

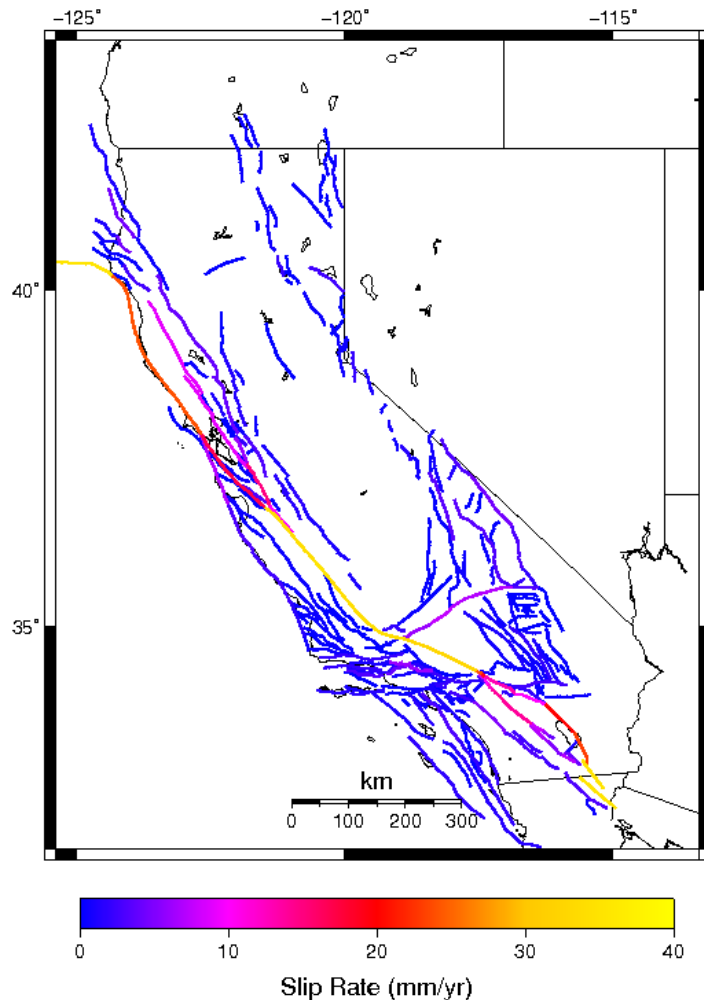
Combinatorial Framework for Obtaining the Optimal Spatial Distribution of Earthquakes on Complex Fault Systems

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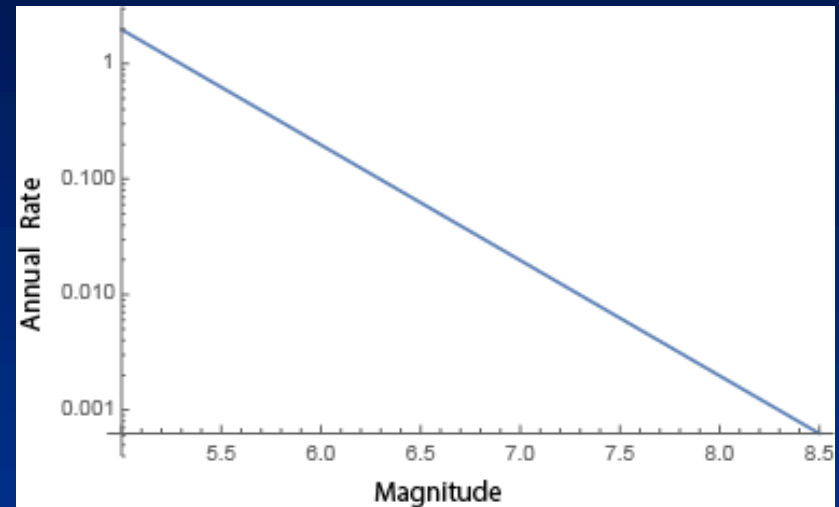
2021 European Geosciences Union General Assembly

