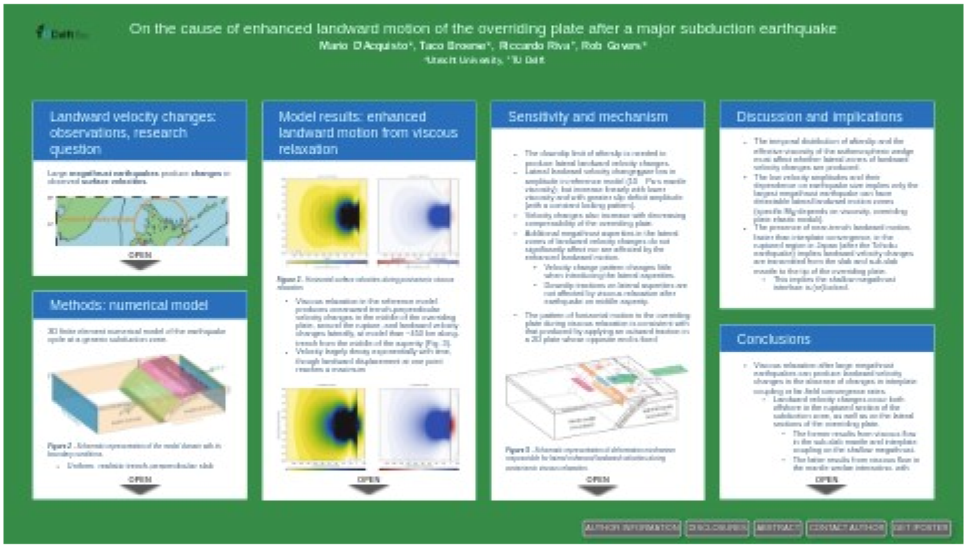
On the cause of enhanced landward motion of the overriding plate after a major subduction earthquake



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PRESENTED AT:

LANDWARD VELOCITY CHANGES: OBSERVATIONS, RESEARCH QUESTION

Large **megathrust earthquakes** produce **changes** in observed **surface velocities**.

