Mechanics-based scenarios for great thrust earthquakes in subduction zones using GNSS data analysis: Released strain energy and dissipated energy

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Summary

A mechanics-based method is proposed to construct scenarios of interplate earthquakes by using geodetically estimated slip-deficit rates.

Static models of coseismic slip are estimated from stress drop distribution assuming the rupture region and accumulation time.

Residual energy is defined to examine whether each scenario can actually happen in the view-point of energy balance.

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Earthquake scenarios based on interplate slip deficits

Kinematic modeling

(e.g., Baranes et al. 2018 GRL; Watanabe et al, 2018 JGR)

Coseismic slip distribution is modeled by multiplying the estimated slip deficit rates by the recurrence time

Positive point: The rupture area and seismic moment can be easily modeled.

Negative point: The model is not always consistent with the mechanics of fault rupture.

Dynamic modeling

(e.g., Hok et al., 2011 JGR; Lozos et al., 2015 GRL; Yang et al., 2019 JGR)

Source models are obtained via dynamic rupture simulations using shear stress calculated from the slip deficits and assuming frictional parameters

Positive point: The rupture processes are reasonably predicted based on the mechanics of fault rupture.

Negative point: A lot of computing resources are needed for parametric studies of the frictional parameters.

We propose a mechanics-based method to bridge the gap between the kinematic and dynamic modeling.

Construction of mechanics-based scenarios

Based on shear stress accumulation

[1] Estimating coseismic slip distribution

Static model

[2] Calculating strain energy released by the earthquake

Small computational load

Based on frictional property

[3] Calculating strain energy dissipated on the fault plane

Consideration of the mechanics of fault rupture

By comparing [2] and [3], we examine whether each scenario actually happens.

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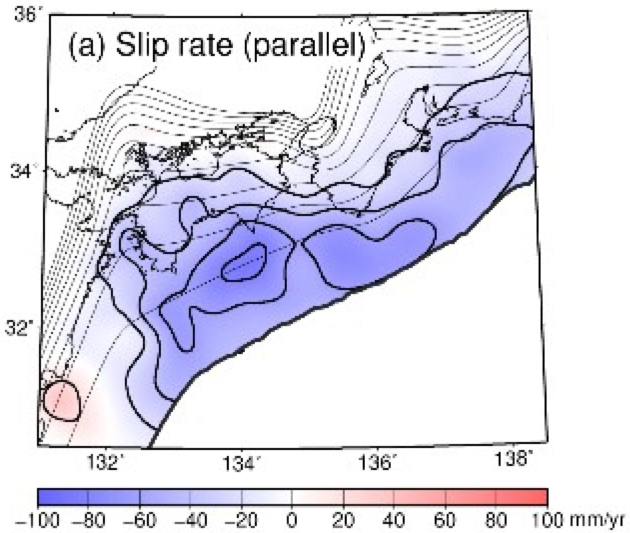
Shear stress accumulation on the plate interface

We calculated shear stress change rates at the plate interface from the slip-deficit rate distribution estimated from GNSS data.

We assumed a rupture region and obtained stress drop distribution by multiplying the shear stress change rates in the region by the accumulation time.

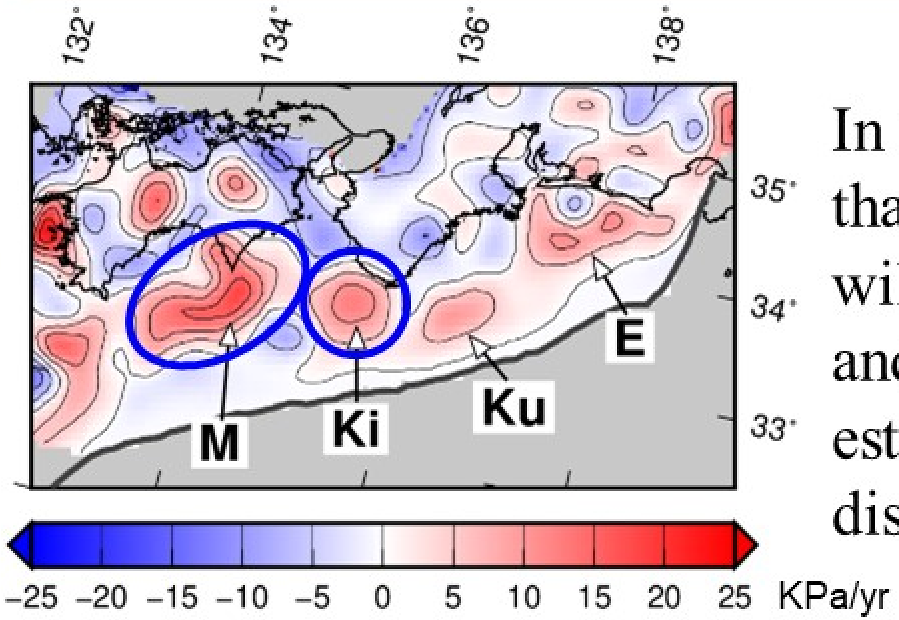
We call each positive peak of the shear stress change rates "asperity".

