Collaboratory for the Study of Earthquake Predictability (CSEP)

T. H. Jordan, D. Schorlemmer, S. Wiemer, M. Gerstenberger, P. Maechling , M. Liukis, J. Zechar & the CSEP Collaboration

5th International Workshop on Statistical Seismology

June 3, 2007

SED

SCEC
an NSF+USGS center

GNS SCIENCE
TE PŪ AO

Collaboratory for the Study of Earthquake Predictability (CSEP)

… an open, international partnership to support a global program of research on earthquake predictability through prospective, comparative testing of scientific prediction hypotheses in a variety of tectonic environments.

Collaboratory for the Study of Earthquake Predictability (CSEP)

Discussions at StatSeis5:

09:30 Introductory talk

- Scientific vs. "useful" earthquake prediction
- Rationale for a global collaboratory
- Proposed CSEP structure and policies
- Current developments and timelines
- Major issues

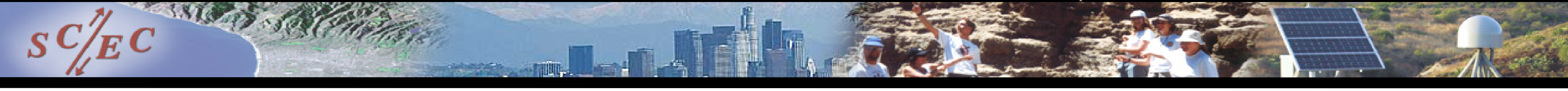
11:00 Panel discussion

15:00 Technical session (upstairs at San Rocco)

Three Definitions

- ***Earthquake predictability***
  - degree to which the future occurrence of earthquakes is encoded in the behavior of an active fault system
- ***Scientific earthquake prediction***
  - a testable hypothesis, usually stated in probabilistic terms, of the location, time, and size (and perhaps other parameters) of fault ruptures
- ***Useful earthquake prediction***
  - advance warning of potentially destructive fault rupture precise and reliable enough to warrant actions to prepare communities

Three Questions



Three Questions

Q1. **How should scientific earthquake predictions be stated and tested?**

- **How should prediction experiments be conducted and evaluated?**

Three Questions

Q1. **How should scientific earthquake predictions be stated and tested?**

- **How should prediction experiments be conducted and evaluated?**

Q2. **What is the intrinsic predictability of the earthquake rupture process?**

- **E.g., are there coherent space-time structures in the chaotic evolution of active fault systems?**

Three Questions

Q1. **How should scientific earthquake predictions be stated and tested?**

- How should prediction experiments be conducted and evaluated?

Q2. **What is the intrinsic predictability of the earthquake rupture process?**

- E.g., are there coherent space-time structures in the chaotic evolution of active fault systems?

Q3. **Can knowledge of large-earthquake predictability be deployed as useful predictions?**

- Is operational earthquake prediction feasible?

Three Questions

Q1. **How should scientific earthquake predictions be stated and tested?**

- **How should prediction experiments be conducted and evaluated?**

Q2. **What is the intrinsic predictability of the earthquake rupture process?**

- **E.g., are there coherent space-time structures in the chaotic evolution of active fault systems?**

Q3. **Can knowledge of large-earthquake predictability be deployed as useful predictions?**

- **Is operational earthquake prediction feasible?**

Three Questions

Q1. **How should scientific earthquake predictions be stated and tested?**

- How should prediction experiments be conducted and evaluated?

Q2. **What is the intrinsic predictability of the earthquake rupture process?**

- E.g., are there coherent space-time structures in the chaotic evolution of active fault systems?

Q3. **Can knowledge of large-earthquake predictability be deployed as useful predictions?**

- Is operational earthquake prediction feasible?

"Silver Bullet" Approach

- **Seeks useful, short-term earthquake predictions; i.e., focuses on direct answer to *Q3***
  - "heroic quest" for a simple solution
  - dominated research in the 1970's and 1980's
- **Searches for signals diagnostic of approach to rupture, including:**
  - foreshocks
  - strain-rate changes
  - electromagnetic signals
  - hydrologic changes
  - geochemical signals
  - animal behavior

- **Has not thus far led to useful prediction methodologies**

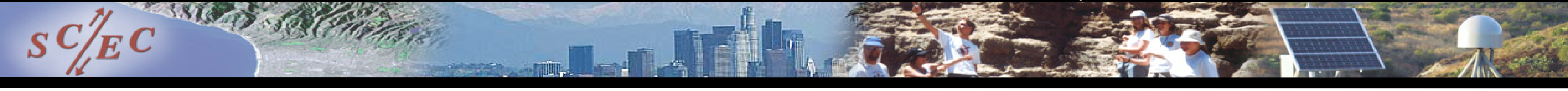
Science @NASA
Inform Inspire Involve
science.nasa.gov

Anticipating Earthquakes

High above Earth where seismic waves never reach, satellites may be able to detect earthquakes--before they strike.

"Although earthquakes seem to strike out of the blue, the furious energy that a quake releases builds up for months and years beforehand in the form of stresses within Earth's crust. At the moment, forecasters have no direct way of seeing these stresses or detecting when they reach critically high levels.

"That may be changing, however. **Satellite technologies being developed at NASA and elsewhere might be able to spot the signs of an impending quake days or weeks before it strikes, giving the public and emergency planners time to prepare."**



Inform Inspire Involve
science.nasa.gov

Anticipating Earthquakes

High above Earth where seismic waves never reach, satellites may be able to detect earthquakes--before they strike.

"Although earthquakes seem to strike out of the blue, the furious energy that a quake releases builds up for months and years beforehand in the form of stresses within Earth's crust. At the moment, forecasters have no direct way of seeing these stresses or detecting when they reach critically high levels.

"That may be changing, however. Satellite technologies being developed at NASA and elsewhere might be able to spot the signs of an impending quake days or weeks before it strikes, giving the public and emergency planners time to prepare."

[i.e., NASA might be able to answer Q3]

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 88 NUMBER 20

15 MAY 2007

PAGES 217–224

Natural Radioactivity, Earthquakes, and the Ionosphere

PAGES 217–218

Air ionization produced by natural ground radioactivity, mainly by radon emanating from the Earth's crust, is a primary source of ions in the planetary boundary layer (PBL) of the atmosphere over land [*Hoppel et al.*, 1986]. These ions provide the air conductivity responsible for fair weather vertical electric current in the global electric circuit (GEC), a system of stationary electric currents between the ground and ionosphere driven by global thunderstorm activity. This activity is considered an electric generator of the potential difference between the ground and ionosphere (200–600 kilovolts), and the return downward current closes the circuit in the areas of fair weather [*Roble and Tzur*, sources of the anomalous ionospheric variations, and radon emanation was named as a principal source.

Here we intend to demonstrate how the large-scale local irregularities of air conductivity produced by natural radioactivity can create irregularities within the ionosphere through coupling within the frame of the GEC model.

Effect of Radon Emissions on the Atmosphere

Hundreds of publications have noted increased radon concentration in the vicinity of active tectonic faults a few weeks before strong seismic events. Ionization of the near-ground layer of the atmosphere proshows the migration over time and space of variations in radon, and its presence will not necessarily be close to the epicenter of an earthquake. However, with satellites, an anomaly can be observed within a much larger area (earthquake preparation area) that for large earthquakes is of the order of several hundred thousand square kilometers. Most important, the thermal anomalies for all recent major earthquakes were registered before the seismic shocks, which proves that radon variation is a real precursor to an earthquake. Of course, the lithology creates the difference in radon emission intensity for different areas of the globe.

Nonetheless, these thermal anomalies are equivalent in size to the air ionization and ions' hydration area, and hence to columnar resistance anomalies that cannot be 'unnoticed' within the ionosphere because of size. The local conductivity anomaly of the order of an individual cloud or even a volcano

EOS

EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 88 NUMBER 20

15 MAY 2007

PAGES 217–224

Natural Radioactivity, Earthquakes, and the Ionosphere

PAGES 217–218

Air ionization produced by natural ground radioactivity, mainly by radon emanating from the Earth's crust, is a primary source of

ior
of
19
ity
tri
(G
rei
dri
ac
the
an

return downward current closes the circuit in the areas of fair weather [*Roble and Tzur*,

sources of the anomalous ionospheric variations, and radon emanation was named as a principal source.

Here we intend to demonstrate how the large-scale local irregularities of air conduc-

before strong seismic events. Ionization of the near-ground layer of the atmosphere pro-

shows the migration over time and space of variations in radon, and its presence will not necessarily be close to the epicenter of an earthquake. However, with satellites, an anomaly can be observed within a much larger area (earthquake preparation area) that for large earthquakes is of the order of several hundred thousand square kilometers. Most important, the thermal anomalies for all recent major earthquakes were registered

of an individual cloud or even a volcano

"Most important, thermal anomalies for all recent major earthquakes were registered before the seismic shocks, which proves that radon variation is a real precursor to an earthquake …

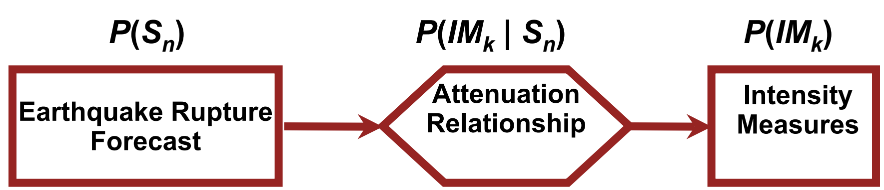
"Short-term earthquake prediction based on ionospheric data may one day become as routine a technique as seismographs."