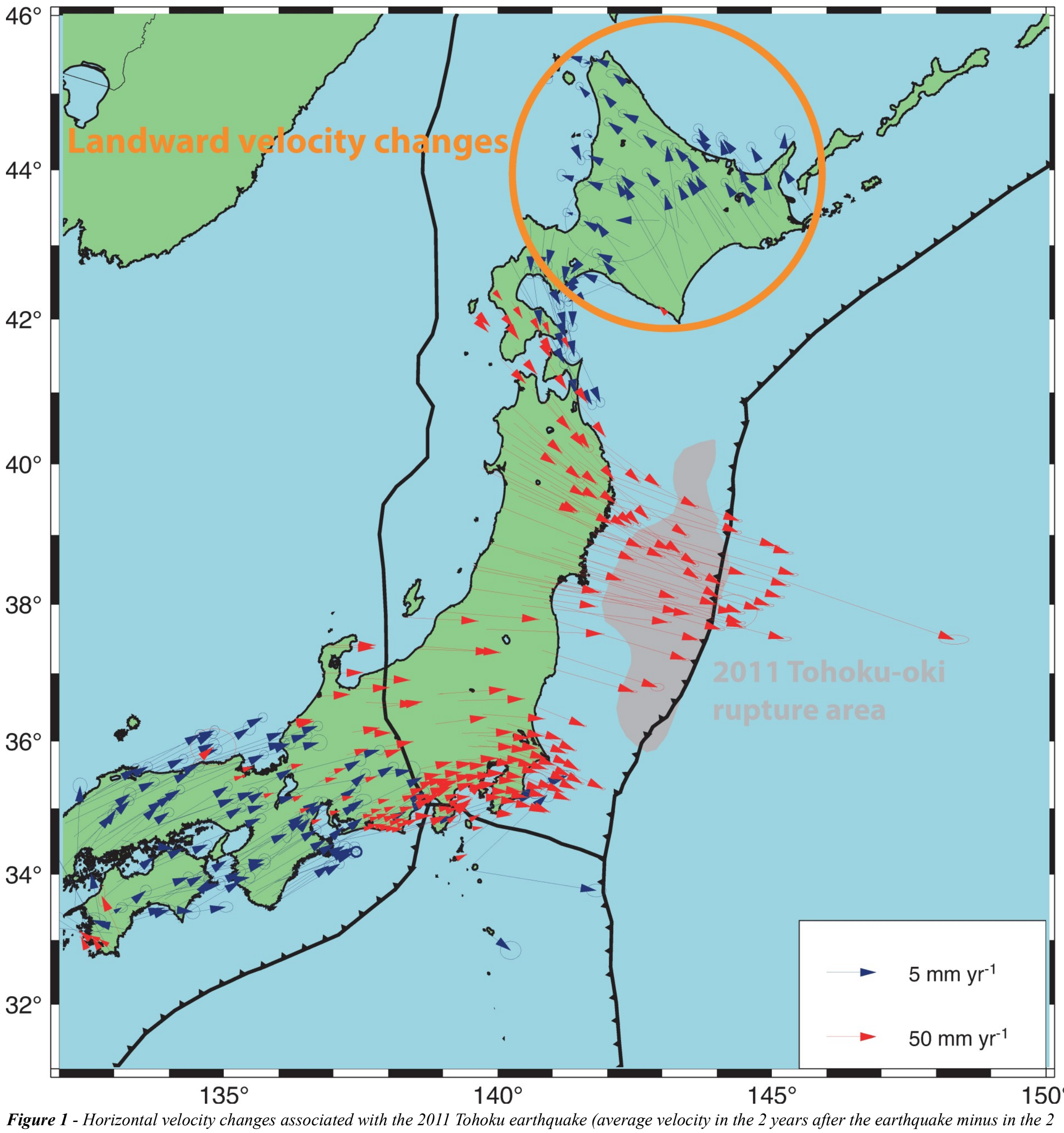

Figure 1 *- Horizontal velocity changes associated with the 2011 Tohoku earthquake (average velocity in the 2 years after the earthquake minus in the 2 alendar years before it).*

Postseismic - preseismic velocity differences are directed **landward** on the overriding plate **on lateral sections of the subduction zone** (hundreds of km along-trench from the earthquake centroid) (shown in Fig. 1 from GPS observations before and after the 2011 Tohoku-oki earthquake, also observed in published analysis of velocities before and after the 2010 Maule earthquake), as well as **offshore in the ruptured section**, on the downdgoing plate and on the very near-trench overriding plate (seen in GPS/A observations after the Tohoku earthquake).

Can this velocity change result from deformation of the lithosphere and mantle associated with the earthquake without changes in far-field plate motion or interplate coupling?

METHODS: NUMERICAL MODEL

3D finite element numerical model of the earthquake cycle at a generic subduction zone.

