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ORIGINAL ARTICLE

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Remote data analysis, visualization and problem solving environment (PSE) based on wavelets in the geosciences

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Abstract We discuss here the issues faced by earth scientists in analyzing and visualizing large datasets over a GRID-like setup from a client-server perspective. We approach this problem by using a remote, web-based visualization and data analysis framework, called WEB-IS, and by employing second-generation wavelets as a means for reducing the amount of data transferred and for extracting coherent features in complex geophysical flows and surface faulting patterns. As an example, we describe how onboard processors on satellites can function as a server for beaming down extracted information to the client computer on the ground, thus exemplifying WEB-IS as a viable middleware on a GRID network for geosciences.

Keywords Data analysis · Internet · Visualization · Wavelet · Wireless

Introduction

Currently all disciplines in science and engineering are facing a crisis of data deluge. Geosciences are no exception to this trend. Its datasets are growing at an exponential rate because of the acquisition of satellite interferometry data (InSAR), geodetic data collection campaigns, such as TOPEX and CHAMP, and more detailed seismic surveys. Inexpensive memory, increasingly large storage media, faster processors and improved data-collecting instruments, such as High Resolution Electron Microscopes, all help fuel the challenging problem of data mining of large data sets. To give some idea, the decade long Earthscope project, initiated in 2003, expects to generate daily outputs of over 10 Terabytes from a wide range of data-acquisition techniques. Although the speed of computers and the affordability of large amounts of onboard memory are increasing at an adequate pace, this is not the case for the available bandwidth. Consequently, the networks cannot keep up with the size of the datasets and novel approaches to analyzing and extracting information from the huge datasets must be developed and implemented. Geoscientists must be able to explore and query very large databases within a simplified framework, while keeping the data-transfer of raw data to a minimum.

Previously we have developed a web-based interrogative system that permits users to analyze data remotely over the Internet using a client-server paradigm (Garbow et al. 2001, 2002, 2003). This system promotes portability, dynamic results on-demand, and collaboration among researchers separated by long distances. This data extraction technique is a form of data mining (Grossman et al. 2001) and provides tools for analyzing data remotely via the Internet. We store a single copy of the dataset on the server, which acts as a data-vault, rather than transferring the full dataset to several geographically distributed machines. We have built an interactive graphical user interface (GUI), which provides a front-end to the user, thus facilitating data analysis from anywhere, provided there is a reliable, fast network.

In this communication, we will describe our vision for interactive data extraction by improving on the current version of our web-based interrogative system to provide remote, interactive visualization of 3-D data and analysis of seismic clusters. We call this second generation of

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our web-based tool, which we are currently developing, WEB-IS. Future versions of WEB-IS will harness the power of the Internet to enhance remote collaboration among researchers, i.e., bring valuable 3-D data visualization and data analysis capabilities into the field using handheld devices connected to the Internet via a wireless connection. The server will carry out intensive processing tasks, such as the visualization and analysis of large 3-D data. The handheld devices will provide the front end user interface, displaying the image created by the server and allowing interaction from the user. While there is an abundance of software packages on the market specifically targeted to the visualization of large datasets, there is at present little effort aimed at coupling data interrogation and visualization using a client-server framework, particularly one aimed at wireless connectivity. Some notable software containing ideas similar to ours, developed by the National Oceanic and Atmospheric Administration (NOAA) are Ferret (http://ferret.wrc.noaa.gov/Ferret/, 2002), ncBrowse (http://ww.epic.noaa.gov/java/ncBrowse/, 2002) and DODS (http://www.unidata.ucar.edu/packages/dods, 2002). In addition, the Seasonal to Interannual Earth Science Information Partnership (SIESIP) developed an online data analysis system that includes a distributed metadata server and the ability to query datasets for analysis (Yang et al. 2003).

Another principal objective of this work is to provide a turnkey system for the analysis of complex images using second-generation wavelets. We will demonstrate a framework to analyze and visualize large-scale nonlinear geophysical processes over a wide range of spatial and temporal scales. The key aspect of this work and its common thread is a recent spatial decomposition of the data into coherent and incoherent components that represent the large-scale structures in the dynamics and the small-scale quasi-random residual fields respectively. This decomposition is achieved through a second-generation wavelet transform of the data combined with thresholding. We are currently working on the statistical analysis of non-stationary/non-homogeneous processes and robust toolkit development (Yuen et al. 2002; Erlebacher and Yuen 2002a, Erlebacher and Yuen 2002b). The advantages of this new approach for the earth sciences are reduced computation time, efficient data representation at multiple scales without sacrificing spatial information and visualization on a user-specified range of scales.