Problem Statement

California's Faults



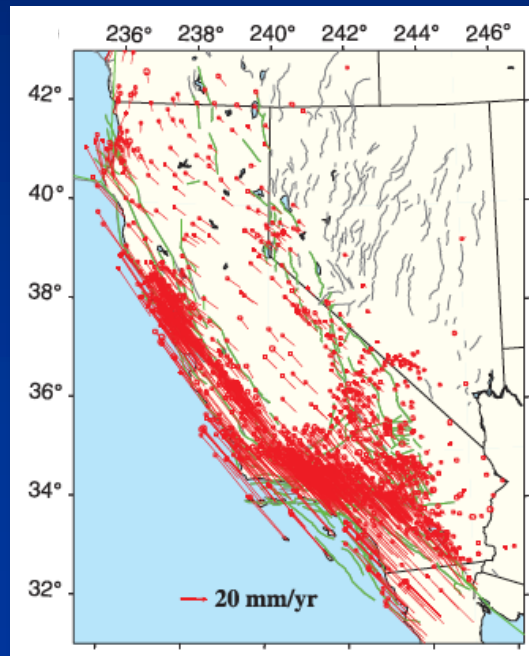
Statewide Gutenberg-Richter Relation



How are earthquakes with magnitudes sampled from a regional G-R relation distributed within a complex fault system?

■ Geological & Geophysical Data

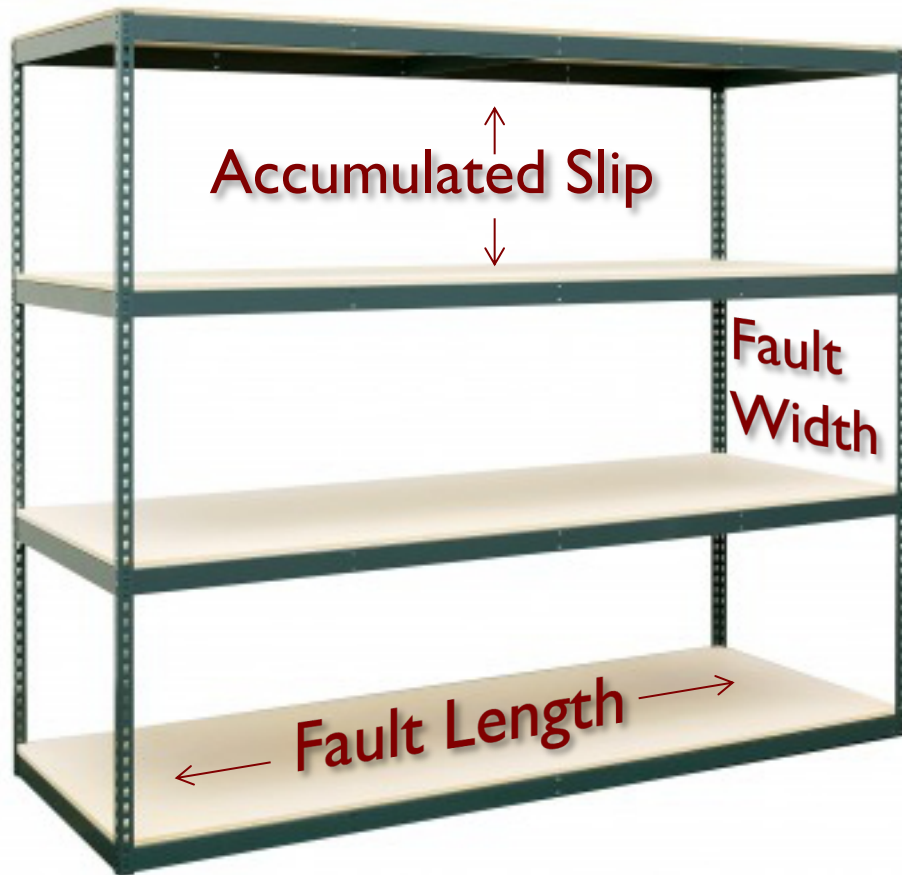
- Mapped faults
- Historical seismicity
- Slip-rate information
 - Geologic offsets
 - Geodetic measurements



