2016 UseIT: Physics-Based Simulations Using High Performance Computing

Morgan Bent[1], David Fu[1], Hernan Lopez[2], Spencer Ortega[3], Kevin Scroggins[3], Scott Callaghan[4], Jacqui Gilchrist[4], Mark Benthien[4], Jozi Pearson[4], Thomas Jordan[4]

(1) University of Southern California, (2) California Polytechnic State University Pomona, (3) Pasadena City College, (4) Southern California Earthquake Center

Abstract

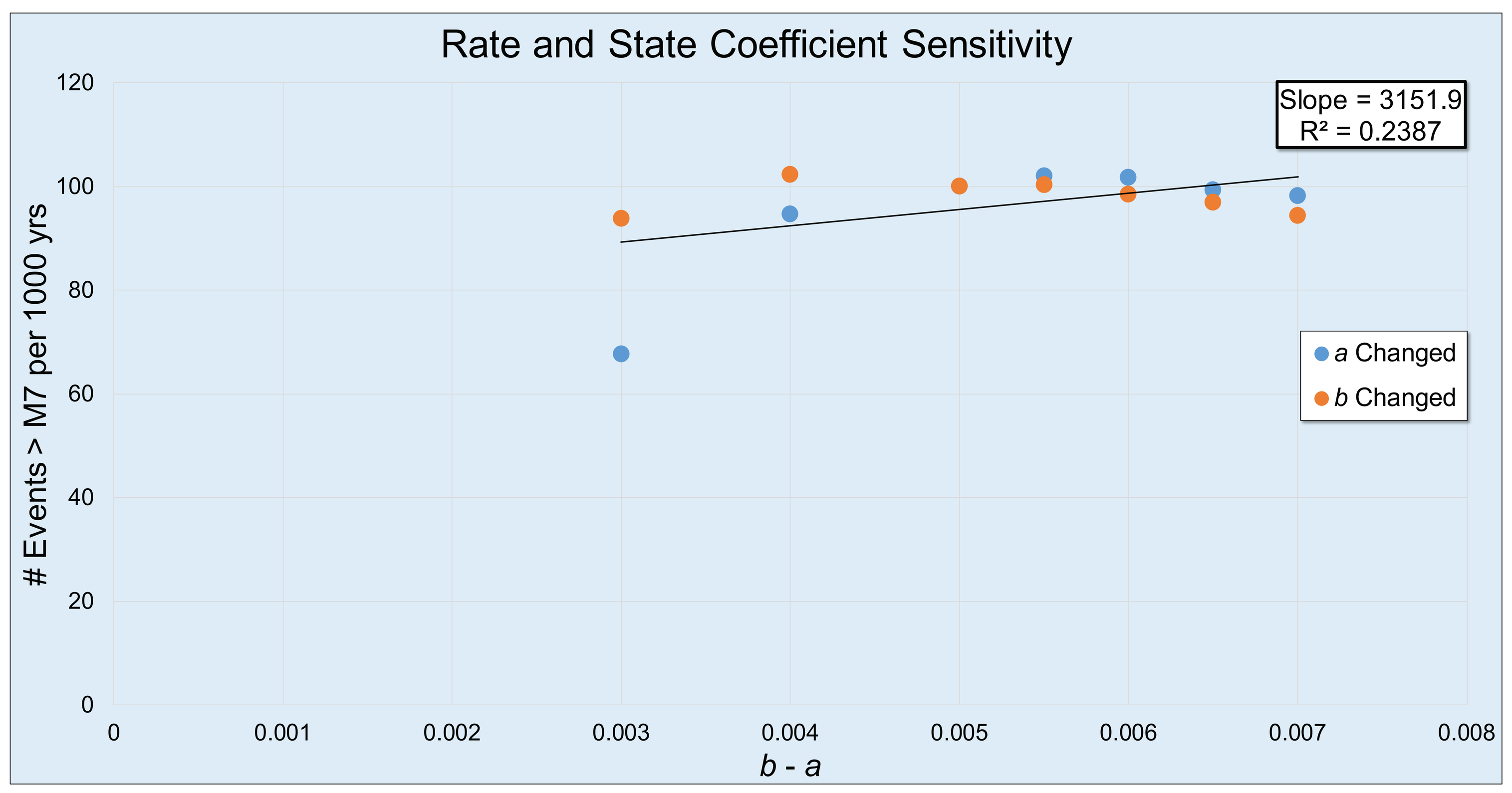
As part of the 2016 Undergraduate Studies in Earthquake Information Technology (UseIT) internship program, students worked in collaborative groups to tackle unsolved problems in earthquake information technology presented in the form of a Grand Challenge. Earthquake forecasting was the overall theme of this year's Grand Challenge. The UseIT High Performance Computing (HPC) Team was challenged to simulate long catalogs of California's seismic activity on a supercomputer. The team used a physics-based earthquake simulator, the Rate-State earthQuake Simulator (RSQSim). The students ran the simulations on the Blue Waters system at the University of Illinois, one of the most powerful open-science supercomputers in the world. To configure an RSQSim simulation, a series of initial physical parameters must be specified, including initial normal and shear stresses, rate- and state-friction parameters, and earthquake slip rate. The HPC Team studied the effects of these parameters on simulated catalogs. Each team member ran several short simulations (25,000 simulated years) with different input parameters and then compared the catalogs with the Uniform California Earthquake Rupture Forecast Version 3 (UCERF3) to determine which parameter set produced the best match. The HPC team also utilized the R Programing Language, a language commonly used by statisticians as well as data miners, in order to analyze the results of each catalog. Varying the parameter sets produced drastic changes in the catalogs generated. With the help of the Probabilistic Forecasting Team, the HPC Team compared each of the short catalogs with multiple aspects of the UCERF3 data. Of the seventeen short catalogs generated, Sigma High had less than a 2% difference from UCERF3 in the recurrence interval of events M ≥ 7 on the Southern San Andreas Fault, which indicated that the parameter set was the best representation of an earth-like system. Based on this information, the team extended the catalog to 530,000 years in order to create a more comprehensive dataspace for earthquake forecasting. The UseIT interns used these catalogs to answer probabilistic questions posted in the Grand Challenge and generate simulator-based forecasts for the San Andreas Fault System.