Wavelet analysis expresses a function as a linear combination of basis functions, localized in both physical and wavelet-transformed spaces (Daubechies 1988). One may think of wavelet decomposition as a multilevel representation of a function, where each level of resolution consists of a linear combination of translated wavelets at that scale. The coefficients of the basis functions are directly correlated to the information at a specific spatial location and at a specific scale. When a function contains isolated small scales on a large-scale background, most wavelet coefficients have a small magnitude. A good approximation is maintained even after discarding a large number of wavelets with the smallest values. This attractive property of wavelets allows one either to compress or to de-noise the function, which aids in the process of feature-extraction.

We propose in this paper to combine these two ideas of data-interrogation and wavelets into a problem-solving environment (PSE) and to communicate these ideas to the community of geoscientists who can then use them within the framework of GRID computing via remote visualization. This aggregate system of web services can be interfaced to users by portal services (Fox 2003). We will first discuss some ideas concerning remote accessing of web-based maps, followed by a description of wavelet-based feature extraction of high-resolution imagery found in the geological and planetary sciences.

Web-based problem solving environment

To accommodate the increasingly large datasets that geophysicists need to analyze, we have created a web-based data interrogation system that operates under a client-server paradigm (Garbow et al. 2001). This system allows users to analyze geophysical data using a Java applet, accessible by any web browser (Fig. 1). The user can then select a region of interest (ROI) within the image (using the pre-rendered data as a "map"). Local statistical information is then computed within this region and displayed; examples that have been implemented include the mean, the standard deviation, the skewness, and a histogram.

This software, optimized to send information efficiently over a TCP/IP network, uses a combination of Java on the client-side with Python and C++ powering the server-side. Additionally, we have ported this system to accommodate handheld devices (Garbow et al. 2003). Handheld devices, in conjunction with wireless Internet technology, allow scientists increased portability for conducting experiments and analyzing the results. Our system successfully overcomes the limitations of handheld devices, including their miniscule screen sizes, relatively slow processors, and small amount of memory, to help them become practical devices for scientific work.

The client-server architecture lets the server take care of the intensive processing tasks, while the client provides a front-end user interface. This setup provides our system with the ability to execute computationally intensive requests on the server, while the client can be a much less powerful desktop computer or handheld device. The large datasets reside only on the server, making it unnecessary for individual users to download the datasets to their own computers. Only sending the data of immediate interest to the client helps prevent bottlenecks in the network. Figure 2 illustrates the client-server setup. The large server has local access to the large datasets, the C++ program is responsible for the

