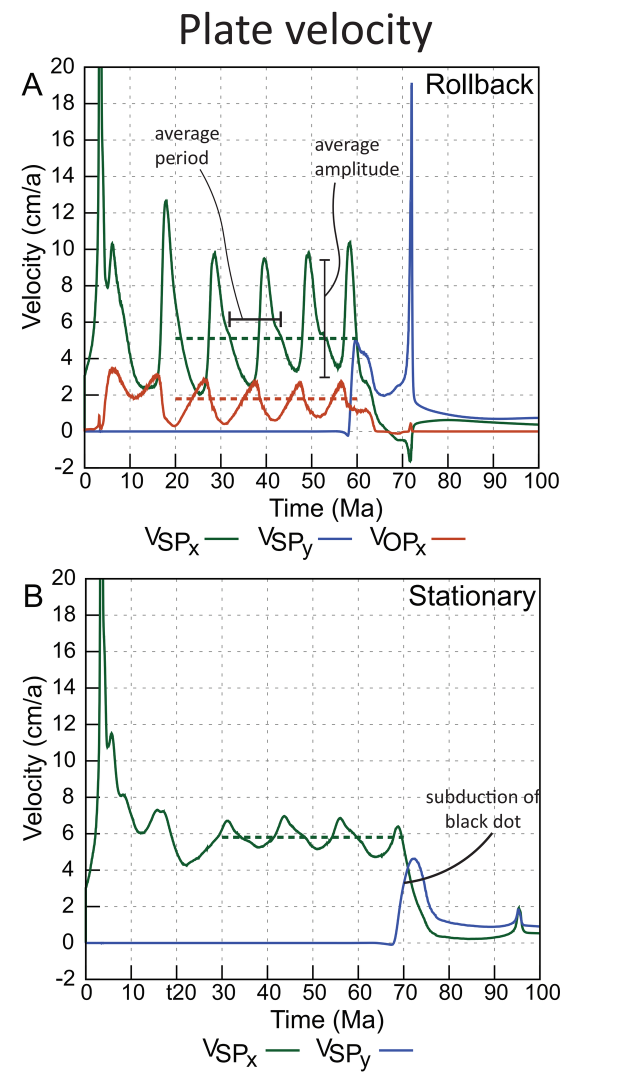

Figure 3: Plate velocity for the black dots of the reference models with rollback (**A** & fig. 2B) and with a stationary trench (**B** & fig. 2C). Shown are the subducting plate velocity (horizontal and vertical) and overriding plate motion (if applicable). The dashed line indicates averages between the shown period.