■ Estimated Parameters

- G-R a -, b -value
- Fault coupling
- Off-fault seismicity
- M-A scaling
- Slip rate
(mean, min, max)
 - Combine geologic offsets with results from deformation models

Adopting Bin (Shelf)-Packing Methods from the Field of Operations Research



Earthquake “packages”



Formulation of Slip-Rate Integer-Programming Problem

minimize $\sum_{j=1}^n c_j x_j$

subject to $\left. \begin{aligned} \sum_{j=1}^n A_{ij} x_j &\leq smax_i; \quad i = 1, \dots, k \\ \sum_{j=1}^n A_{ij} x_j &\geq smin_i; \quad i = 1, \dots, k \end{aligned} \right\} \text{slip-rate constraints}$

Implicit constraint:
 M_{max} for each fault

$alldifferent(x_1, \dots, x_n) = \{(m_1, \dots, m_n) \mid m_i \in M(x_i), m_i \neq m_j \text{ for } i \neq j\}$

$\left. \sum_{j=1}^n x_j = p \right\} \text{catalog-length constraint}$

$0 \leq x_j \leq 1; x_j \in \text{integers} \} \text{binary constraint}$

x_j : decision vector

c_j : objective function
(L1-norm misfit)

A_{ij} : constraint matrix

m_j : magnitude associated
with each x_j

NP-hard

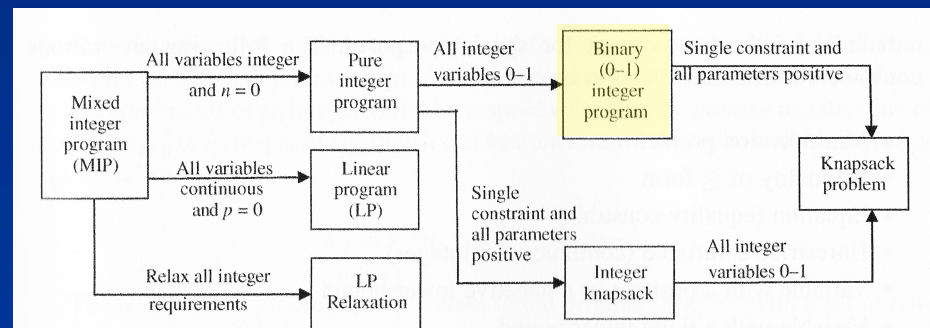


FIGURE 1.1 A simple classification of integer programs.