Metadata

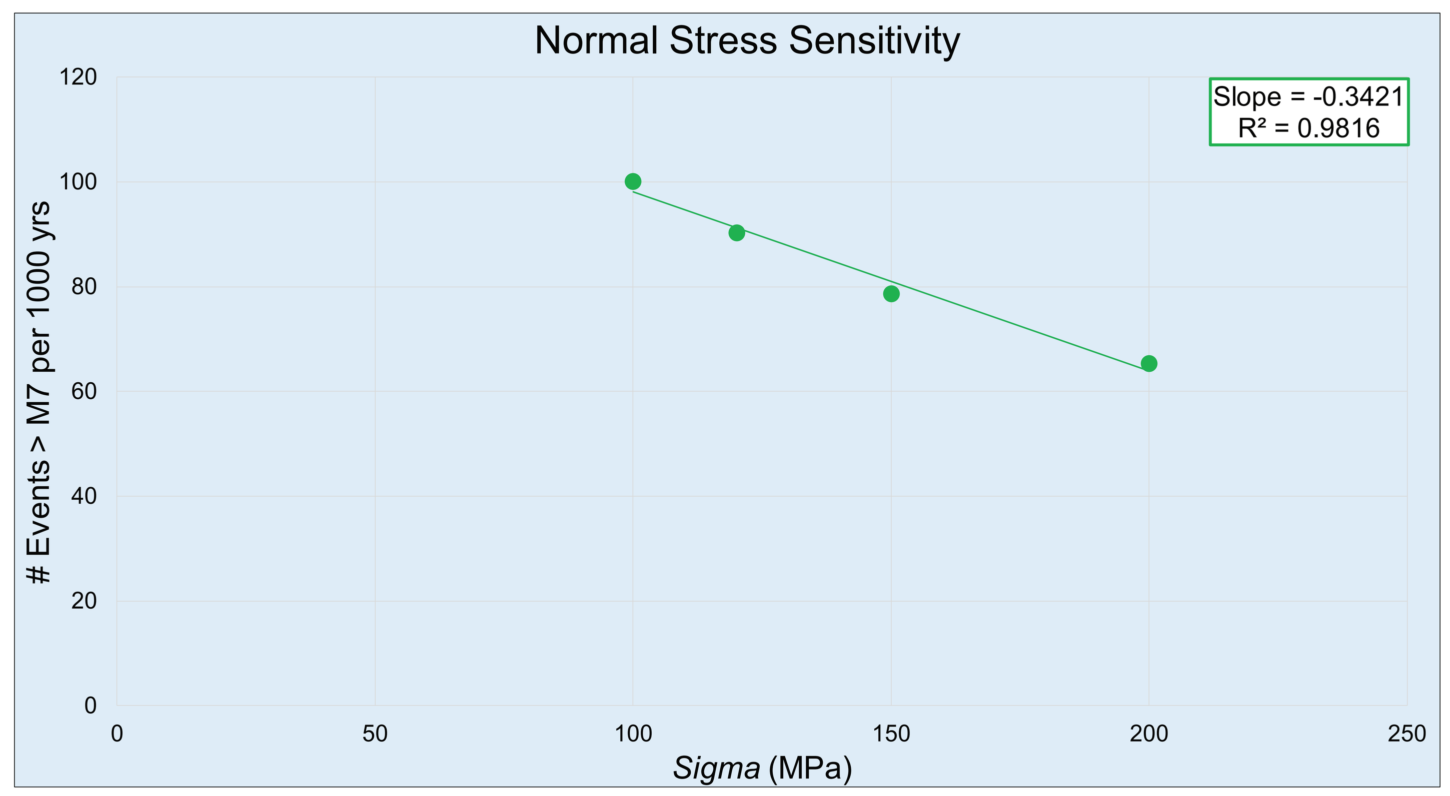
Run Name	*a* (Rate) Coefficient	*b* (State) Coefficient	*b* - *a*	Shear Stress	Normal Stress
Base	0.01	0.015	0.005	60	100
Rate	0.008	0.015	0.007	60	100
Rate 2	0.009	0.015	0.006	60	100
State	0.01	0.013	0.003	60	100
Sigma High	0.01	0.015	0.005	120	200
Sigma Mid	0.01	0.015	0.005	90	150
Sigma Low	0.01	0.015	0.005	72	120