"Brick-by-Brick" Approach

- Focused on experimentation (*Q1*) and predictability (*Q2*), not operational prediction (*Q3*)
  - Long-term effort to understand and improve predictability, even if probability gains are small
- Based on *system-specific, synoptic* models of earthquake recurrence, stress evolution, and triggering
  - Framework for time dependence is the long-term, synoptic forecasting required for probabilistic seismic hazard analysis
- Demonstrates predictability by rigorous testing based on *intercomparison* of models
  - RELM program and its extension to a Collaboratory for the Study of Earthquake Predictability (CSEP)

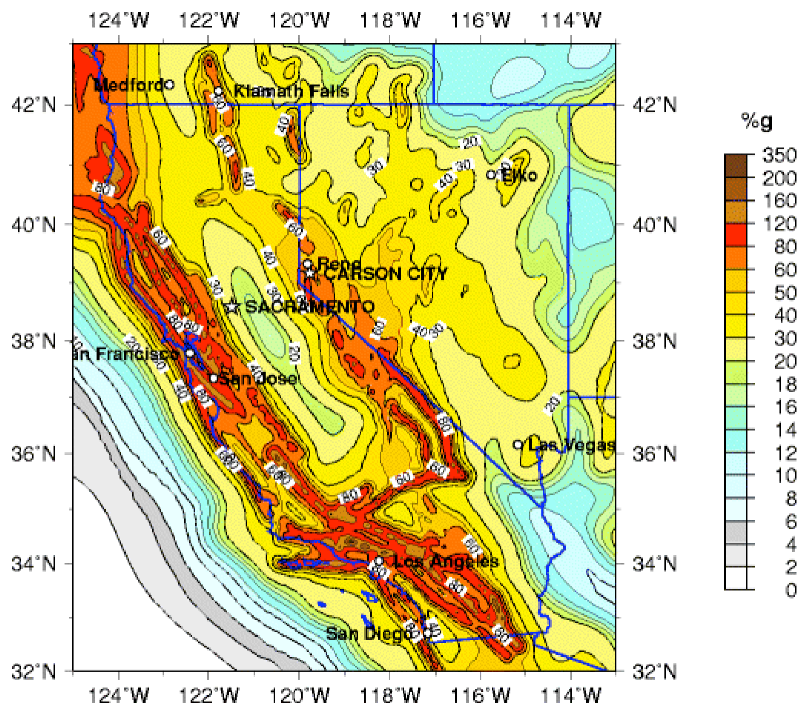
Rationale for a Brick-by-Brick Approach

- **PSHA requires long-term, system-specific earthquake rupture forecasts**
  - Time-dependent ERF methodologies not widely implemented nor validated
  - Comparisons across different fault systems could accelerate progress



Probabilistic Seismic Hazard Analysis (PSHA)

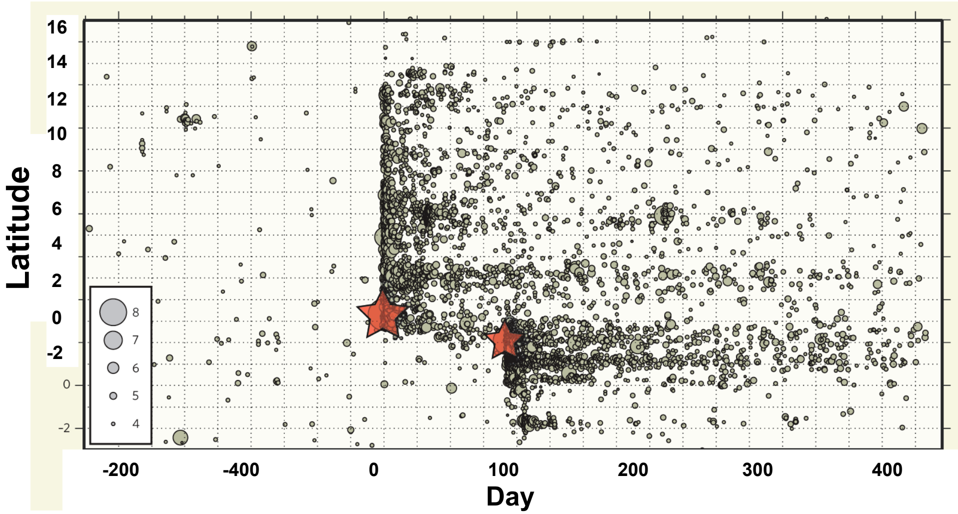
U.S. National Seismic Hazard Map (2002)



Peak Acceleration (%g) with 2% Probability of Exceedance in 50 Years
site: NEHRP B-C boundary
National Seismic Hazard Mapping Project

Rationale for a Brick-by-Brick Approach

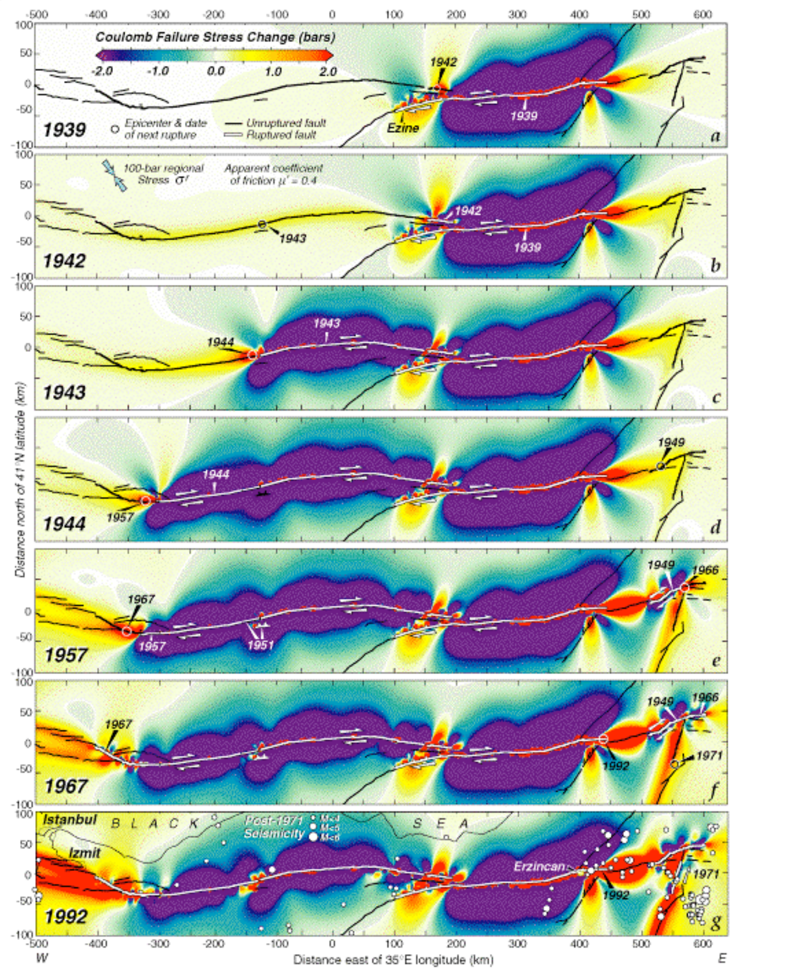
- PSHA requires long-term, system-specific earthquake rupture forecasts
  - Time-dependent ERF methodologies not widely implemented nor validated
  - Comparisons across different fault systems could accelerate progress
- Earthquake catalogs demonstrate short-term predictability
  - Statistical triggering models (e.g. ETAS) capture significant predictability
  - High-resolution imaging of faulting-related transients may improve models



Sumatra Earthquake Sequence
(Ammon, 2006)

Rationale for a Brick-by-Brick Approach

- **PSHA requires long-term, system-specific earthquake rupture forecasts**
  - Time-dependent ERF methodologies not widely implemented nor validated
  - Comparisons across different fault systems could accelerate progress
- **Earthquake catalogs demonstrate short-term predictability**
  - Statistical triggering models (e.g. ETAS) capture significant predictability
  - High-resolution imaging of faulting-related transients may improve models
- **Stress-evolution models may provide a physical basis for intermediate-term predictability**
  - Better catalogs can improve the testing of scientific prediction experiments



Stress Evolution of the North Anatolian Fault System (Stein et al., 1997)

Problems in Assessing Earthquake Forecasts and Prediction Experiments

- Scientific publications provide insufficient information for independent evaluation
- Active researchers are constantly tweaking their procedures, which become moving targets
- Standards are lacking for testing predictions against reference forecasts
- Data to evaluate prediction experiments are often improperly specified
- Infrastructure for conducting and evaluating long-term prediction experiments does not exist

Collaboratory for the Study of Earthquake Predictability (CSEP)

- **Motivation**
  - Earthquake prediction research is hampered by inadequate infrastructure for conducting scientific prediction experiments
- **Primary goal**
  - Rigorous *comparative* testing of scientific prediction experiments spanning a variety of fault systems to study the physical basis for earthquake predictability
- **CSEP will build on the RELM program and similar efforts**
  - International partnerships will establish natural laboratories for scientific earthquake prediction experiments

The Collaboratory Concept

<u>Collaboratory</u>: a networked environment with the computational and communication tools for supporting a geographically distributed scientific collaboration.