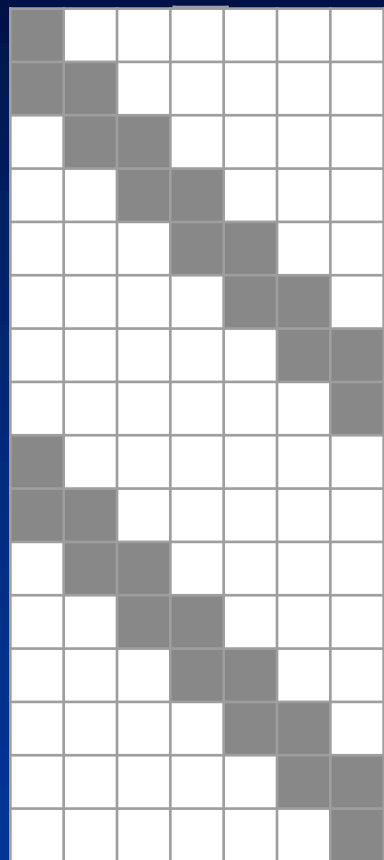
“unwrap”
fault

fault

strike

eq

dip

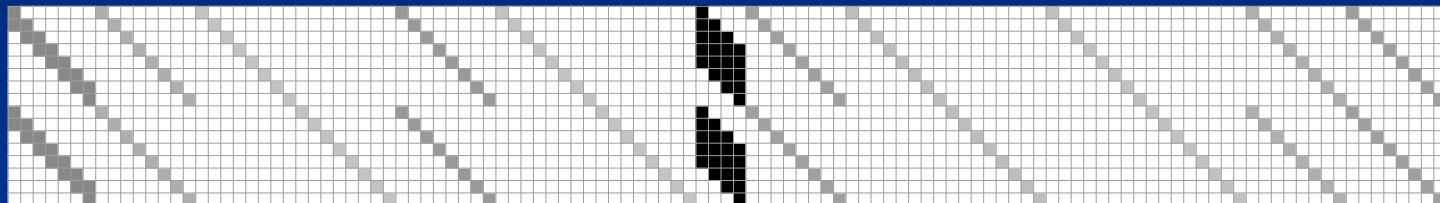


all possible
positions of eq

earthquake catalog



binary decision vector $\mathbf{x}$