Slip-deficit rate distribution



(Noda et al. 2018 JGR)

Shear stress change rates



In the next slide, we assume that two asperities M and Ki will rupture in the next event and show the procedure to estimate coseismic slip distribution.

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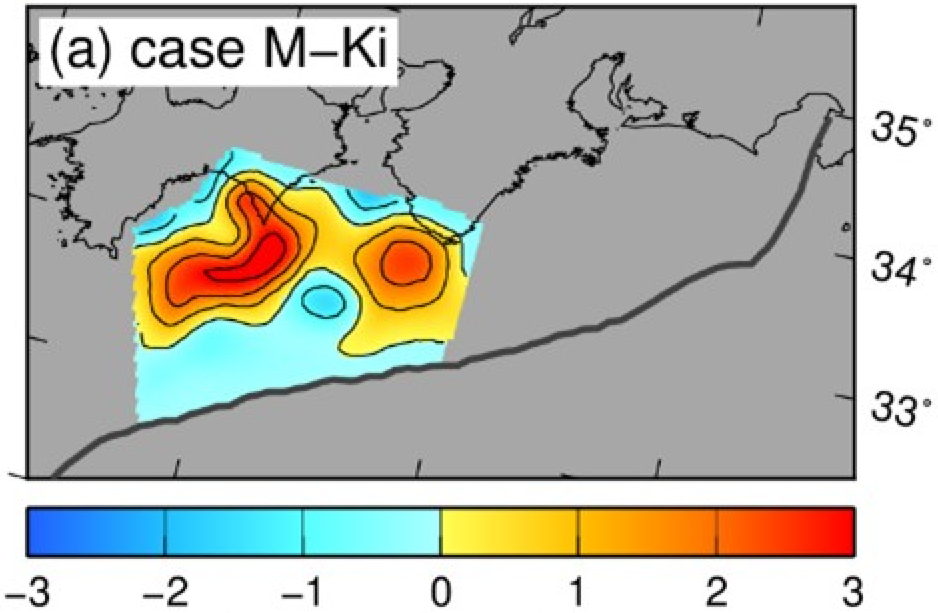
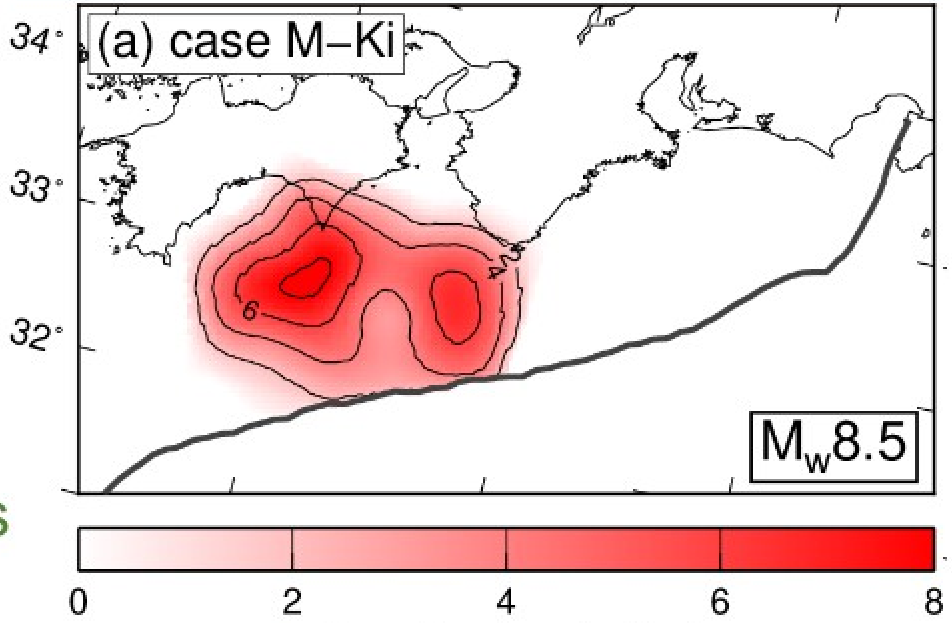
Inversion to estimate slip distribution of stress drop