"A *center without walls*, in which [scientists] can perform their research without regard to geographical location, interacting with colleagues, accessing instrumentation, sharing data and computational resources, [and] accessing information in digital libraries."

– **William Wulf, NSF, 1989**

"The fusion of computers and electronic communications has the potential to dramatically enhance the output and productivity of researchers. A major step toward realizing that potential can come from [creating] *integrated, tool-oriented computing and communication systems to support scientific collaboration*. Such systems can be called 'collaboratories'."

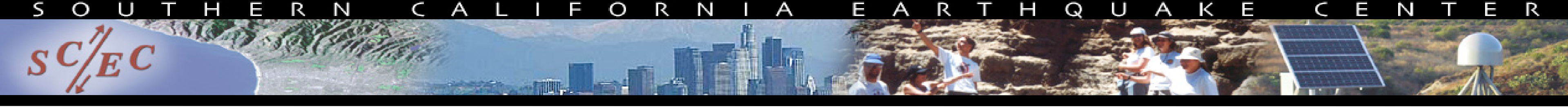
– ***National Collaboratories: Applying Information Technology for Scientific Research*, National Research Council, 1993.**

CSEP Status

- **Organization discussed at international forums**
  - Jun 7-8, 2006 SCEC/CSEP Workshop #1, Mandalay Beach, CA
  - Aug 14-18, 2006 NAF-SAF Workshop, Istanbul, Turkey
  - Jan 28-30, 2007 International Conference on Earthquake Predictability and Time-Dependent Forecasting, Rüschlikon, Switzerland
  - Feb 13-15, 2007 Workshop on a Centre for Time-Varying Earthquake and Volcanic Hazard Research, Wellington, NZ
  - Apr 23, 2007 SCEC/CSEP Workshop #2, Los Angeles, CA
  - May 31-Jun 6, 2007 5th International Conference of Statistical Seismology, Erice, Sicily
- **Collaboratory infrastructure under development**
  - Resources
    - W.M. Keck Foundation (SCEC)
    - NERIES Project (ETH)
    - NZ Earthquake Commission (GNS proposal)
  - Development driven by augmenting RELM and working end-to-end examples
  - CSEP V1.0 software release scheduled for September, 2007
  - Project web sites:
    - http://www.testing.ethz.ch

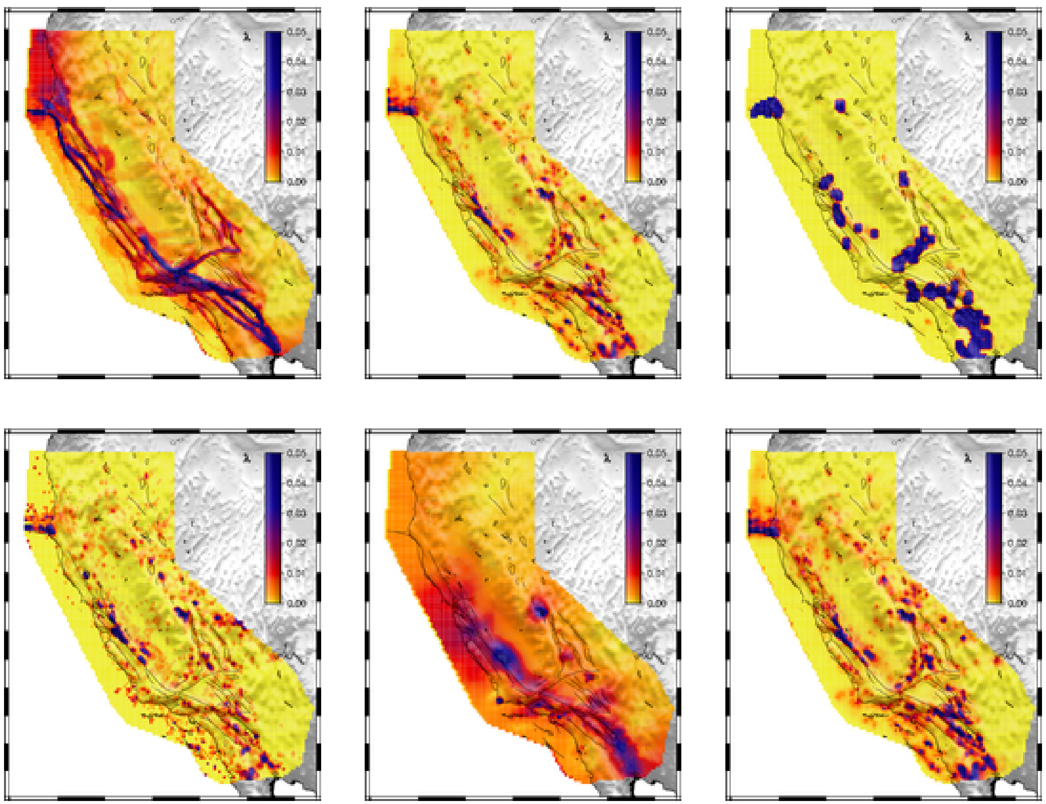
Four Essential CSEP Components

1. Regional natural laboratories with adequate, authorized data sources
2. Community standards for the registration and evaluation of scientific prediction experiments
3. Testing facilities with validated procedures for conducting and evaluating prospective (true) prediction experiments
4. Communication grids that connect the natural laboratories and testing centers to
   - the scientific community, including professional societies
   - government ministries responsible for risk management
   - the general public and other end-users



SCEC/USGS Working Group on

Regional Earthquake Likelihood Models (RELM)



5-yr RELMs submitted to the ETHZ Testing Center

Bird & Liu
SHIFT main shock model
SHIFT main shock + aftershock model

Ebel et al.
5-yr main shock+aftershock model
5-yr main shock model

Helmstetter, Kagan, Jackson
HKJ 2005 long-term main shock model
HKJ 2005 long-term main shock + aftershock model

Holliday et al.
Pattern Informatics

Kagan et al.
5-yr main shock model
5-yr main shock + aftershock model

Shen, Jackson, and Kagan
Geodetic main shock model
Geodetic main shock + aftershock model

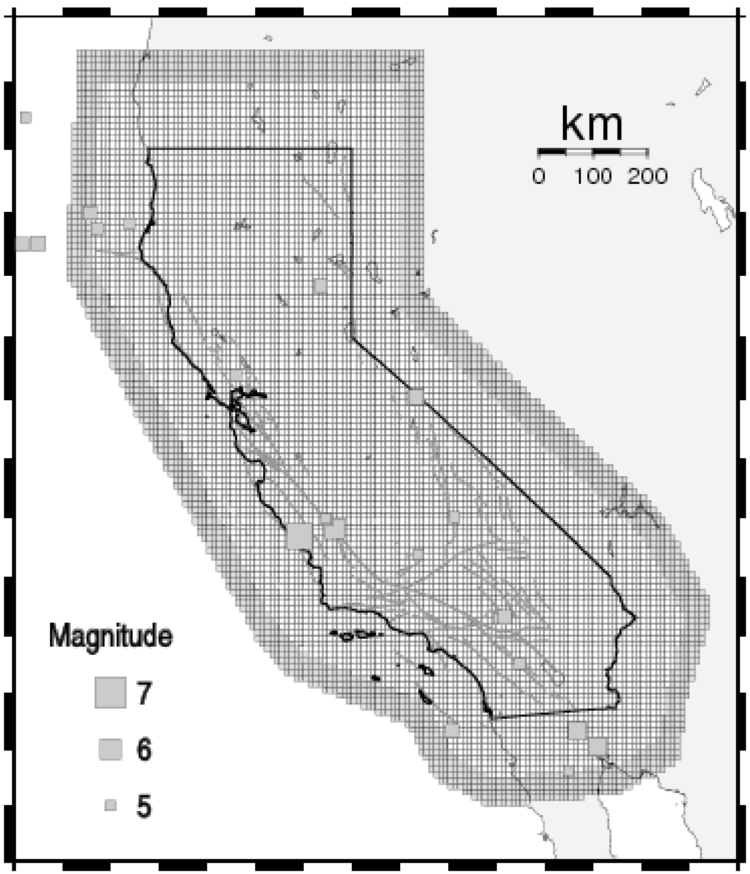
Ward
combo81
geodetic81
geodetic85
geologic81
seismic81
simulation