constraint matrix $\mathcal{A}$

...etc. for all other faults

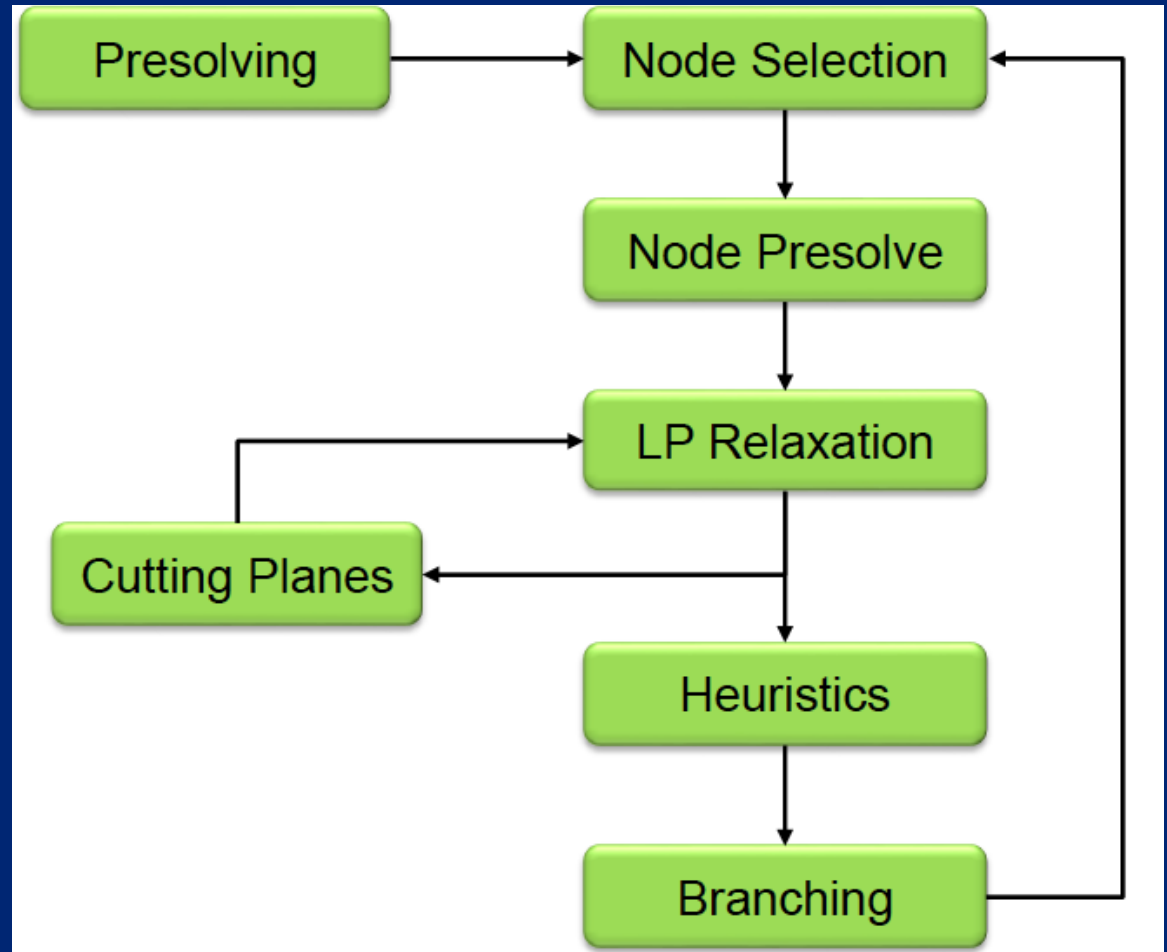
Mixed Integer Programming (MIP) Solvers

■ Open Source

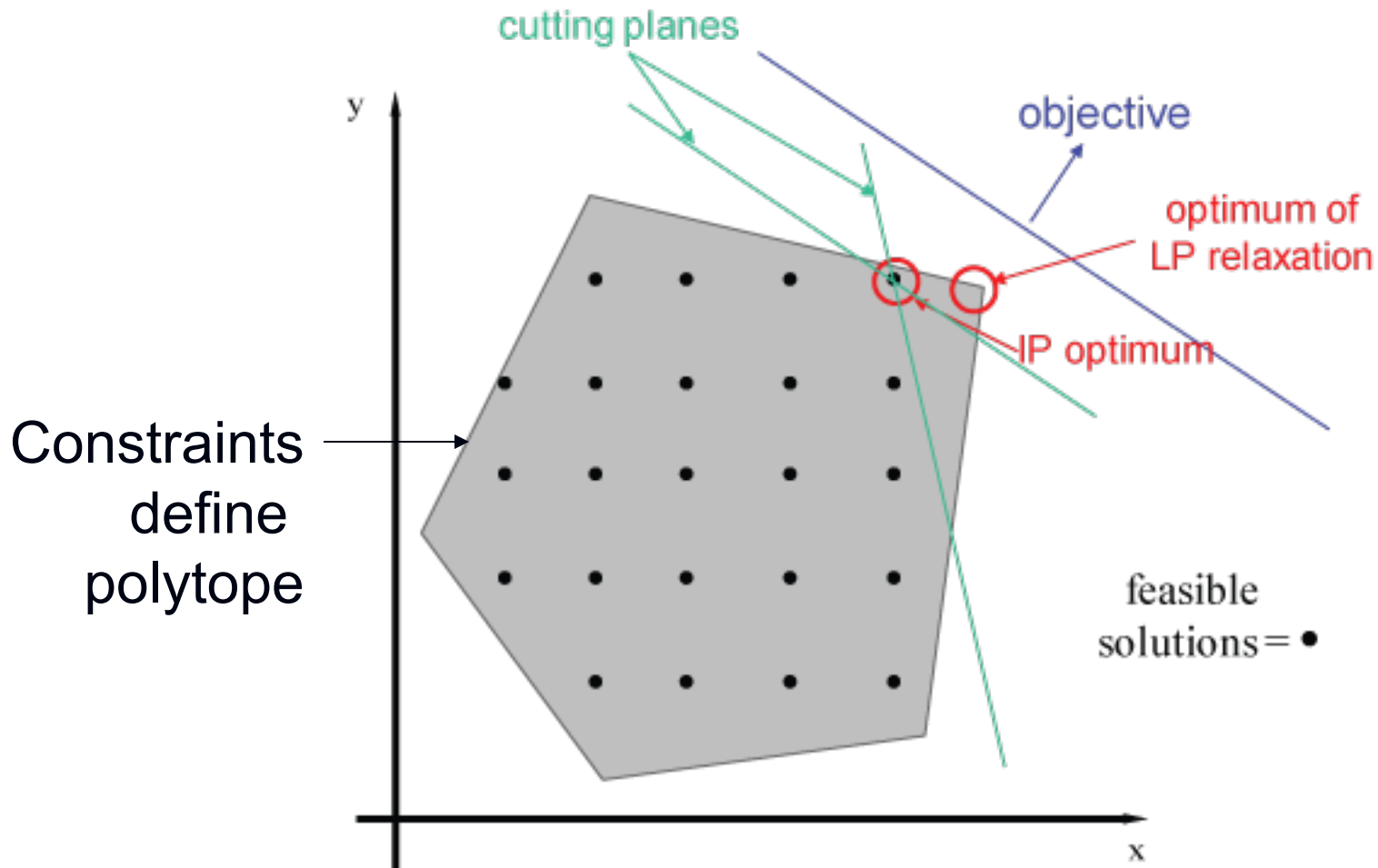
- SCIP
- LP_Solve
- etc.