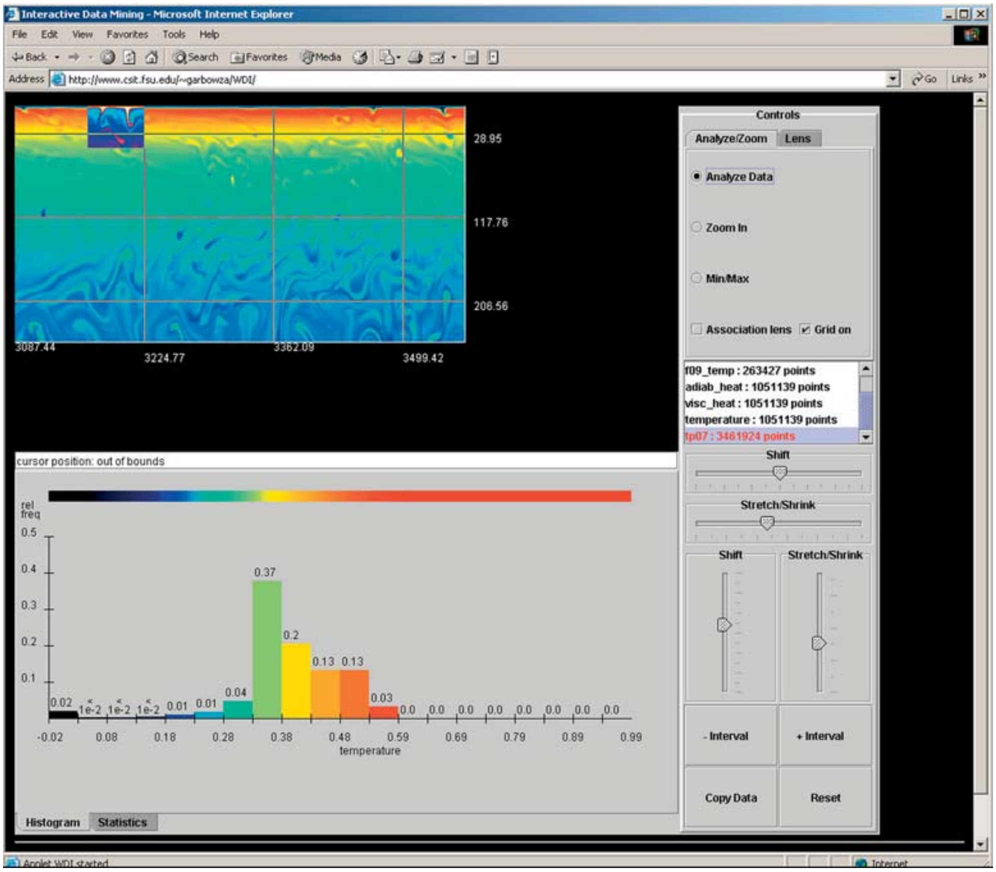

Fig. 1 Web-based map allows user to interrogate datasets over the Internet from a web browser via Java applets

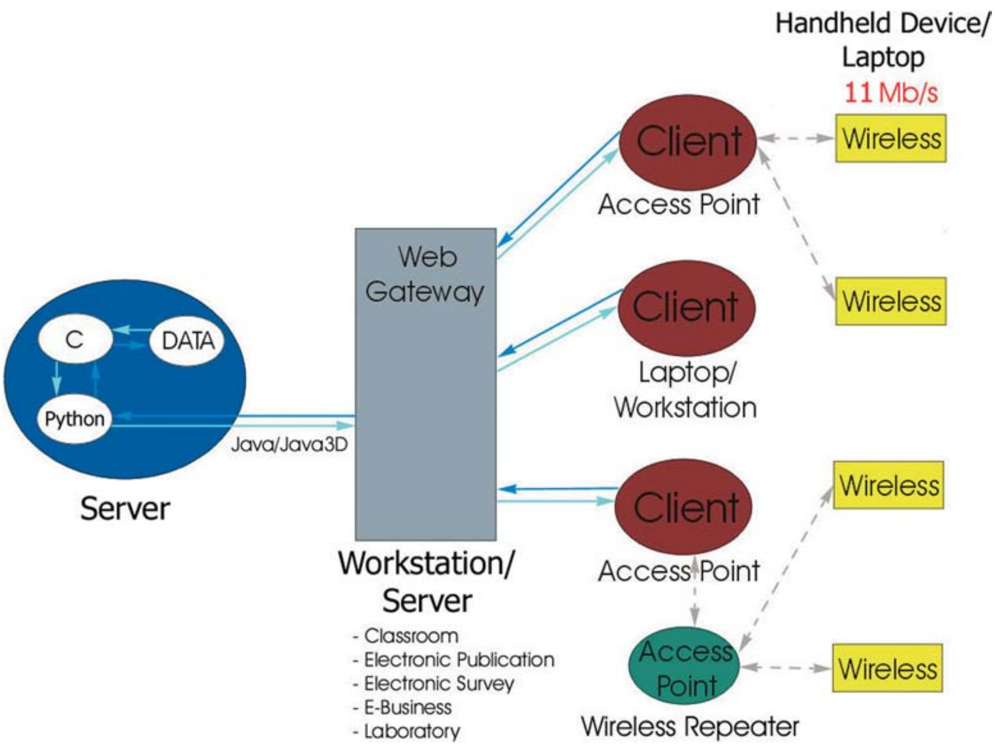

Fig. 2 Schematic diagram of the client-server setup used for the web-based maps

efficient analysis of local regions selected by the remote user, and the Python CGI program mediates between the C++ program and the applet. First, the applet sends data to the python script. The script then executes a C++ executable using this data as arguments. The C++ code ensures maximum efficiency on the server side, the python "glue" is very flexible, python modules are easy to prototype, while the Java code provides a flexible and robust user interface.

The client-server architecture is also well suited for the integration of handheld devices into our framework. Because of their slower processors, reduced memory, and slower bus speeds, handheld devices cannot be relied upon for computationally intensive tasks. Our setup accounts for this by relegating all the computations to the server, while just running the Java applet user interface on the client. Furthermore, the client need only send a minimal set of parameters over the Internet to the server, which reduces the necessary bandwidth and allows the program to work correctly, even with a poor wireless signal. Using the client, the user accesses the Java applet and selects the area he or she wishes to study. The applet then sends this information back to the server to perform the analysis, and the server returns the results to the applet, which is responsible for the final display on the client.