WG 2002
National Hazard Model

Wiemer & Schorlemmer
Asperity Likelihood Model

SCEC/USGS Working Group on

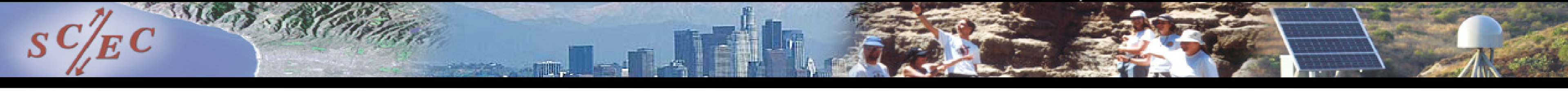
Regional Earthquake Likelihood Models (RELM)



1. California is the natural laboratory
   - ANSS catalog is the authorized data source
2. Model types are well defined
   - Grid-based probabilities of M > 5 events with forecast times of 1-day, 1-yr & 5-yr
3. Testing procedures are standardized
   - *N*, *L*, *R* tests
4. Communication protocols are agreed upon
   1. Cognizance by NEPEC & CEPEC

Papers describing 19 RELMs have appeared in a special issue of *SRL*, February, 2007

http://www.relm.org



CSEP will build on RELM…

by extending the testing standards to include

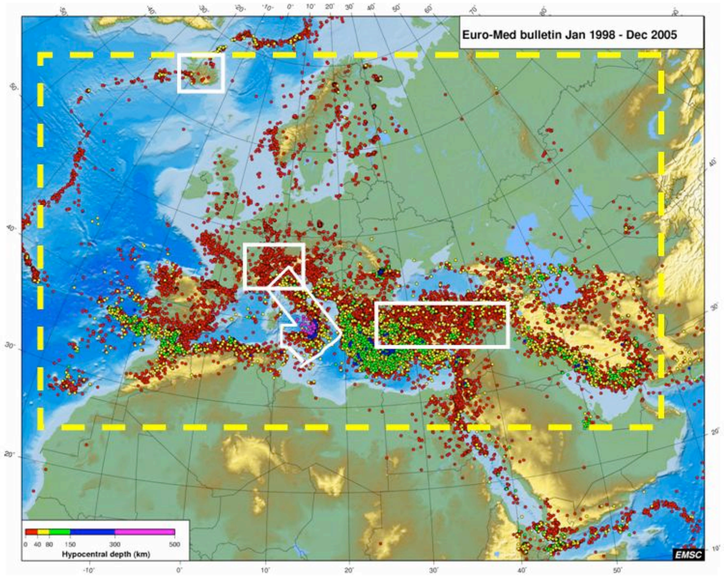
- other probability distributions
- new testing procedures, including alarm-based methods

by expanding the model space to include

- fault-based predictions
- additional data sources
- other natural laboratories

Draft Policy for CSEP Natural Laboratories

- Delineated region with defined areas for data collection and prediction testing
- Sponsorship by a regional organization of earthquake scientists willing to participate in CSEP
- Data streams authorized by agreements with appropriate regional agencies, including a low-latency earthquake catalog for testing prospective predictions
- Calibration of the seismic networks, including the quantification of hypocenter & magnitude uncertainties and mapping of completeness thresholds



Some of the natural laboratories proposed within the Euro-Med region (1998-2005 epicenters from EMSC)

CSEP Testing Centers will support:

- Procedures for registering prediction experiments on regional and global scales
- Access to authorized data streams and monitoring products from CSEP natural laboratories
- Standardized methods for evaluating probability-based and alarm-based predictions
- Software to help scientists participate in prediction experiments

Centers are currently under development in

- Europe (at ETH Zürich)
- United States (at SCEC/USC)
- New Zealand (at GNS Science)

CSEP Model Classes

All models within a particular class should be comparable to each other; e.g., produce the same type of output that can be evaluated by the same testing procedures

- Forecast time scale
  - e.g., 1-day, 1-year, 5-year
- Geographic basis
  - grid cells or fault sections
- Forecast output
  - magnitude range & binning
  - probability or alarm

Draft Policy for Input Data Streams

Data types other than seismicity catalogs may be used to formulate and condition prospective predictions, provided that

- the data coverage and uncertainties are properly characterized
- the physical relationships between the data and earthquake rupture processes are sufficiently well understood

Examples:

- geologic fault models
- geodetic data streams

CSEP Design

Objective is to provide trustworthy answers to two questions:

1. **How was the earthquake prediction produced?**
2. **How was the earthquake prediction evaluated?**

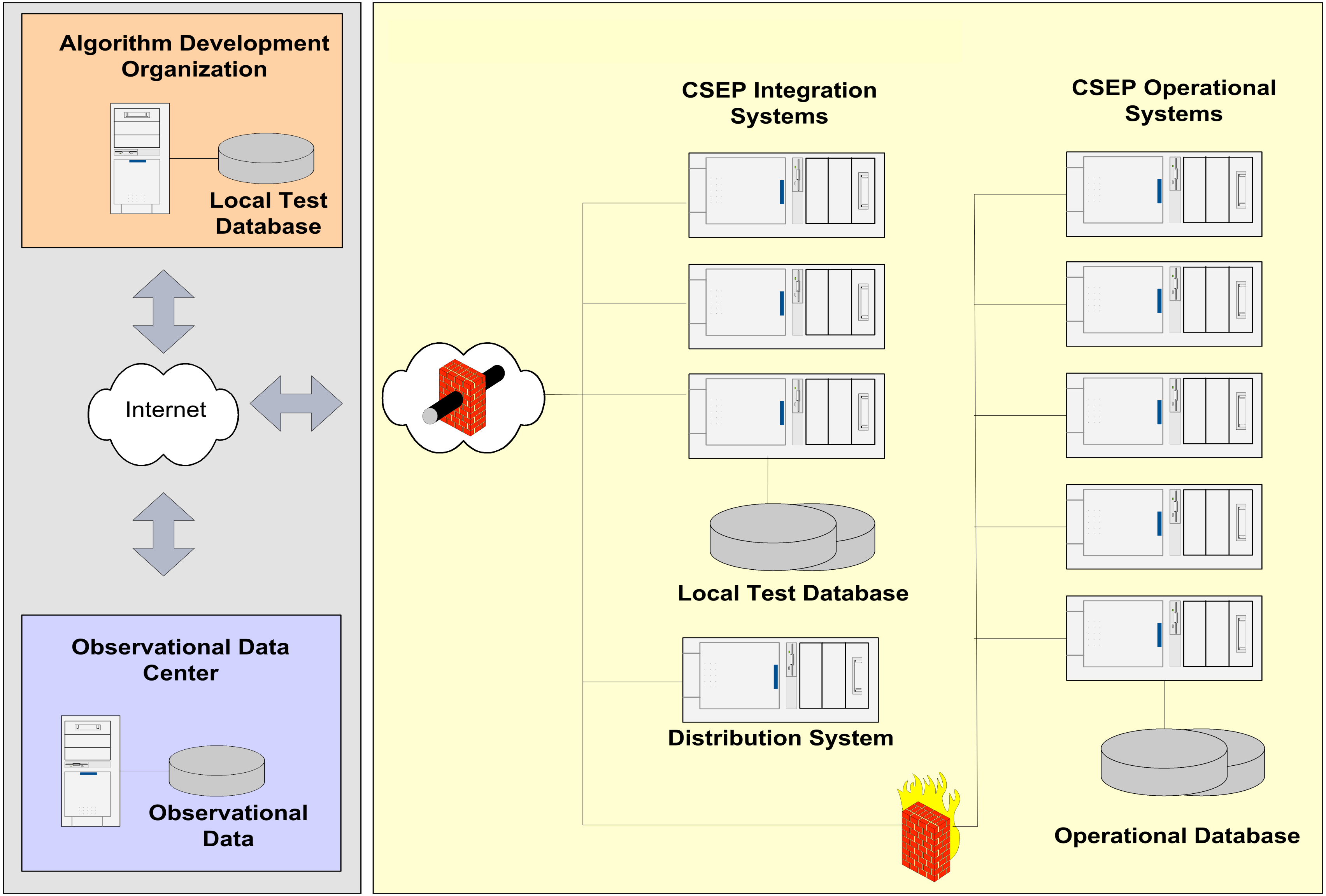
Design goals (Rhoades & Evison, 1989; Kagan & Jackson, 1995; Schorlemmer & Gerstenberger, 2007) :

- **Data streams must be *authorized* and *calibrated***
- **Environment must be *controlled* and *transparent***
- **Results must be *reproducible* and *comparable***