■ Commercial

- CPLEX (IBM)
- Gurobi
- etc.



MIP Solvers: Graphical Depiction (2 variables, non-binary)



Single-Fault Results: Fit to Target Slip Rate

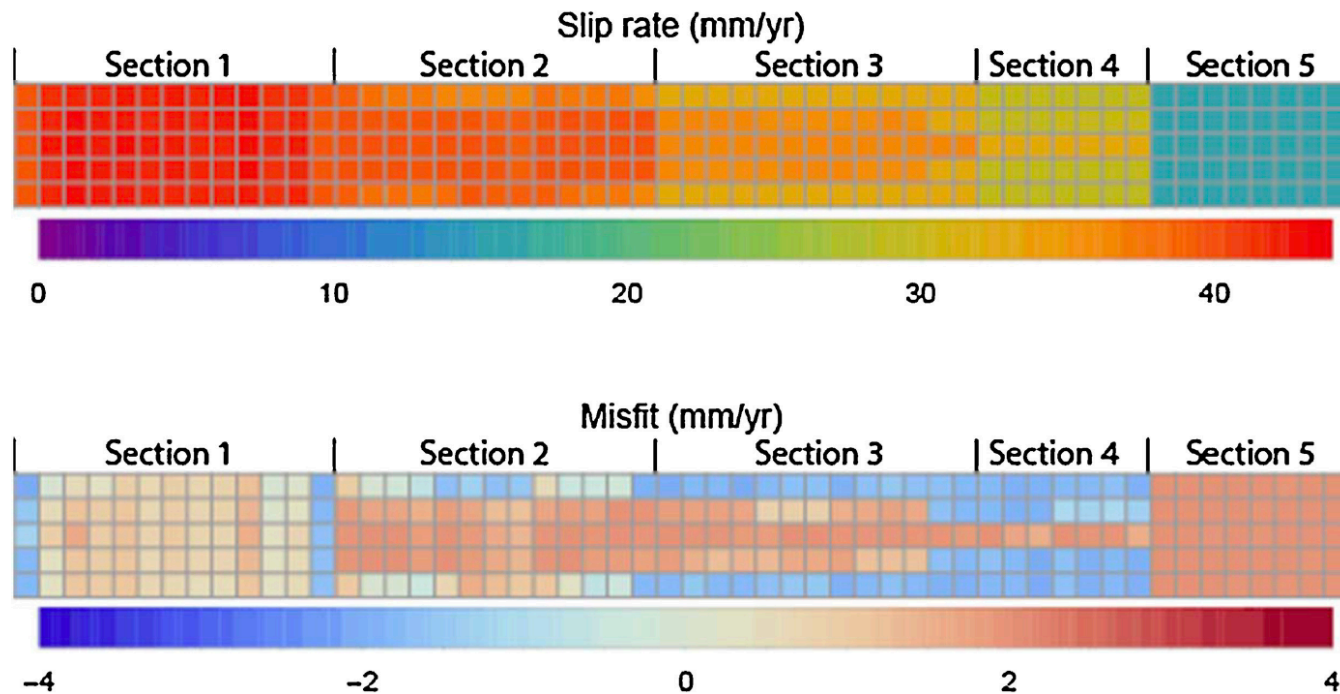


Figure 8. (top) Slip rate resulting from the integer-programming solution using the stepped slip-rate target (Fig. 5a). (bottom) Misfit with respect to the target slip rate (mean bias = $+0.50 \text{ mm yr}^{-1}$; RMS error = 1.47 mm yr^{-1}).

