Numerical Simulations for Active Tectonic Processes: Increasing Interoperability and Performance

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The objective of this project is to produce a system to fully model earthquake-related data. This task develops simulation and analysis tools to study the physics of earthquakes using state-of-the-art modeling, data manipulation, and pattern recognition technologies with the objective of developing a solid earth science framework for understanding and studying active tectonic and earthquake processes. We are developing clearly defined accessible data formats and code protocols as inputs to the simulations. These are adapted to high-performance computers because the solid earth system is extremely complex and nonlinear resulting in computationally intensive problems with millions of unknowns. With these tools it will be possible to construct the more complex models and simulations necessary to develop hazard assessment systems critical for reducing future losses from major earthquakes.

***Key Words** : Earthquake, high performance computing, interoperability*

1. Approach

We are building a new Problem Solving Environment (QuakeSim) for use by the seismological, crustal deformation, and tectonics communities for developing an understanding of active tectonic and earthquake processes. The top-level operational architecture of our proposed solid earth research virtual observatory (SERVO) shows science users interacting with interface programs as well as modeling, simulation, and analysis tools. The general architecture follows the "Web Services" model being developed by business interests, but is applied to scientific applications and supporting software resources (such as databases). The system is divided into three tiers: a user interface layer (implemented as a browser interface), a system resource layer, and a middle control layer that maintains proxies (or brokers) to the system resources (Figure 1). The middle tier provides a uniform interface to the resource layer. Following the Web Services approach, we define XML interface abstractions (in WSDL) for basic services (such as File Management) and implement the interface with appropriate technologies (such as with a relational database). Communication between the services is done with an XML messaging architecture (SOAP).

One of the most critical aspects of our proposed system is supporting interoperability given the heterogeneous nature of data sources as well as the variety of application programs, tools, and simulation packages that must operate with data from our system. Interoperability will be implemented by using distributed object technology combined with development of object API's that conform to emerging standards. We will define our object API's in XML and dynamically map this specification into the chosen object model. This strategy was successfully used in the Gateway portal, which currently uses a CORBA middle tier but has used a pure Java solution with the same objects.

Three simulation codes are targeted for improved performance, chiefly through design changes that make them efficient high-performance parallel codes. These codes are PARK, a boundary-element based code for studying unstable slip at the Parkfield segment of the San Andreas fault, Virtual California, which simulates the dynamic interaction of hundreds of fault segments comprising the active tectonics of California, and GeoFEST, a fully three-dimensional finite element code to model active tectonics and earthquake processes. Together with an adaptive mesh generator that constructs

embedded in a heterogeneous earth structure.

2. High Performance Computer Programs

PARK is a model for unstable slip on a single earthquake fault. Because it aims to capture the instability it is designed to represent the slip on a fault at many scales, and to capture the developing seismic slip details over an extraordinary range of time scales (subseconds to decades). Its simulation of the evolution of fault rupture is the most realistic of the tools considered here. When transformed into an efficient parallel simulation, it will be the tool of choice for researchers seeking to determine the nature and detectability of earthquake warning signals such as surface strains and patterns of microseismicity. This is the first earthquake simulation code to seek enhanced scalability and speed by employing a multipole technique. The multipole experience gained here will also be transferable to the Virtual California code and other boundary element simulations. The power of massive parallel computing is required for this problem in order to support many small slip patch elements in order to cover the nucleation scale that initiates the instability.

GeoFEST simulates stress evolution, fault slip and plastic/elastic processes in realistic materials. The products of such simuluations are synthetic observable time-dependent surface deformation on scales from days to decades. Diverse types of synthetic observations will enable a wide range of data assimilation and inversion techniques for ferreting out subsurface structure and stress history. In the short term, such a tool allows rigorous comparisons of competing models for interseismic stress evolution, and the sequential GeoFEST system is being used for this at JPL and UC Davis. Parallel implementation is required to go from local, single-event models to regional models that cover many earthquake events and cycles.

Virtual California simulates fault interaction to determine correlated patterns in the nonlinear complex system of an entire plate boundary region. The evolution of these patterns enables forecasts of future large events. The model produces synthetic seismicity and surface deformation, enabling an eventual data assimilation system for exploiting regional data collection. Capturing the nonlinear pattern dynamics of the fault system along a plate boundary implies the realization of a digital laboratory, which allows understanding of the mechanisms behind the observations and patterns. Our technology development aims to produce and demonstrate a scalable cluster code. When that is deployed researchers will be able to create and verify patterns down to smaller spatial scales, which will enable cross-scale parameterization and validations, which will in turn enable plate-boundary system analysis and greatly enhanced forecasts of large earthquakes.

Scientific Objectives

The full interoperable system will allow users from many environments to discover and exploit a very wide range of applications, models, and physical measurements in distributed databases. This is seen as of crucial importance for gaining full advantage of massive new national programs for gathering new regional and global data sets, such as the Plate Boundary Observatory, Earthscope, and NASA orbiting inSAR missions.

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Pattern analysis methods are another tool type we are developing. One method bins many decades of seismic activity on a gridded representation of Califorinia. Eigensystem analysis reveals clusters of correlated space and time activity, which have been subjected to a phase dynamics forecast. When this method attains parallel speedup we will produce better forecasts and enable rapid tests of earthquake correlations and predictions. This will be due to the ability to use much smaller geographic cell sizes and so forecast the frequent magnitude 4 earthquakes, not just the rare magnitude 6 events.

3. International Collaborations

Members of this project work closely with the international community through the APEC Cooperation on Earthquake Simulations (ACES). ACES aims to develop realistic supercomputer simulation models for the complete earthquake generation process, thus providing a "virtual laboratory" to probe earthquake behavior. This capability will provide a powerful means to study the earthquake cycle, and hence, offers a new opportunity to gain an understanding of the earthquake nucleation process and precursory phenomena. The project represents a grand scientific challenge because of the complexity of phenomena and range of scales from microscopic to global involved in the earthquake generation process. It is a coordinated international effort linking complementary nationally based programs, centers and research teams.

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