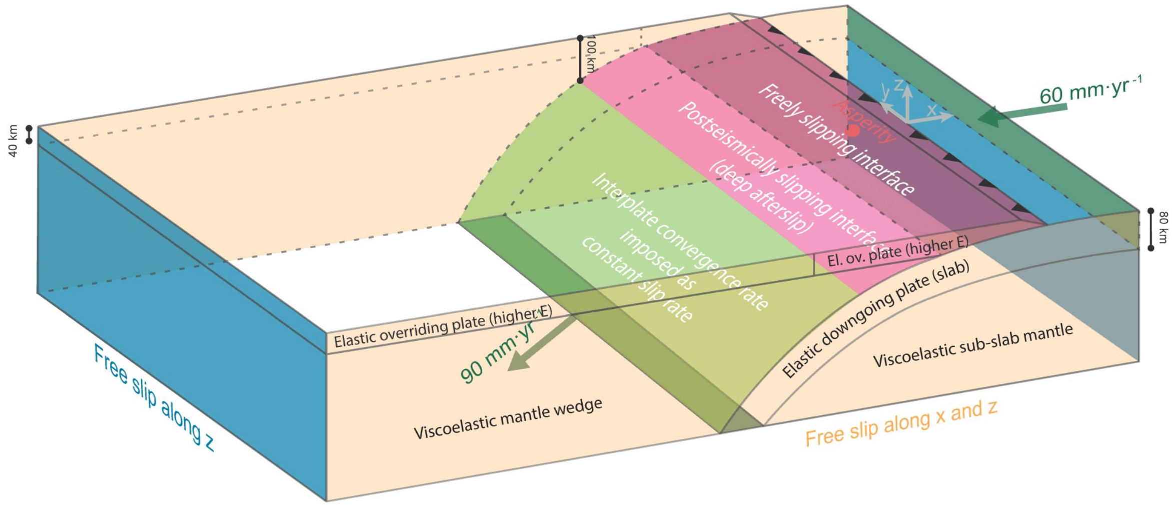

Figure 2 *- Schematic representation of the model domain with its boundary conditions.*

- Uniform, realistic trench-perpendicular slab profile.
- 2 elastic plates, 2 Maxwell visco-elastic mantle domains, allowing for postseismic visco-elastic relaxation.
- Far field interplate converge rate imposed at slab ends.
- Dynamically driven slip and afterslip (primary afterslip instantaneous on shear zone downdip of megathrust, secondary afterslip on megathrust due to viscous flow).
- One fully coupled asperity on megathrust (50 km across, circular in plan view), with partial slip deficit accumulation in the surrounding megathrust interface, unlocked periodically causing earthquakes.
- Contrast in elastic modulus *E* of the overriding plate 700 km away from the trench, to reproduce interseismic behavior of surface velocities while allowing coseismic displacement in the far-field (cf. T43C-09 presentation in this meeting).
- Downdip limit of coseismic slip at 40 km depth, of afterslip at 100 km depth

MODEL RESULTS: ENHANCED LANDWARD MOTION FROM VISCOUS RELAXATION

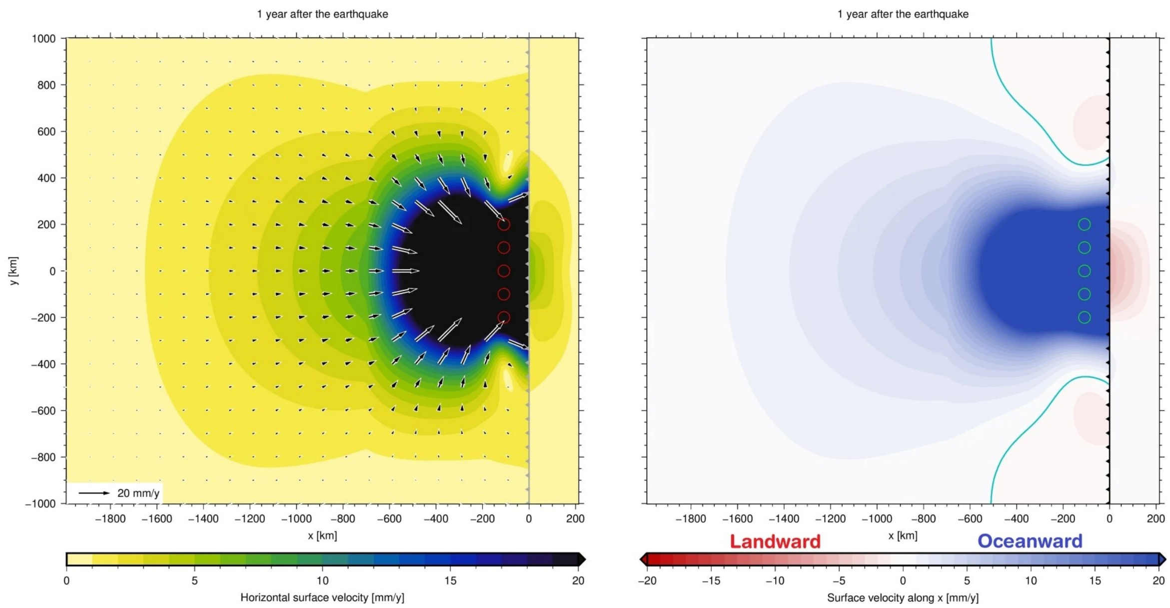

Figure 3 *- Horizontal surface velocities during postseismic viscous relaxation*

- Viscous relaxation in the reference model produces oceanward trench-perpendicular velocity changes in the middle of the overriding plate, around the rupture, and landward velocity changes laterally, at model than ~450 km along-trench from the middle of the asperity (Fig. 3).
- Velocity largely decay exponentially with time, though landward displacement at one point reaches a maximum