Single-Fault Results: Cell Participation & Survival Functions

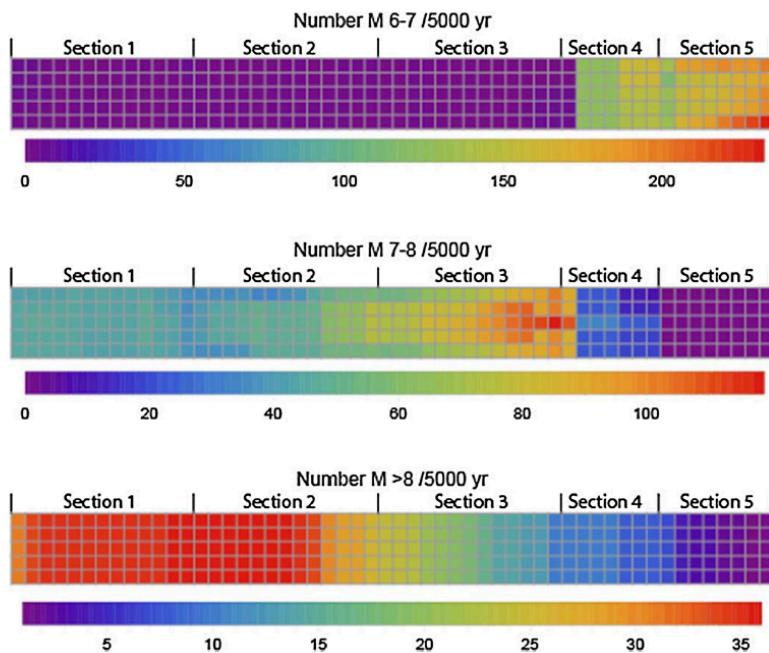


Figure 10. Number of earthquakes of select magnitudes (M) that participate in rupture at each grid cell, using the integer-programming method and stepped slip-rate target (Fig. 5a).

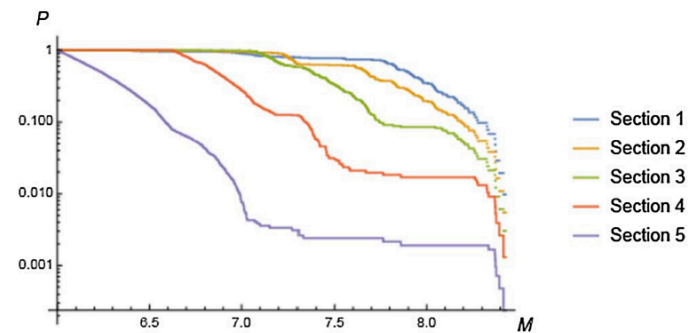


Figure 9. Magnitude (M) distributions (survival functions) for five fault sections along the Nankai megathrust (Fig. 4), resulting from the optimal integer-programming solution using the stepped slip-rate target (Fig. 5a).