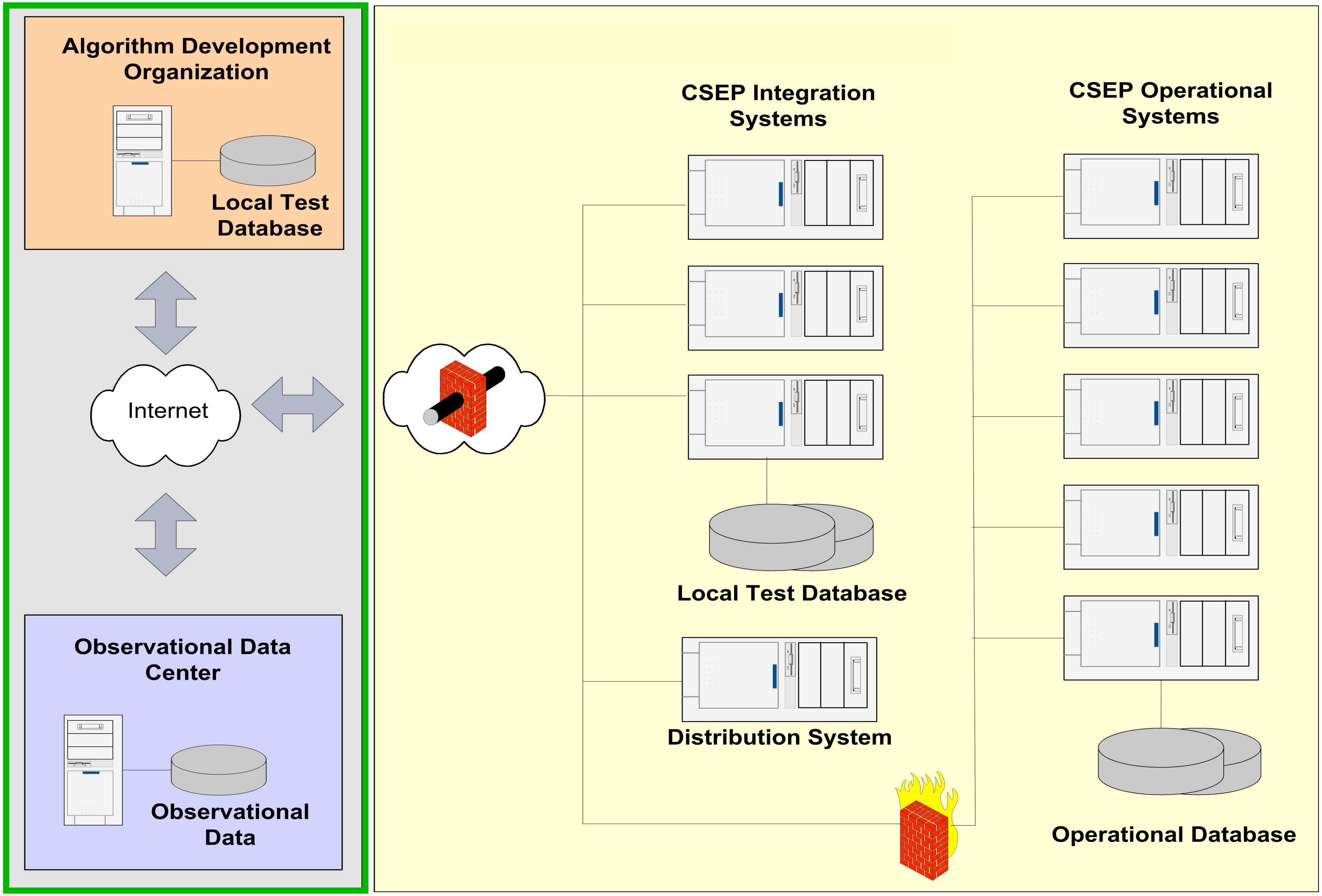
CSEP Software Development

- **QuakeML**
  - Community standard for seismological data exchange, including earthquake catalogs and supplemental information
  - Under development at GFZ, ETHZ, and SCEC
- **CSEP V1.0**
  - Software for routine daily operational forecast testing
  - Under development at SCEC testing center