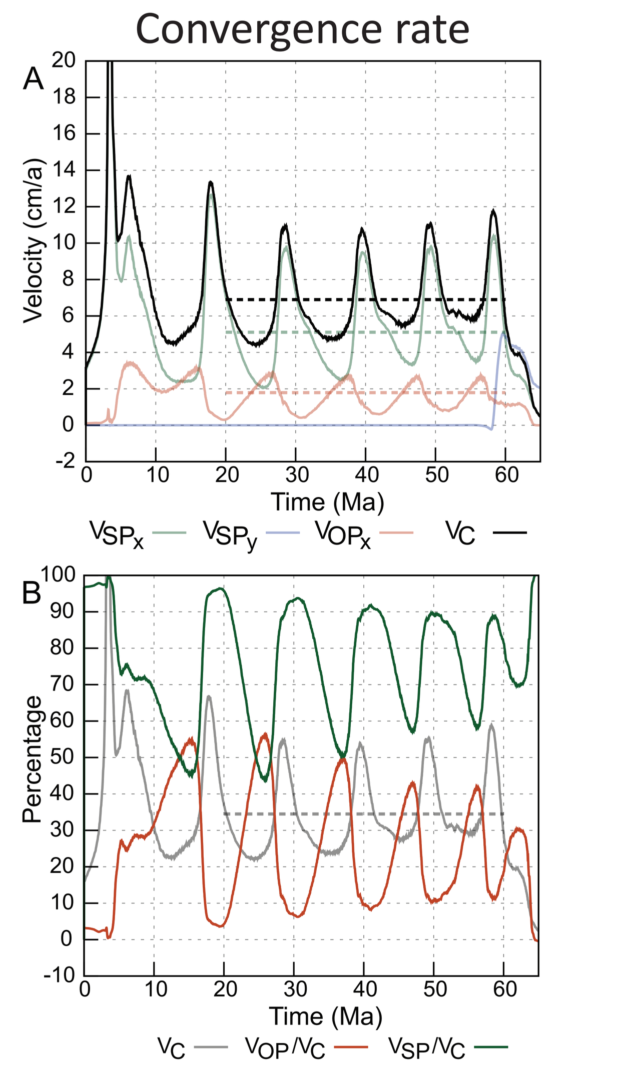

Figure 4: (**A**) Same as figure 3a but with added convergence rate of the reference model with rollback. (**B**) Percentage of the total convergence taken by the subducting plate (SP) and overriding plate (OP).