This table lists the important parameters of a representative sample of the simulations we ran. The boxes highlighted in yellow show the values that were altered from the values in the Base simulation. The coefficients, *a* and *b*, are the rate and state coefficients in the rate- and state-friction equation. The *a* and *b* values were varied up to 20% from the Base model. The normal and shear stresses are the stresses orthogonal and parallel to the fault plane. Normal stress was varied up to 100%.

Parameter Sensitivity

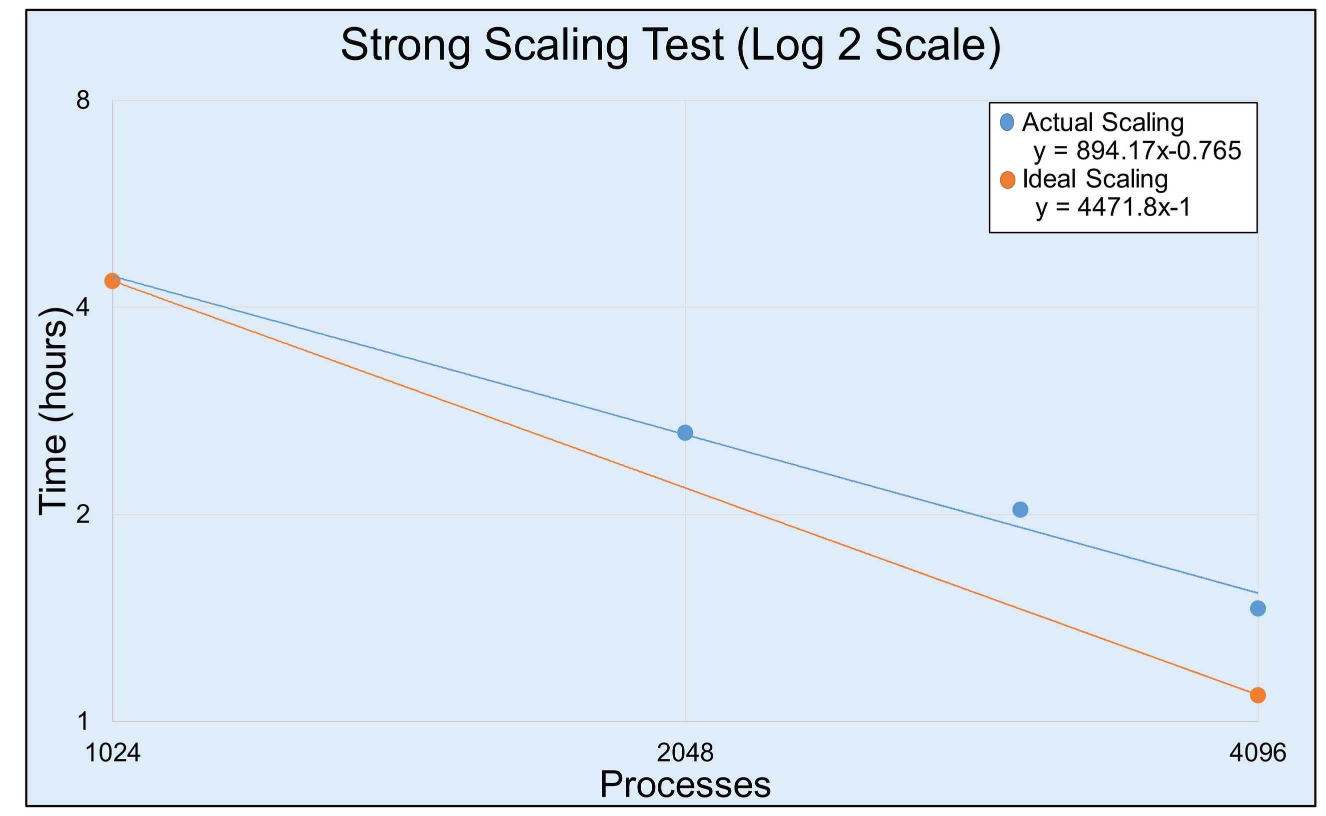


This figure illustrates the sensitivity of the rate of large events (M ≥ 7) to the change in the difference between the frictional coefficients, *a* and *b*, used by RSQSim. There are two points per x value for every value except 0.005, which is the Base catalog: blue for the catalog in which the *a* value was altered from the Base, and orange for the catalog in which the *b* value was altered. There was a ~10% variation in number of large events over a ~40% variation in (*b* - *a*), which indicates that the rate of large events is not very sensitive to the difference between *a* and *b*.



This figure illustrates the sensitivity of the rate of large events (M ≥ 7) to the change in the normal stress used by RSQSim simulation. Normal stress (σ) is the orthogonal stress on a fault. When *sigma* is doubled from 100 MPa to 200 MPa, the number of large events decreases by almost 40%. This means that the rate of large events in a catalog is greatly affected by the initial normal stress.