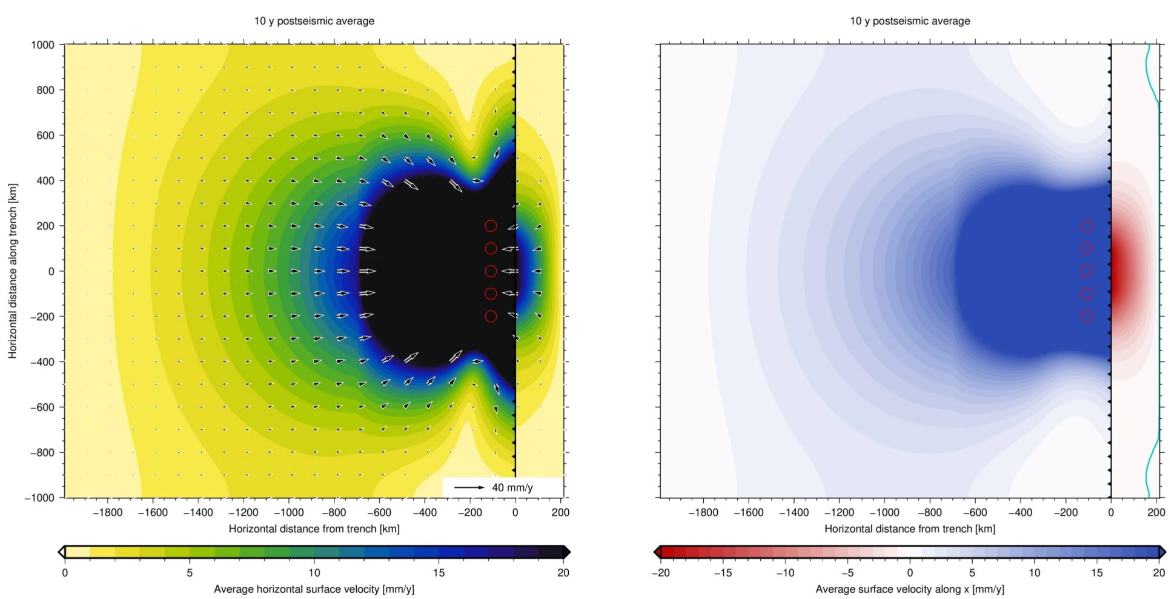

Figure 4 *- Cumulative surface displacement during the 10 years after the earthquake, including primary afterslip*

- No locking on the lateral subduction zone in reference model. Landward motion is produced by deformation of the system due to the (earlier) locking and earthquake in the middle asperity.
- Landward velocity changes are produced also offshore, in the locked portion of the megathrust, because of viscous relaxation in the sub-slab mantle, consistently with previous published results (Fig. 3).
- In our model the shallow megathrust is free to slip and the near-trench landward velocities only occur in the

downgoing plate

- Surface motion due to primary afterslip cancels out lateral landward motion during the following decade, with reference model viscosity and earthquake size (Fig. 4).

SENSITIVITY AND MECHANISM

- The downdip limit of afterslip is needed to produce lateral landward velocity changes.
- Lateral landward velocity changes are low in amplitude in reference model (10^{19} Pa·s mantle viscosity), but increase linearly with lower viscosity and with greater slip deficit amplitude (with a constant locking pattern).
- Velocity changes also increase with decreasing compressibility of the overriding plate.
- Additional megathrust asperities in the lateral zones of landward velocity changes do not significantly affect nor are affected by the enhanced landward motion.
  - Velocity change pattern changes little when introducing the lateral asperities.
  - Downdip tractions on lateral asperities are not affected by viscous relaxation after earthquake on middle asperity.
- The pattern of horizontal motion in the overriding plate during viscous relaxation is consistent with that produced by applying an outward traction in a 2D plate whose opposite end is fixed