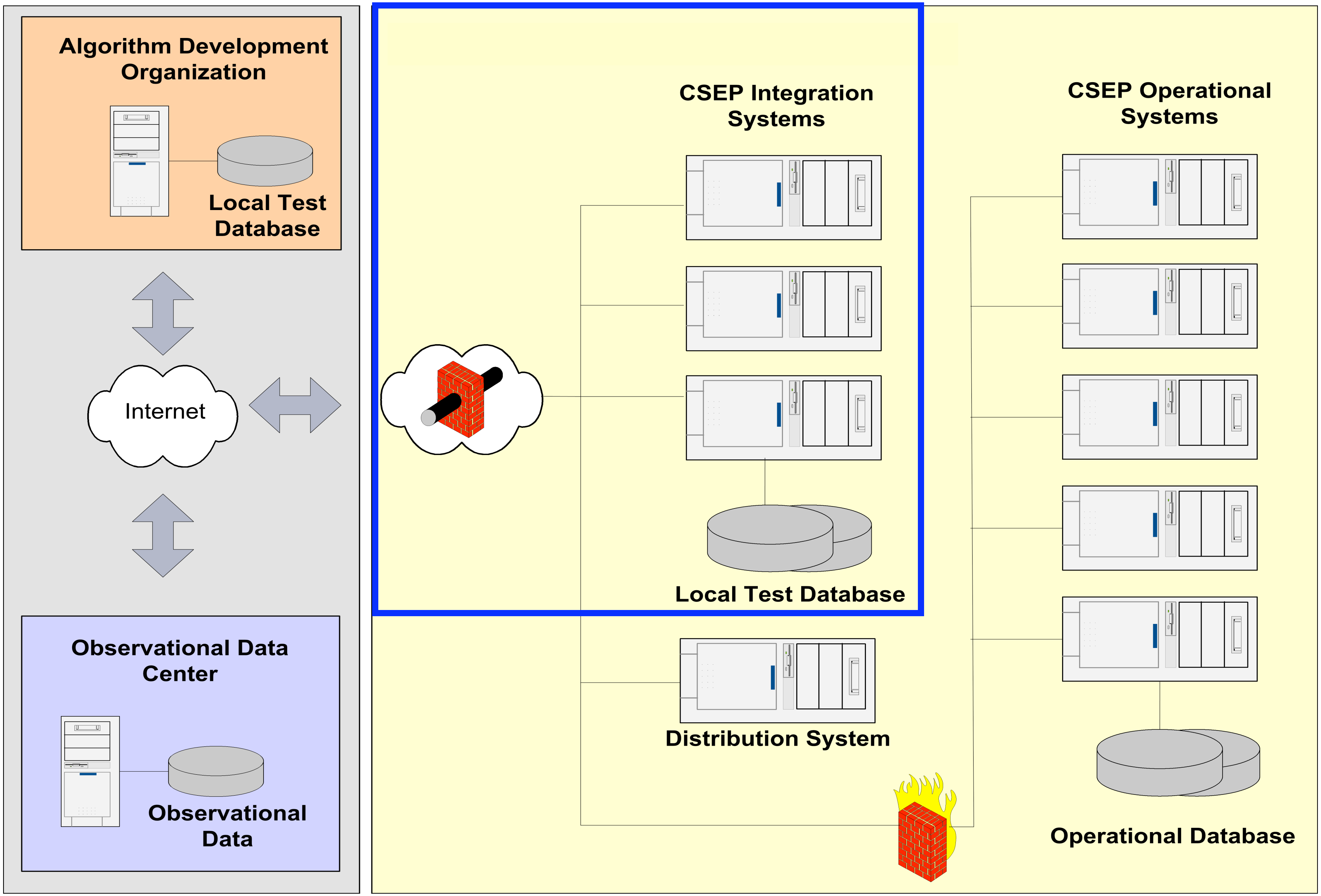
SCEC Testing Center



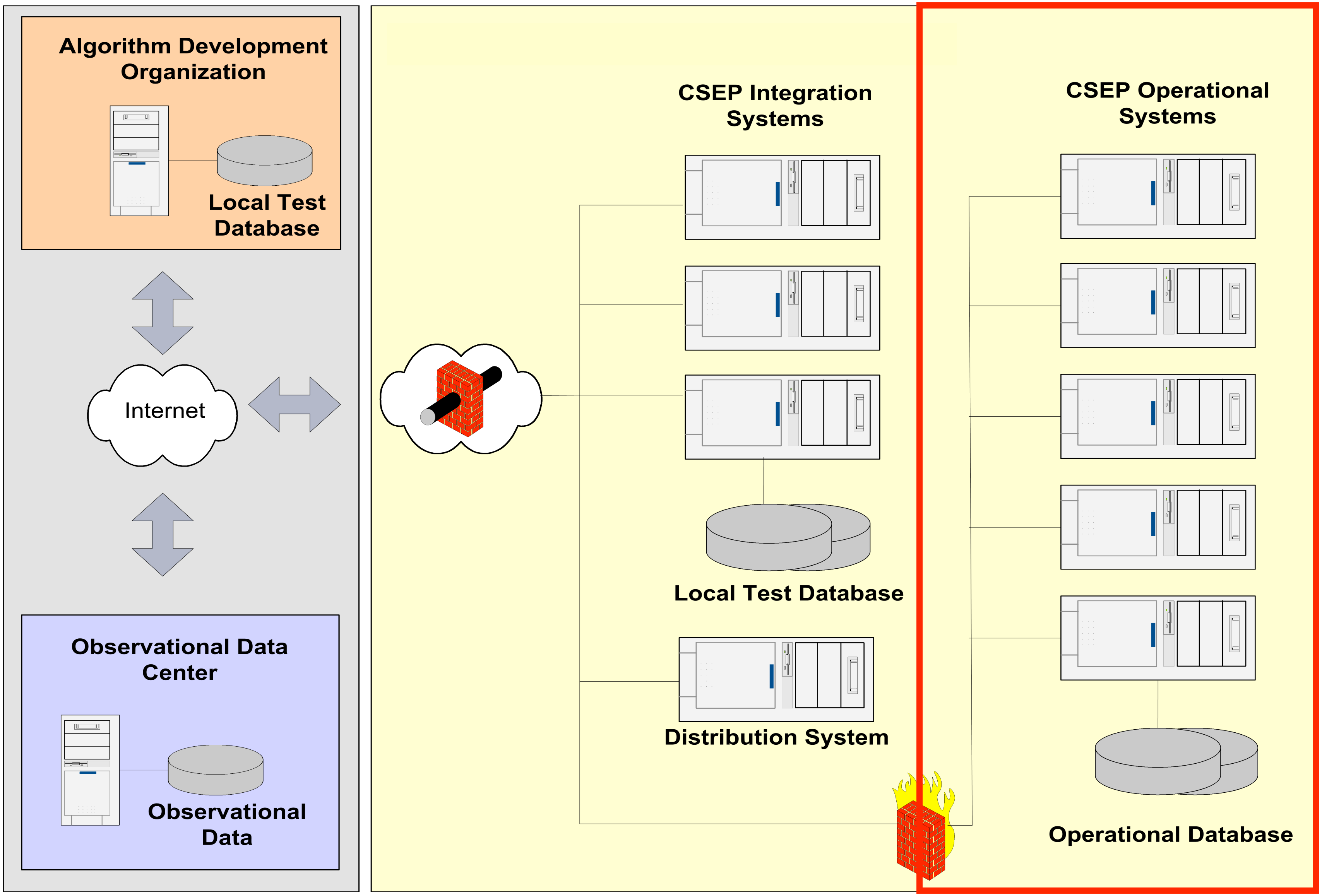
SCEC Testing Center



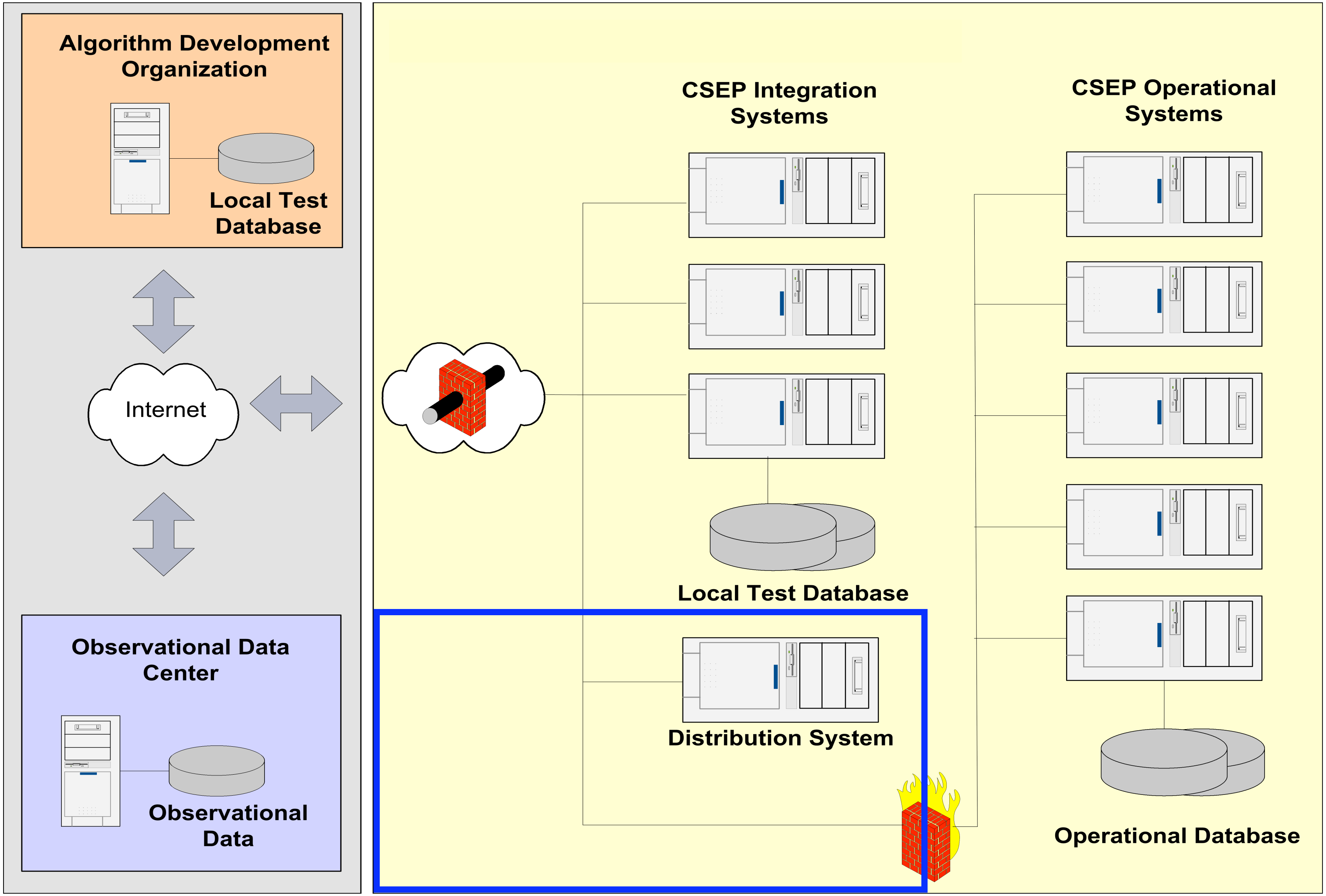
SCEC Testing Center



SCEC Testing Center



SCEC Testing Center

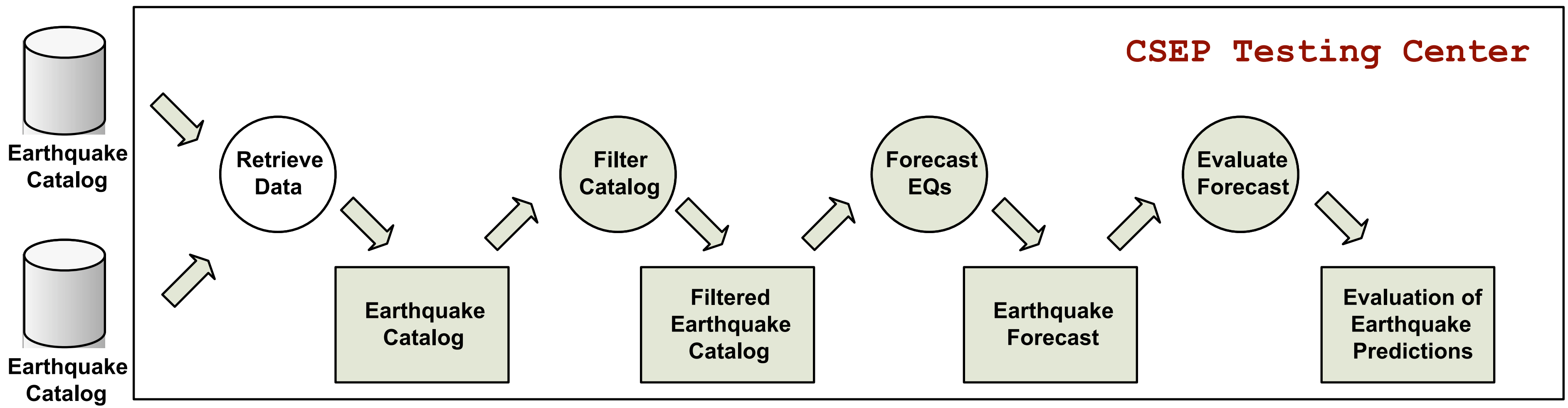


CSEP V1.0 Software

Open-source and shared among testing centers, with development focused in two main areas:

- Acceptance test framework
  - verifies that system changes, either hardware or software, by running previously verified test cases
- Dispatcher
  - automates end-to-end processing from data retrieval to forecast evaluation
  - archives the results along with a description of the codes and data used to produce the results
  - run on a daily basis or on-demand
- Scheduled for release in September, 2007