Scaling Test

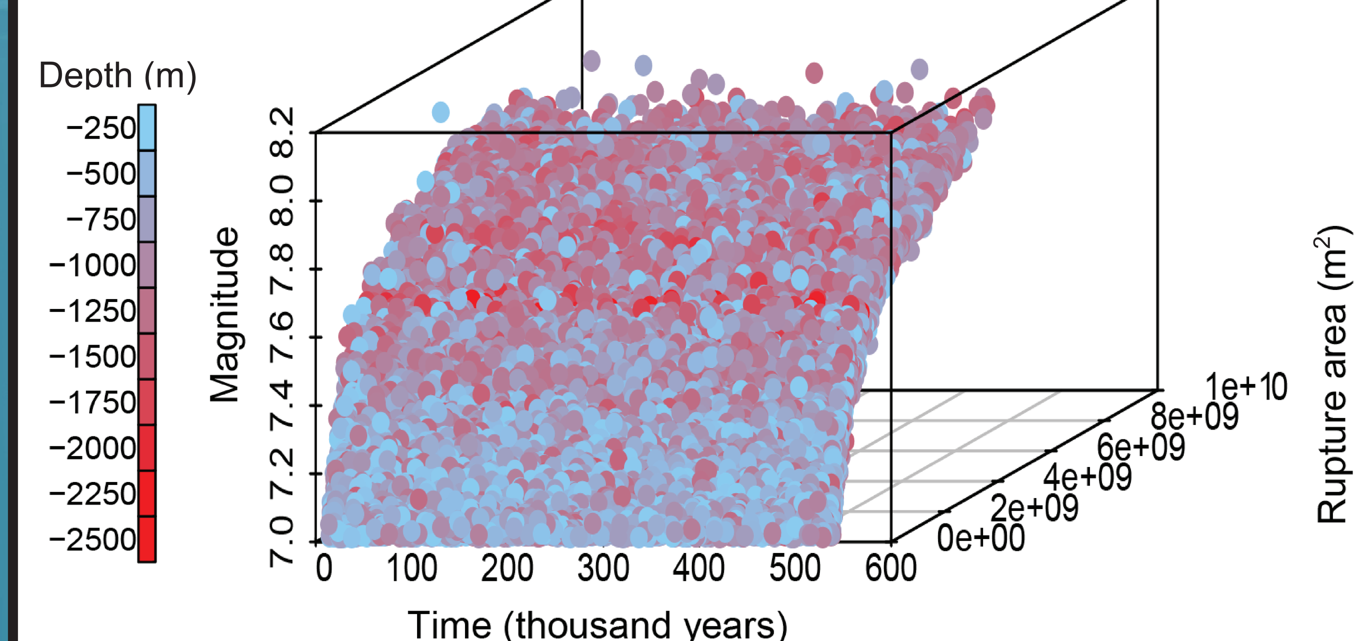


A strong scaling test determined the scalability performance of RSQSim. The four blue data points represent the four measurements performed with 1024, 2048, 3072, and 4096 processes with 1024 being the base case. The orange line represents ideal scaling with a strong scaling efficiency of 1, where the amount of time decreases by a scale of 2 when the number of processes is doubled.

Strong scaling efficiency for 2048, 3072, and 4096 processes are calculated respectively relative to the base case using $(t_0 / (N * t_N))* 100\%$, where t_0 is the processing time