3. Amplitude and Period of plate motions

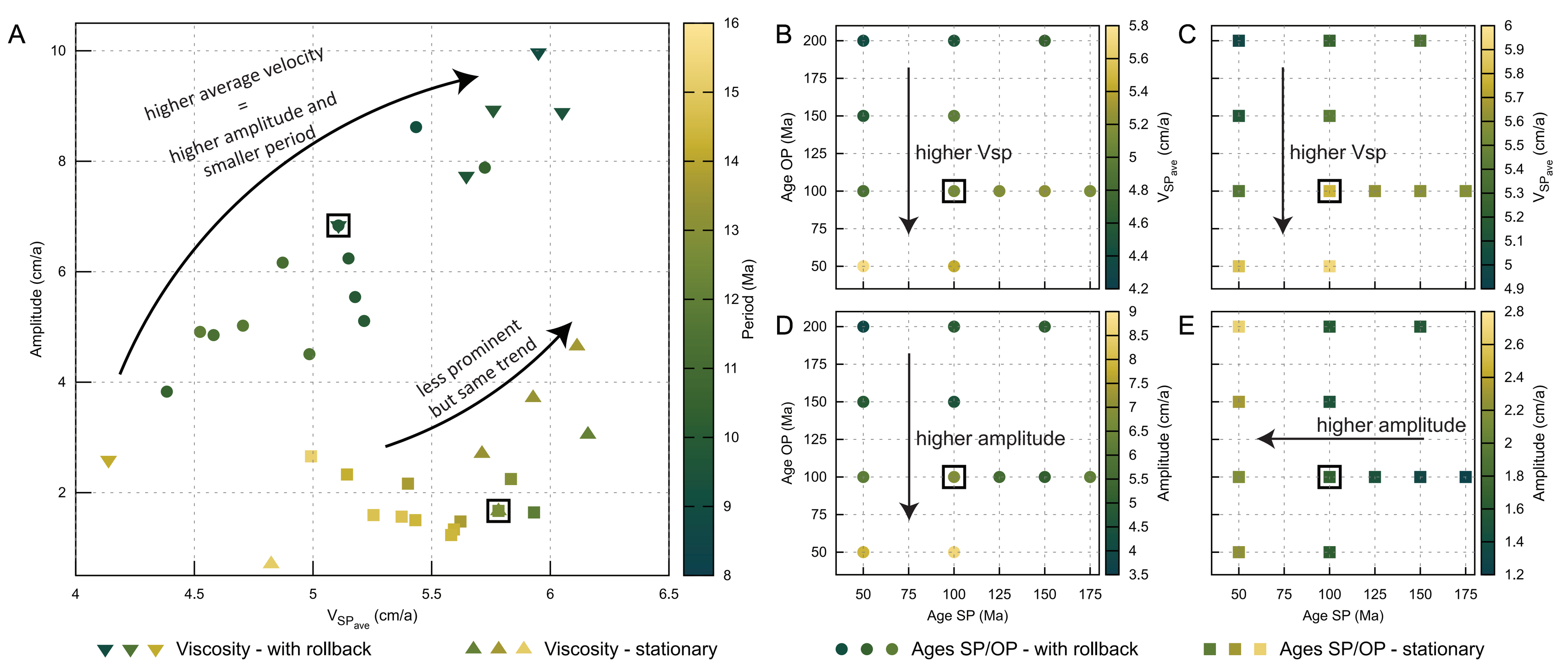

Figure 5: Amplitude, Period and Average Plate Velocity of the subducting plate are the three main values we measure. **A** shows how these three values are connected with the trend that an increase in average subducting velocity is linked to higher amplitudes, as well as a decrease in the period between two oscillations. The average subducting plate velocity is dependent on age of the overriding and subducting plate **B-E** or by a change in the crustal viscosity used on the subduction interface (figure 6). The black squares resemble the two reference models with rollback (circles & upside-down triangles) or with a stationary trench (squares & normal triangles).

Besides differences in allowed trench motion (stationary vs. rollback) we also change the age of the subducting-plate (SP) and overriding plate (OP), or the viscosity of the weak crustal layer (figure 2A). This leads to a change in average SP velocity which controls the amplitude and period of the oscillations. Faster subduction leads to an increase in amplitude and a decrease in period (figure 5A). Smaller periods in faster subduction zones makes sense as the time to reach the MTZ decreases, so buckling happens faster. An older and therefore thicker OP increases the friction on the subduction interface, thereby decreasing the V_{sp} (figure 5B-C). The effect of the SP age is less profound, although older SP subducts slightly faster (figure 5B-C). For cases with rollback higher V_{sp} lead to higher amplitudes (figure 5D), while a younger SP leads to higher amplitudes in the stationary models (figure 5E), although amplitudes for the models with stationary trenches are always lower than for models with rollback and subduction therefore occurs relatively constant (figure 3B).

4. Sampling interval - need for higher resolution data?

In plate tectonic reconstruction, oceanic plates are reconstructed through marine magnetic reversals, generally on 3-10 Ma timescales for every stage rotation (Euler Pole). If the buckling of slabs has a profound effect on the velocity of subducting plates, we could have missed several stages of faster and slower moving tectonic plates. DeMets and Merkouriev 1 showed that higher resolution data can be obtained from oceanic plates and we show (Figure 6) that a sampling interval of 5 Ma per stage can already smoothen the rapid oscillations obtained from subduction zones with globally average subduction speeds (e.g. 6 cm/a).

Furthermore, these oscillations occur also in the OP (figure 3A, 4A-B), meaning that OP-extension, back-arc basin opening, volcanism and/or magmatism might also show periodic oscillations as an effect of slab buckling. This would mean that deformation and ore formation could also be periodic and that insights in in these fields of study could also benefit from higher resolution data and/or reconstructions.

1. High resolution marine data show rapid oscillations in plate motion rate
2. Slab buckling could be a viable mechanism to explain these oscillations
3. The amplitude and period depend on average subduction velocity

4a. Current resolution of marin data could miss these oscillations by smoothing stage rotations

4b.Oscillations in overriding plate deformation might also be attributed to slab buckling