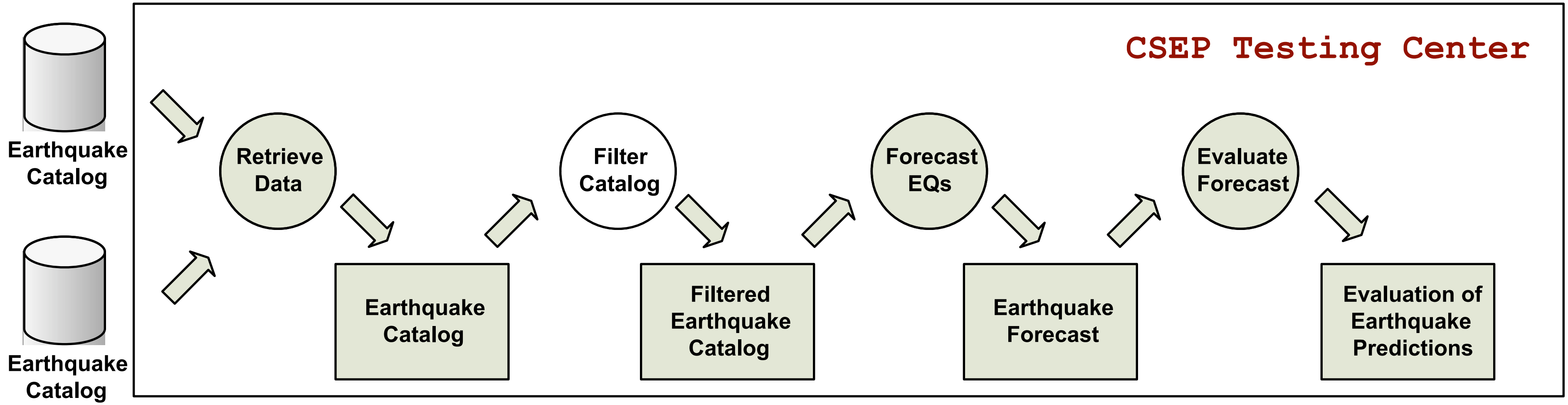
CSEP V1.0 Workflow Model



Data Retrieval Codes

- Implemented in CSEP:
  - Retrieval of ANSS catalog for California Natural Lab
- Planned:
  - Retrieval of EQ catalogs for other natural labs
  - Retrieval of fault parameters from fault database
  - Retrieval of other observational data (e.g. GPS)

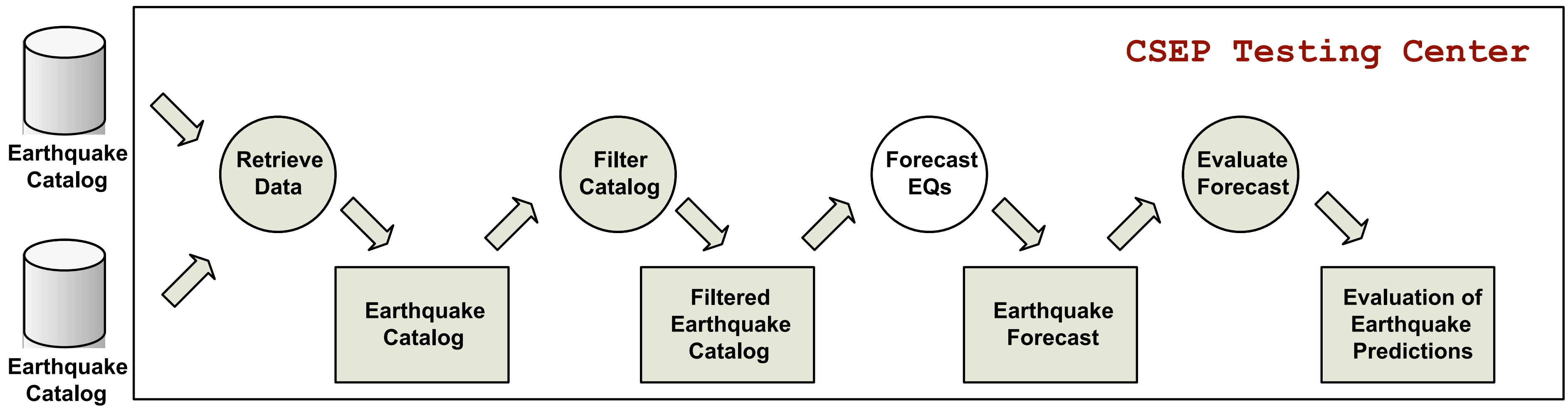
CSEP V1.0 Workflow Model



Data Filter Codes

- Implemented in CSEP:
  - Geographical filter
  - Magnitude filter
  - Start time/end time filter
  - Declustering algorithm
- Planned:
  - Additional declustering and filter codes

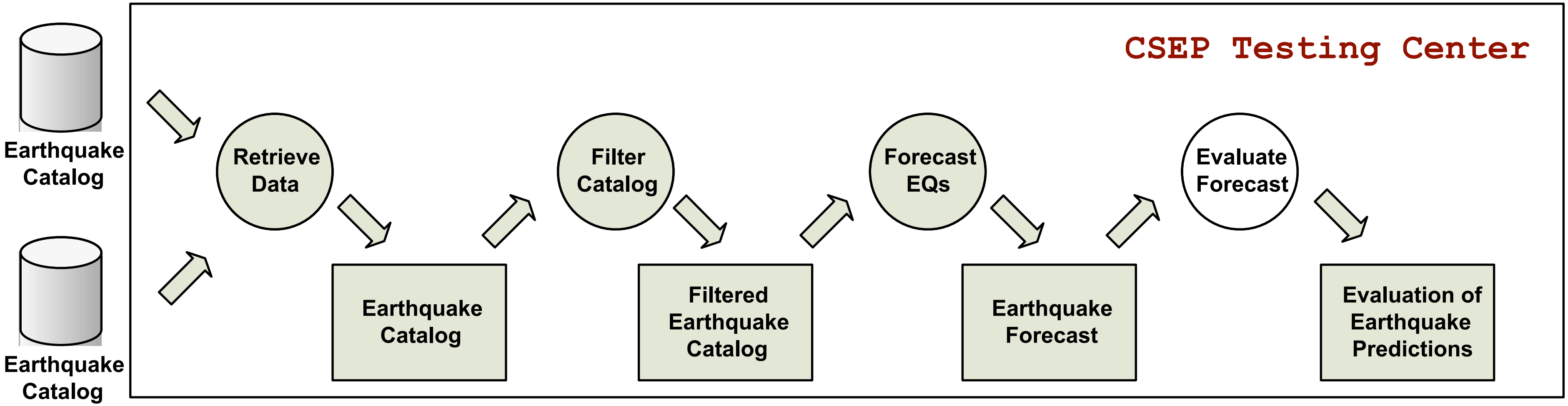
CSEP V1.0 Workflow Model



Forecast Model Codes

- **Implemented or in development in CSEP:**
  - **5-yr: 15 RELM Models (data models only); Cellular Seismology (Kafka & Ebel)**
  - **1-yr: STEP (Gerstenberger et al.); ETAS, EEPAS, PPE (Rhoades), ETES (Zhuang et al.)**
  - **1-day: STEP (Gerstenberger et al.), ETES (Zhuang et al.)**
- **Planned:**
  - **Fault-based: Acceleration Moment Release (Bowman)**
  - **Global: Western Pacific Smoothed Seismicity (Kagan & Jackson)**

CSEP V1.0 Workflow Model



Forecast Evaluation Codes

- Implemented in CSEP:
  - N Test (Number)
  - L Test (Likelihood)
  - R Test (Likelihood Ratio)
- Planned:
  - Alarm-based tests (e.g., Molchan trajectories)
  - Fault-based tests

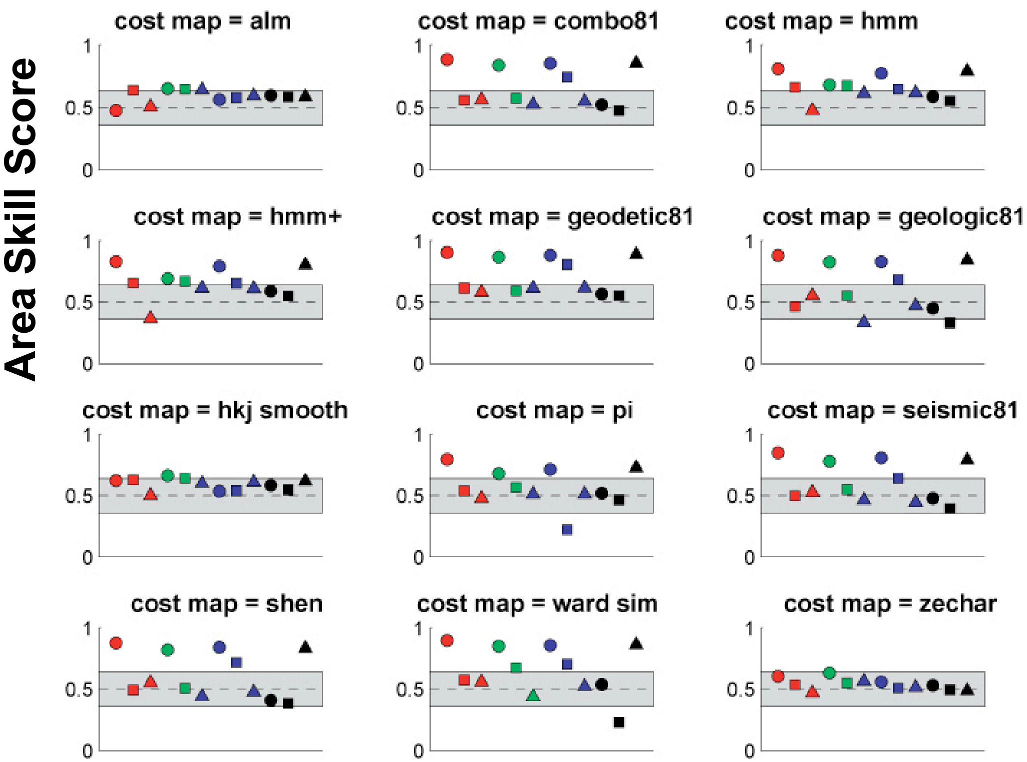
Alarm-Based Testing

Area skill score of Molchan trajectory

(Zechar & Jordan, 2007)