used with 1024 processes, N is the ratio of the number of processes relative to 1024, and t_N is the processing time used. The resulting strong scaling efficiencies are: 83.02%, 71.71%, 74.78%.

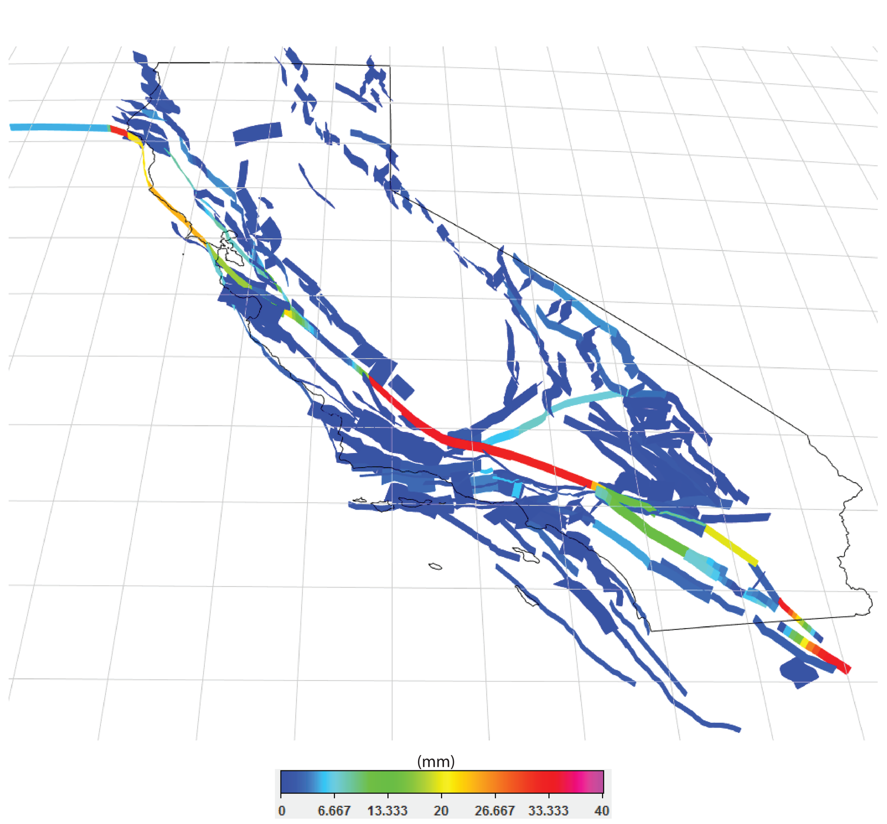
Catalog Graph

Sigma High 530 thousand years Magnitude ≥ 7 Earthquakes



Sigma High catalog's M ≥ 7 earthquakes in California plotted by time, rupture area, and magnitude, and colored by depth. The graph shows the expected logarithmic relationship between magnitude and rupture area, a distribution of deep earthquakes at 7.7, and shallow earthquakes at relatively lower magnitudes.