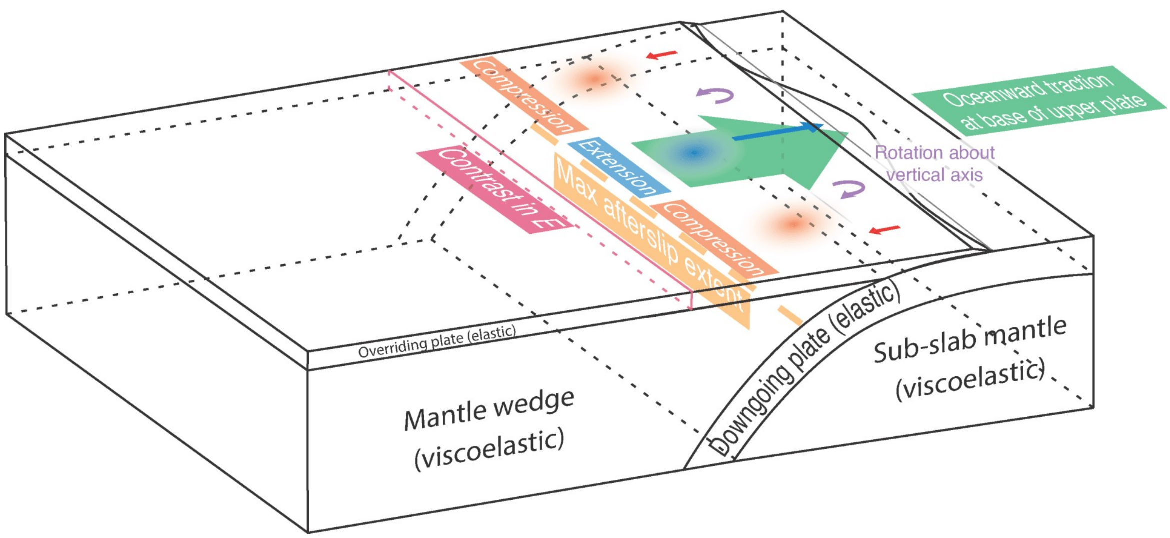

Figure 5 *- Schematic representation of deformaiton mechanism resposnisble for lateral enhanced landward velocities during postseismic viscous relaxation.*

- **Interpretation**: the lateral landward velocity changes are caused by the stretching-compression (controlled by finite compressibility) and in-plane bending of the overriding plate and mantle wedge, on which viscous relaxation exerts an oceanward traction in the middle and in which the contrast in *E* and the downdip limit on afterslip restrict trench-perpendicular motion.

DISCUSSION AND IMPLICATIONS

- The temporal distribution of afterslip and the effective viscosity of the asthenospheric wedge must affect whether lateral zones of landward velocity changes are produced.
- The low velocity amplitudes and their dependence on earthquake size implies only the largest megathrust earthquake can have detectable lateral landward motion zones (specific M_W depends on viscosity, overriding plate elastic moduli).
- The presence of near-trench landward motion, faster than interplate convergence, in the ruptured region in Japan (after the Tohoku earthquake) implies landward velocity changes are transmitted from the slab and sub-slab mantle to the tip of the overriding plate.
  - This implies the shallow megathrust interface is (re)locked.

CONCLUSIONS

- Viscous relaxation after large megathrust earthquakes can produce landward velocity changes in the absence of changes in interplate coupling or far-field convergence rates.
  - Landward velocity changes occur both offshore in the ruptured section of the subduction zone, as well as on the lateral sections of the overriding plate.
    - The former results from viscous flow in the sub-slab mantle and interplate coupling on the shallow megathrust.
    - The latter results from viscous flow in the mantle wedge interacting, with an in-plane shear component, with the finite compressibility and compliance contrast of the overriding plate, as well as with the downdip limit of afterslip (beyond which steady-state shearing occurs).