Single-Fault Results: Spatial Position of Large Mag. EQs

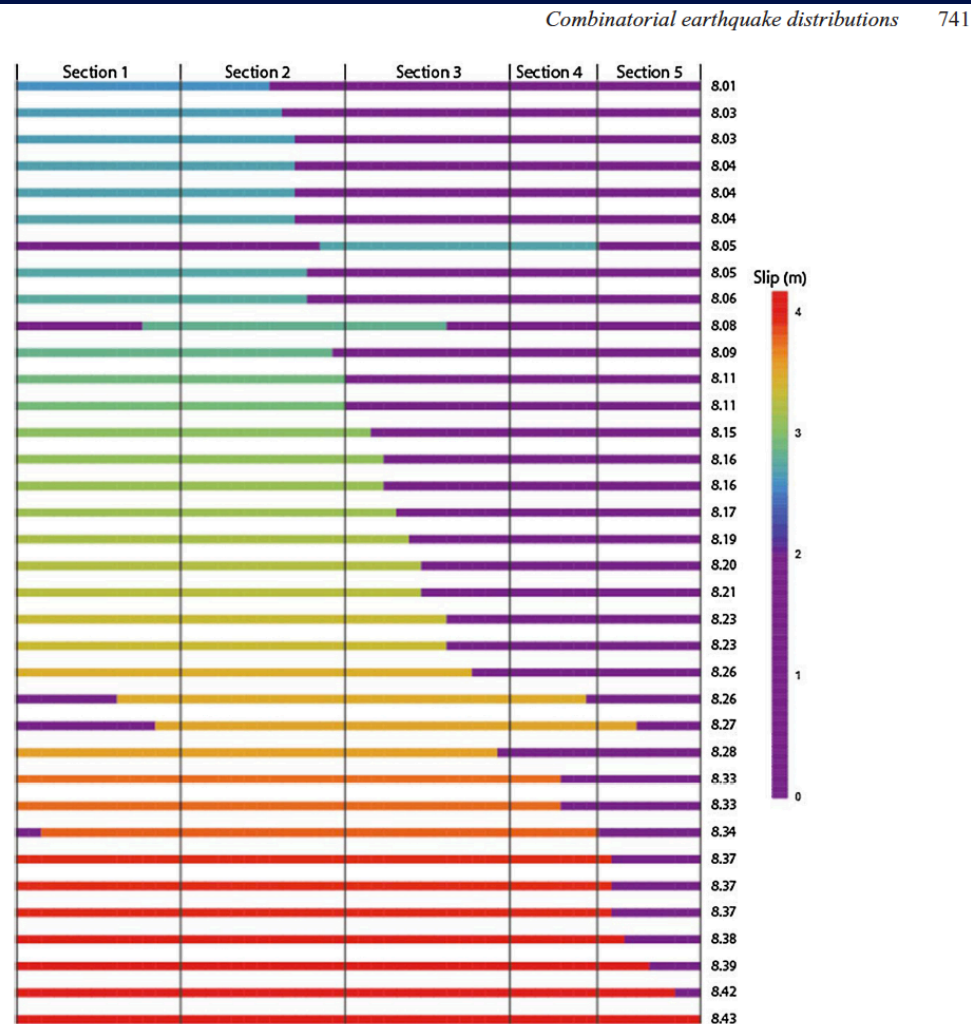


Figure 11. Position of $M > 8$ earthquakes along strike, using the integer-programming method and stepped slip-rate target. Magnitude indicated along left side.

Papers Describing Method & Applications

Geist, E. L., and T. Parsons (2018), Determining on-fault earthquake magnitude distributions from integer programming, *Computers & Geosciences*, 111, 244-259, <https://doi.org/10.1016/j.cageo.2017.11.018>.

Parsons, T., E. L. Geist, R. Console, and R. Carluccio (2018), Characteristic earthquake magnitude frequency distributions on faults calculated from consensus data in California, *J. Geophys. Res.*, 123, 10,761-710,784, <https://doi.org/10.1029/2018JB016539>.

Geist, E. L., and T. Parsons (2019), A combinatorial approach to determine earthquake magnitude distributions on a variable slip-rate fault, *Geophys. J. Int.*, 219(2), 734-752, doi:10.1093/gji/ggz294.

Geist, E. L., and T. Parsons (2020), Distribution of Earthquakes on a Branching Fault System Using Integer Programming and Greedy-Sequential Methods, *Geochemistry, Geophysics, Geosystems*, 21(9), e2020GC008964, <https://doi.org/10.1029/2020GC008964>.

ResearchGate

<https://www.researchgate.net/profile/Eric-Geist>

<https://www.researchgate.net/profile/Tom-Parsons-2>