Stress drop distribution at 4-km intervals



Accumulation time 200 years

Estimated coseismic slip distribution at 4-km intervals



Simple simultaneous equations

$$\underline{\mathbf{d}} = \underline{\mathbf{H}}\,\underline{\mathbf{a}}$$

d	H	a
N × 1	N × M	M × 1
Data vector (stress drop)	Coefficient matrix	Model parameter (coseismic slip)

N=M

N: The number of data

M: The number of model parameters

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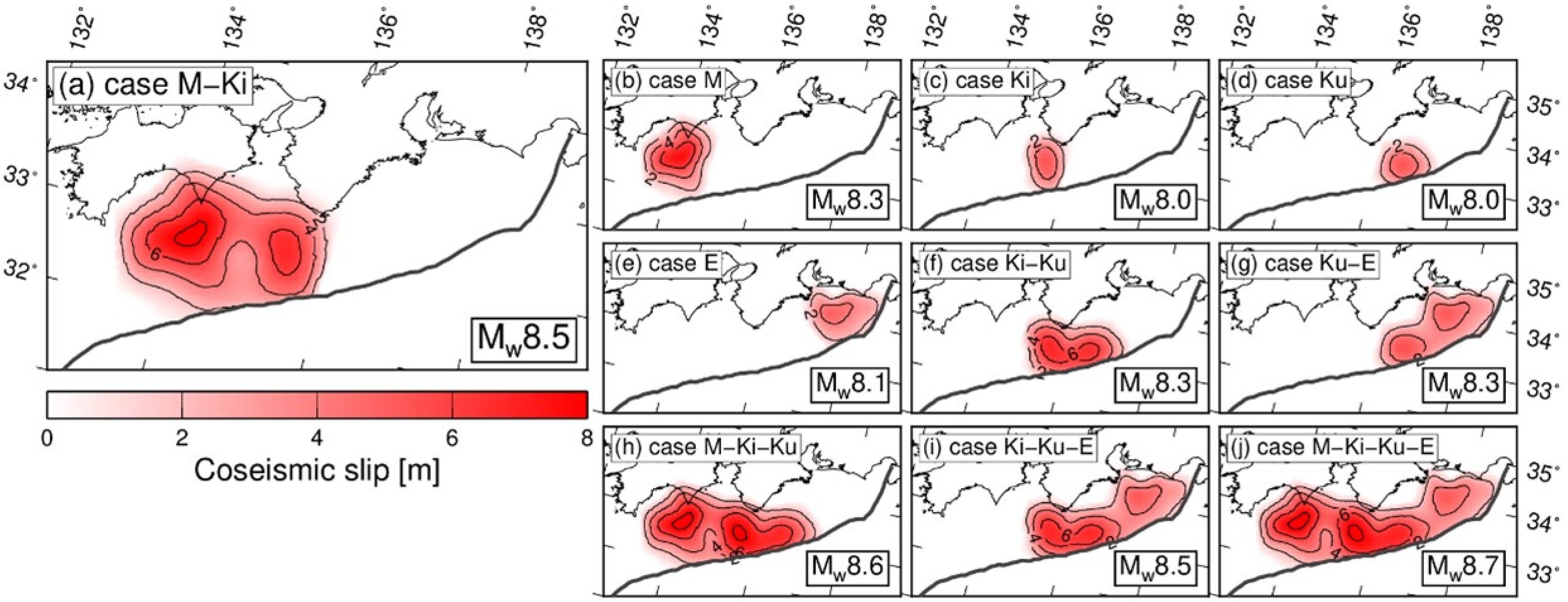
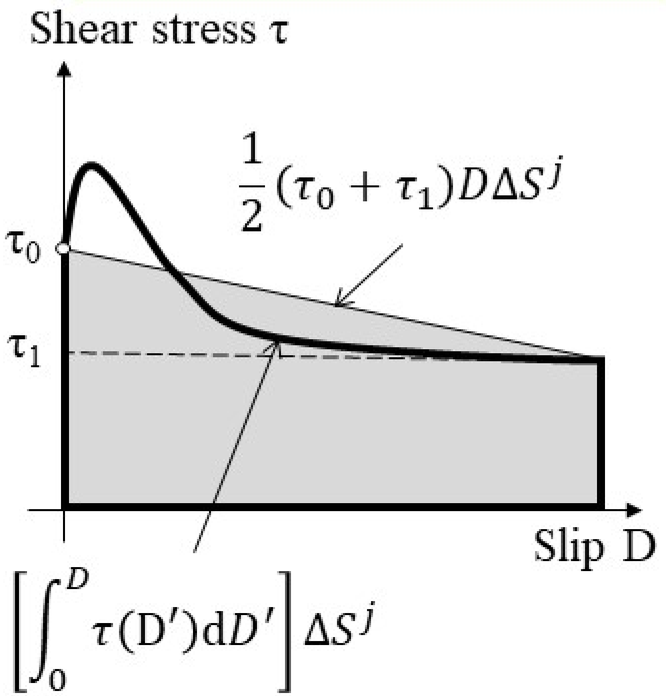
10 earthquake scenarios: Accumulation time 200 years



Energy balance in earthquake generation

Energy partitioning
in a sub-fault j



Strain energy released by an earthquake

$$E^{release}=\sum_{j=1}^{M}\frac{1}{2}(\tau_0+\tau_1)D\Delta S^j$$

We can calculate it from earthquake scenarios.