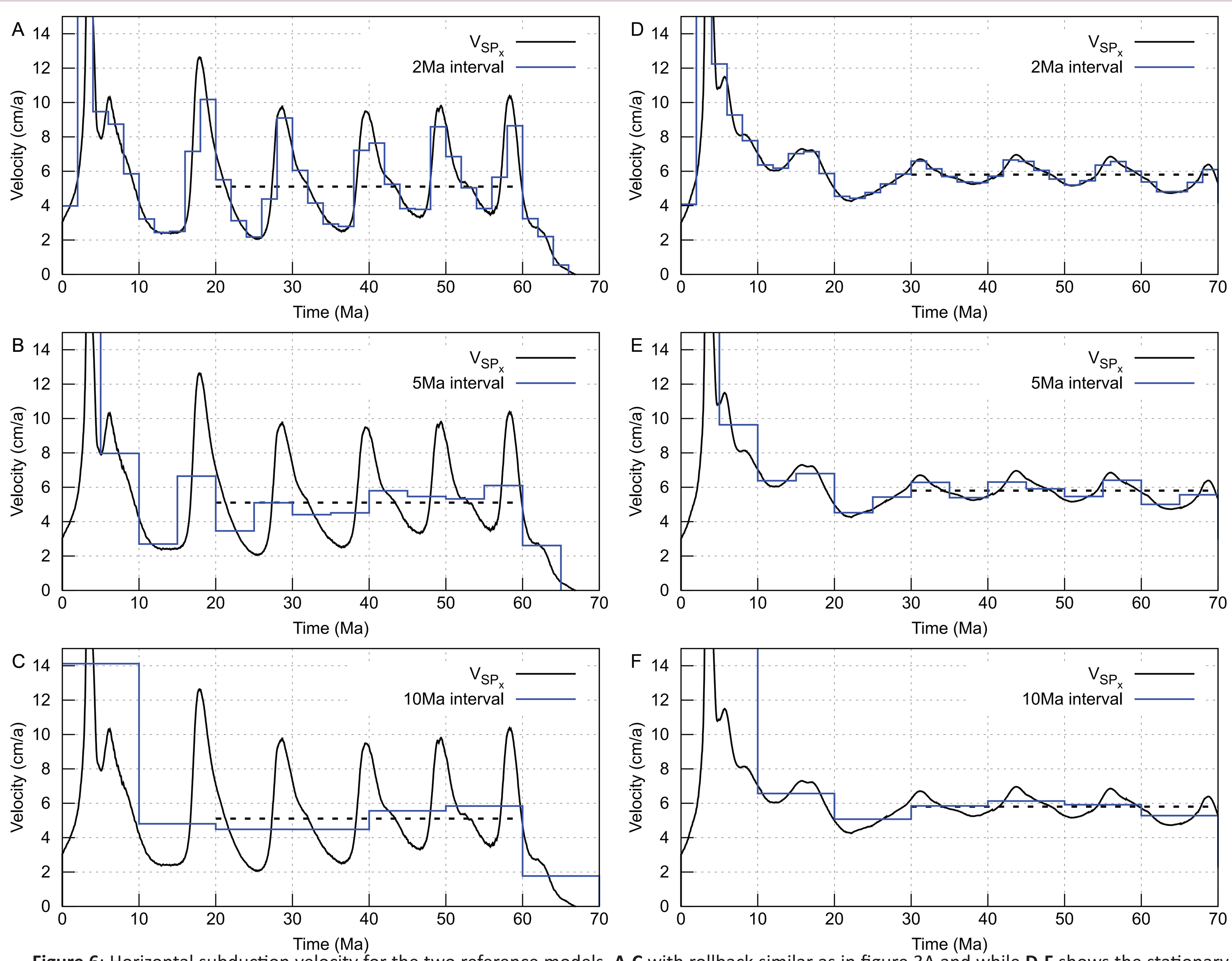

Figure 6: Horizontal subduction velocity for the two reference models, **A-C** with rollback similar as in figure 3A and while **D-F** shows the stationary model from figure 3B. However, here we also show average velocity at different time-intervals, as would be obtained from marine magnetic anomalies due to irregular geomagnetic reversals. 2 Ma intervals **A&D** are needed to capture short time-scale oscillations in plate motion speed, 5 Ma intervals **B&E** show acceleration and decelerations but not the entire amplitude captured by the 2 Ma intervals. 10 Ma intervals **C&F** do not capture any plate motion change and show stage velocities equal to the average velocity (dashed lines). The effect is most obvious in models with rollback rather than a stationary trench.

References

1: DeMets, C., & Merkouriev, S. (2021). Detailed reconstructions of India–Somalia Plate motion, 60 Ma to present: implications for Somalia Plate absolute motion and India–Eurasia Plate motion. GJI, 227(3), 1730-1767.
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3: Pokorný, J., Čížková, H., & van den Berg, A. (2021). Feedbacks between subduction dynamics and slab deformation: Combined effects of nonlinear rheology of a weak decoupling layer and phase transitions. PEPI, 313, 106679.
4: Čížková, H., van den Berg, A. P., Spakman, W., & Matyska, C. (2012). The viscosity of Earth's lower mantle inferred from sinking speed of subducted lithosphere. PEPI, 200, 56-62.