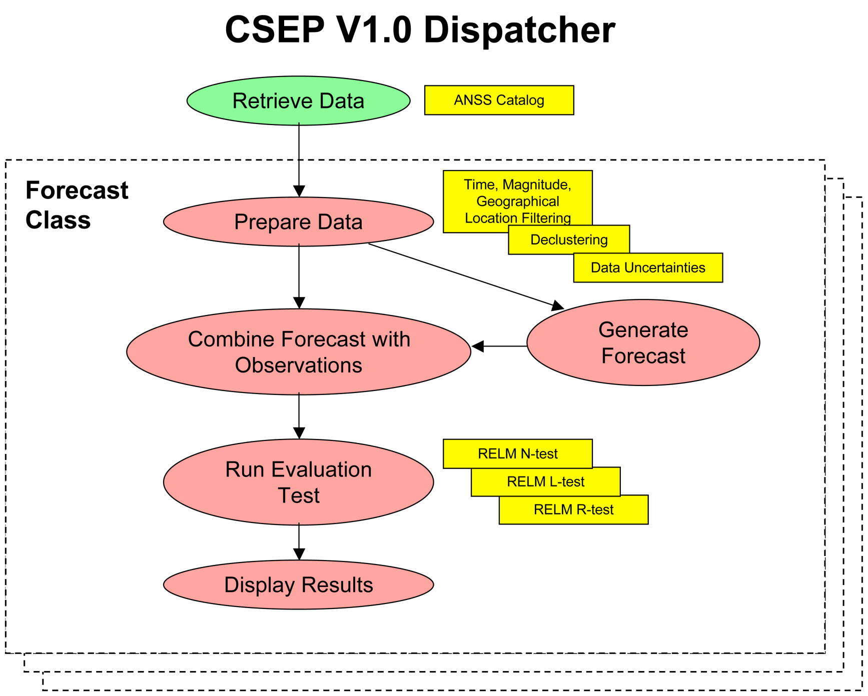
Forecast	Reference	Symbol
Asperity Likelihood	Schorlemmer & Wiemer 2007	
Combo 8.1	Ward, 2007	
Hidden Markov Model	Ebel et al., 2007	
HMM + Aftershocks	Ebel et al., 2007	
Geodetic 8.1	Ward, 2007	
Geologic 8.1	Ward, 2007	
HKJ Smoothing	Helmstetter et al., 2007	
Pattern Informatics	Holliday et al., 2007	
Seismic 8.1	Ward, 2007	
Shen Geodetic	Shen et al., 2007	
Ward Simulator	Ward, 2007	
Zechar RI/GR	Zechar, 2007	

round robin-test results

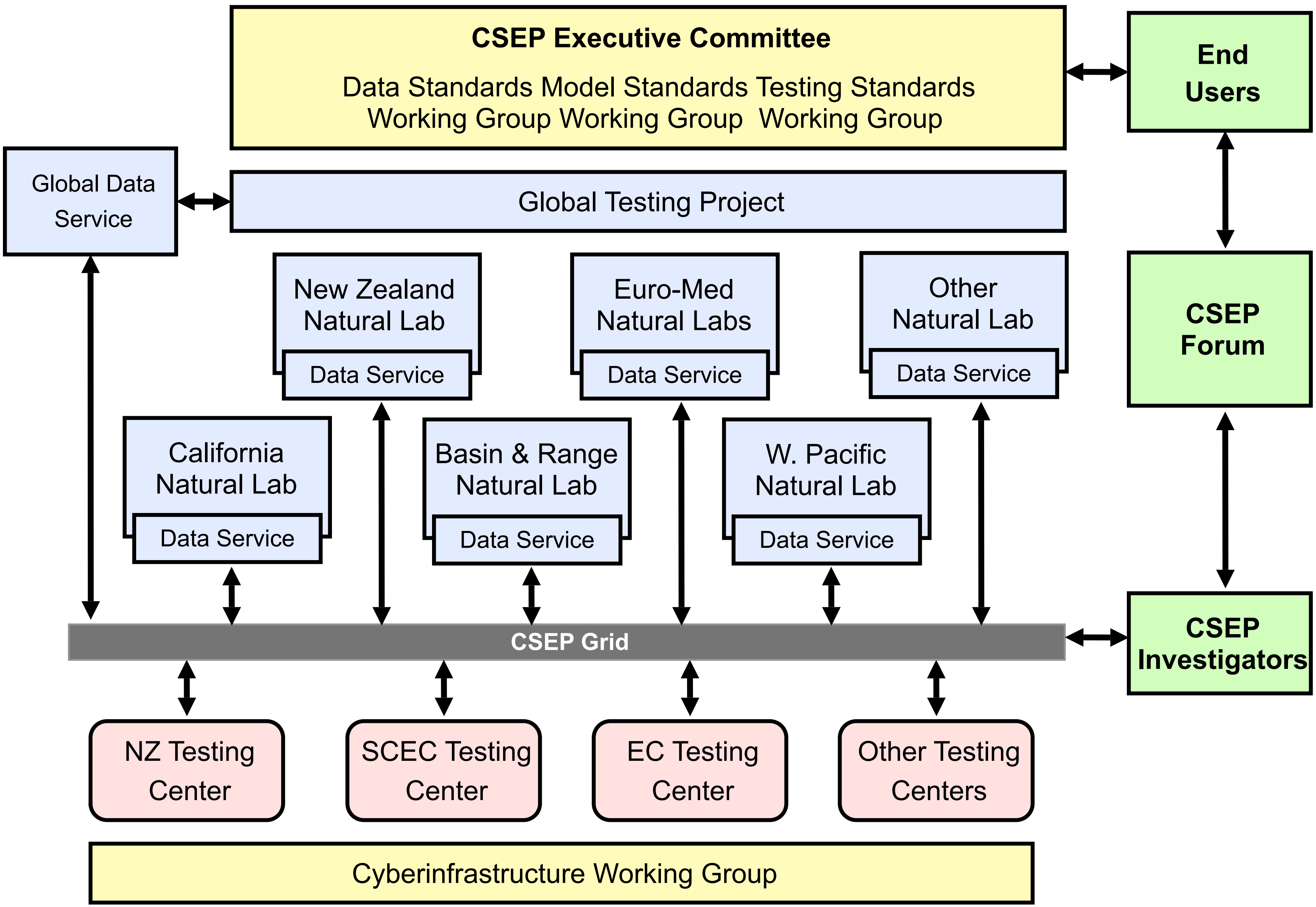


CSEP V1.0 Features

- Daily Automated Earthquake Forecast Generation
  - STEP, ETAS forecast models
- Automated Earthquake Forecast Evaluation
  - RELM *N*, *L* and *R* tests
- Automated Testing Framework
  - Acceptance tests
- Reproducibility of Results
  - Software version control
  - System configuration archive
  - Data set archive
- Identical Integration and Operational Systems
  - Common, standardized software stack



Collaboratory for the Study of Earthquake Predictability



CSEP Working Groups

- **Data Standards**
  - Negotiates authorized data streams with agencies monitoring regional natural laboratories, and sets criteria for data quality, characterization and coverage
- **Model Standards**
  - Specifies model classes; evaluates scientific merit of proposed model experiments; sets criteria for model documentation and registration at testing centers
- **Testing Standards**
  - Specifies testing metrics and explores new testing methods. Oversees communication of testing results to the scientific community
- **Cyberinfrastructure**
  - Develops standards for collaboratory cyberinfrastructure, including testing platforms and communication grids, and oversees software development

CSEP Participation

Open to qualified scientists and organizations interested in collaborative research on earthquake predictability

- Members of the CSEP Forum and working groups
- Model developers conducting experiments in the CSEP environment
- Operators of CSEP natural laboratories and providers of authorized data streams
- Operators of CSEP testing centers
- Sponsors of collaboratory activities and predictability research

The success of CSEP as an open, international collaboration will advance three goals:

1. Reducing the controversy surrounding earthquake prediction through a collaboratory infrastructure to support a wide range of scientific prediction experiments

2. Promoting rigorous research on earthquake predictability through global partnerships

3. Helping responsible government agencies assess the feasibility of earthquake prediction and the performance of proposed prediction algorithms

Major Questions

1. What are the criteria for CSEP natural laboratories and catalogs used to evaluate prediction experiments?
2. What types of scientific prediction hypotheses should be tested?
3. How should global prediction experiments be organized?
4. What input data should be allowed in the formulation and conditioning of prospective predictions?
5. How can CSEP approach its goals of transparency and reproducibility?
6. What protocols should govern the distribution of CSEP results?
7. How should CSEP communicate its activities to the larger scientific community and to the public?
8. How should the relationship between CSEP and IASPEI be structured?
9. What resources will support CSEP as a long-term international collaboration for the study of earthquake predictability?

End