Strain energy dissipated on the fault plane

$$E_D=\sum_{j=1}^{M}\left[\int_0^D \tau(\mathrm{D}')\mathrm{d}D'\right]\Delta S^j$$

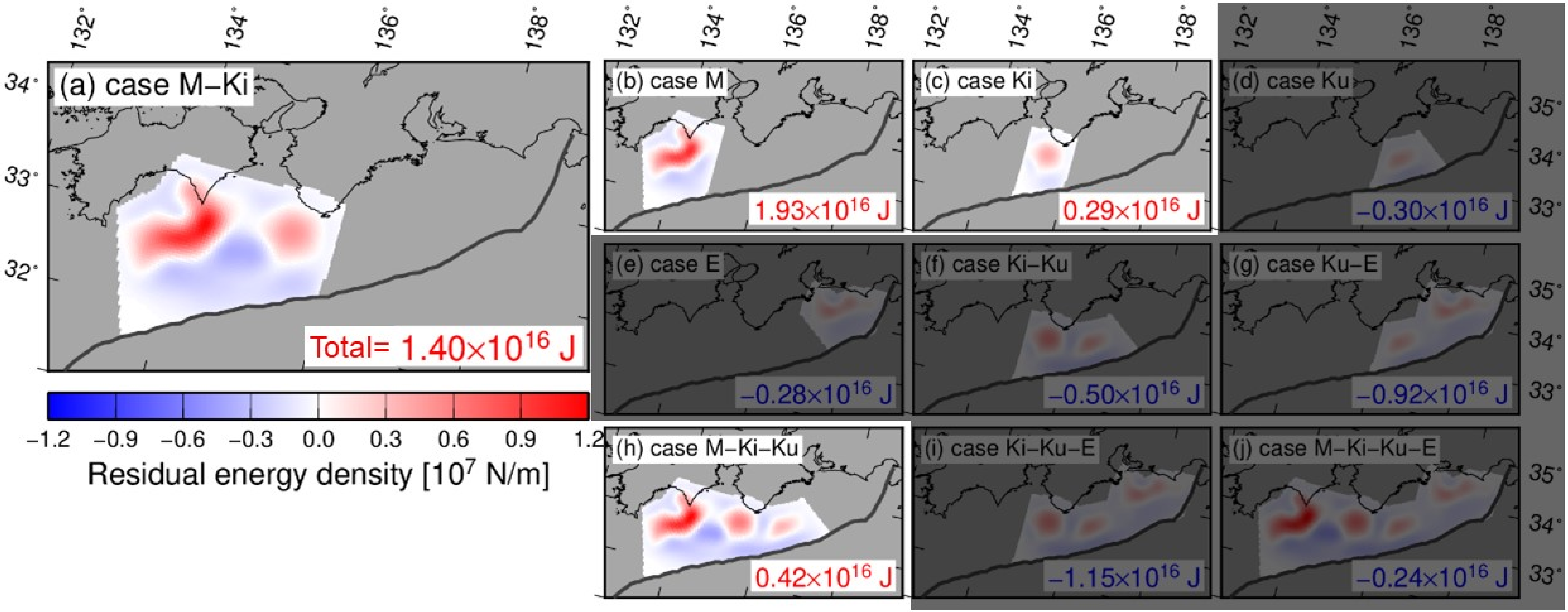
We can calculate it from a frictional constitutive law.

Here we assumed a frictional constitutive law used in Hok et al. (2011 JGR).

Necessary condition for earthquake generation:

$$Residual\ energy \equiv E^{release}-E_D>0$$

Distribution of residual energy density and total amounts



Shaded cases: Residual energy < 0

These cases do not meet the necessary condition for earthquake generation.

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Conclusion

A mechanics-based method is proposed to construct scenarios of interplate earthquakes by using geodetically estimated slip-deficit rates.

Assuming the rupture region and accumulation time, static models of coseismic slip are estimated from stress drop distribution with small computational load.

For consideration of fault mechanics, we defined residual energy to examine whether each scenario can actually happen in the view-point of energy balance.