California Fault Model



The UCERF3 California Fault Model is plotted by the visual software SCEC-VDO (Virtual Display of Objects). This fault model was used for all of the simulations presented here. The faults are colored by long-term slip rate. Through this improved visualization software, we are able to gain new perspective on large event ruptures in California.

UCERF3 Comparison

		UCERF3	Base	Rate	Rate_2	State	Sigma Low	Sigma Mid	Sigma High[2]
# of Events ≥ M7[1]	CA	692.14	1076.53	1031.72	1073.01	992.90	827.01	953.28	690.69
			55.54%	49.06%	55.03%	43.45%	19.49%	37.73%	0.21%
	SoCal	363.52	656.69	624.98	657.52	629.86	500.68	577.51	413.96
			80.65%	71.93%	80.88%	73.27%	37.73%	58.87%	13.88%
	sSAF	107.21	192.07	199.94	205.92	209.30	140.14	168.75	109.88
			79.14%	86.48%	92.06%	95.21%	30.71%	57.40%	2.49%
	SJF	28.06	49.33	47.62	47.21	55.23	36.84	39.60	35.29
			75.79%	69.72%	68.24%	96.82%	31.31%	41.14%	25.76%
Recurrence Interval (yrs)	CA	14.45	9.29	9.69	9.32	10.07	12.09	10.49	14.48
			35.71%	32.91%	35.50%	30.29%	16.31%	27.39%	0.21%
	SoCal	27.51	15.23	16.00	15.21	15.88	19.97	17.32	24.16
			44.64%	41.84%	44.71%	42.29%	27.40%	37.05%	12.19%
	sSAF	93.27	52.07	50.02	48.56	47.78	71.36	59.26	91.01
			44.18%	46.38%	47.93%	48.77%	23.49%	36.47%	2.43%
	SJF	356.38	202.73	209.98	211.82	181.07	271.41	252.50	283.37
			43.11%	41.08%	40.56%	49.19%	23.84%	29.15%	20.48%

% Differences
Higher than UCERF3
Lower than UCERF3

[1] Average values per 10,000 years

[2] Extended run on 64 nodes instead of 32

This table contains the average numbers of large events per 10,000 years (blue), and average recurrence intervals (purple) of faults throughout all of California (CA), Southern California (SoCal), the southern San Andreas Fault (sSAF), and the San Jacinto Fault (SJF) for each of the simulated catalogs as well as UCERF3. UCERF3 was used as the baseline, and the percentages show the percent difference of each value to the corresponding UCERF3 value. Orange cells indicate the value was greater than the corresponding UCERF3 value, and yellow cells indicate that the value was less than the corresponding UCERF3 value. Sigma High was the best overall match to UCERF3.

Conclusion

- The HPC team ran seventeen 25,000+ year simulations, each with varied parameters to analyze the effect of the parameters on the catalog statistics.
- The catalogs were compared to the rate and recurrence intervals for events, magnitude 7 and greater, with the data from UCERF3.
- In the Sigma High catalog, the normal stress was increased from the Base value which produced the best match for UCERF3; therefore, it was extended.
- The percent differences for the recurrence intervals for all of California (CA), Southern California (SoCal), the Southern San Andreas Fault (sSAF), and the San Jacinto Fault (SJF) are 0.21%, 12.19%, 2.43%, and 20.48% respectively, compared to UCERF3.
- Based on the results of the sensitivity test, we concluded that the rate of large events are more sensitive to changes in the normal stress than changes in the rate- and state-friction coefficients.

References

Dieterich, J. H., and K. B. Richards-Dinger (2010). Earthquake recurrence in simulated fault systems, Pure Appl. Geophys. 167, 1087–1104, doi: 10.1007/s00024-010-0094-0.

Richards-Dinger, K.B., Dieterich, J. H. (2012). RSQSim Earthquake Simulator, Pure Appl. Geophys. doi: 10.1785/0220120105.