DISCLOSURES

Mario D'Acquisto was funded through the project "Using Space Geodesy to assess the re-locking time after a major subduction earthquake" (WBS WE.248002.1) of the Dutch Organization for Scientific Research (Nederlandse Organisatie voor Wetenschappelijk Onderzoek, NWO).

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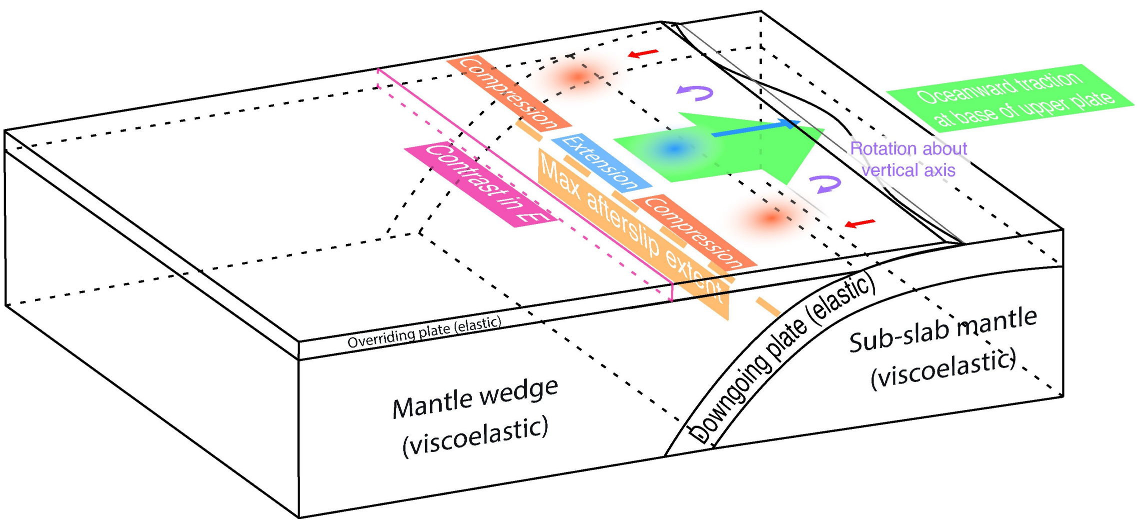
ABSTRACT

Relaxation following large subduction earthquakes produces landward changes in surface velocities. Near-trench landward velocity changes in the vicinity of the rupture zone have been attributed to rapid viscoelastic relaxation in the sub-slab asthenosphere. Lateral landward velocity changes, hundreds of km along-trench from the rupture, have been variously explained invoking interplate coupling changes, transient slab acceleration, or overriding plate bending, with different implications for seismic hazard. We investigate whether the lateral landward velocity changes can result from postseismic relaxation with constant interplate coupling and convergence rate. We use a finite element model with periodic megathrust earthquakes resulting from unlocking of asperities on the megathrust, with instantaneous, dynamically driven coseismic slip and afterslip and with bulk visco-elastic relaxation. A mechanical contrast in the overriding plate is required to reproduce the observed near-trench focusing of interseismic deformation. A maximum depth limit to afterslip of around 100 km is consistent with inverted afterslip distributions and the hypothesized depth extent of the megathrust. The presence of both the contrast and depth limit causes viscous relaxation in the mantle wedge to result in lateral landward velocity changes. We discuss the responsible mechanism, which amounts to elastic deformation of the overriding plate and is due to the finite compressibility of the plate and its in-plane bending. The spatial pattern of landward velocity changes is consistent with observations for the Maule and Tohoku earthquakes. Velocity change magnitudes are comparable with observations, scale with viscosity and seismic moment, are only partly counteracted by the effect of primary afterslip, and are little affected by interplate coupling pattern. In the years following the largest earthquakes with rapidly decaying afterslip, this mechanism is expected to produce detectable landward velocity changes. The models also shows near-trench landward velocity changes close to the rupture, consistently with previous research. However, we find that the extent and timing of shallow interface (re)locking is critical for reproducing near-trench observations on the overriding plate.



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