To further enhance our web-based data analysis interface, we are upgrading our system to visualize clusters of earthquake events in three dimensions and analyze them over local regions of interest. This improved, second-generation version of our data analysis system is called WEB-IS, for Web Based Interrogative System. Once complete, WEB-IS will provide insight into the interrelationships between earthquake events, and could help improve forecasts made by seismologists (Kaneko et al. 2002; Dzwinel et al. 2003). Clustering earthquake events permits earthquakes with similar properties to be grouped together (Hinneburg et al. 2003) and enables the detection of correlations between small seismic events and the big ones that they lead to (Fig. 3). The first generation of our software uses static, 2-D images that were pre-rendered and subsequently loaded into the program to act as a visual map of the data. In contrast, WEB-IS actually manipulates 3-D data on the server, and returns the dynamically rendered 2-D image over the Internet, while providing improved data analysis capabilities that will enable scientists to interrogate and view their data more thoroughly.

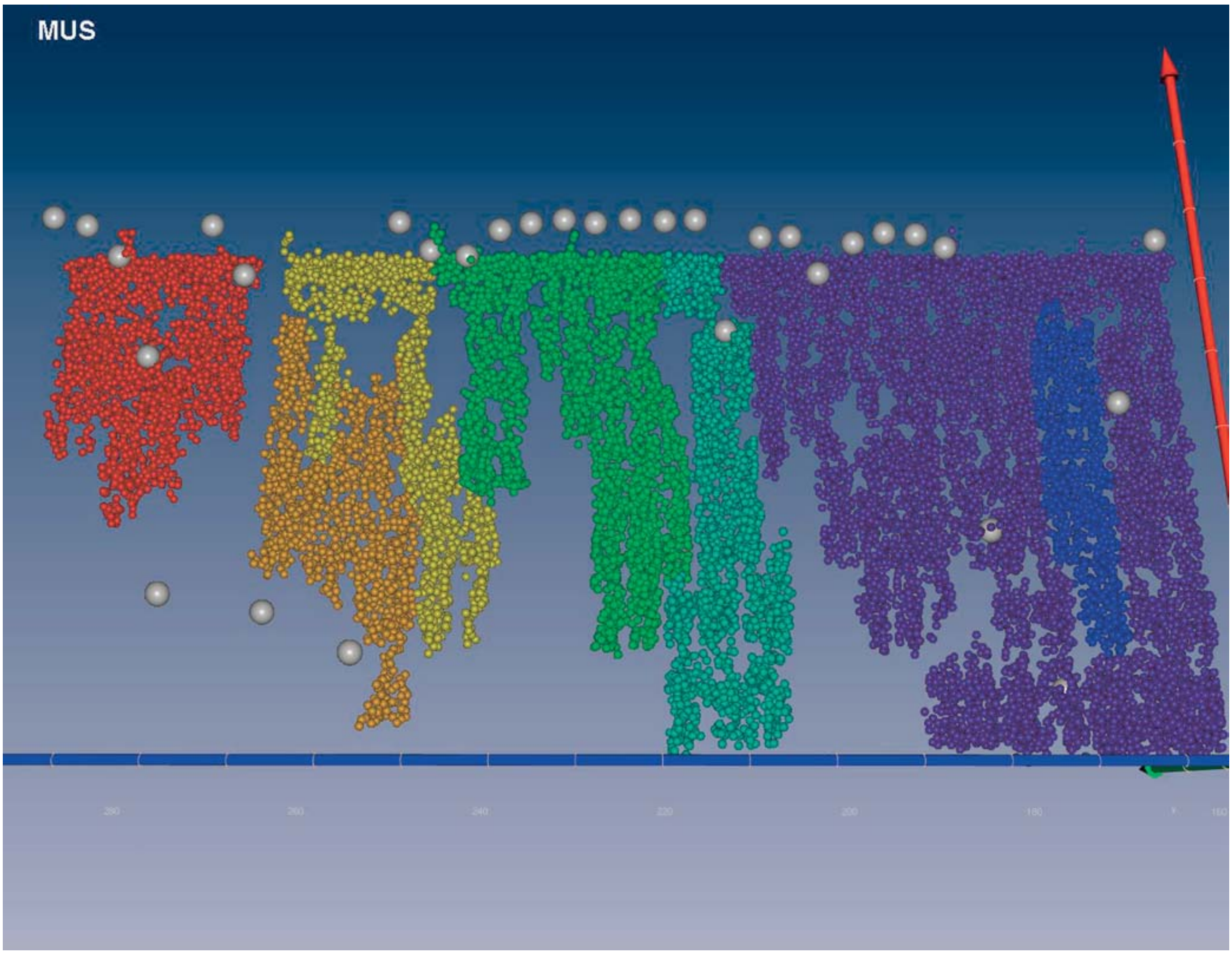

Fig. 3 3-D visualization of earthquake clusters may shed light on how small, stress-relieving earthquakes are related to large, devastating ones

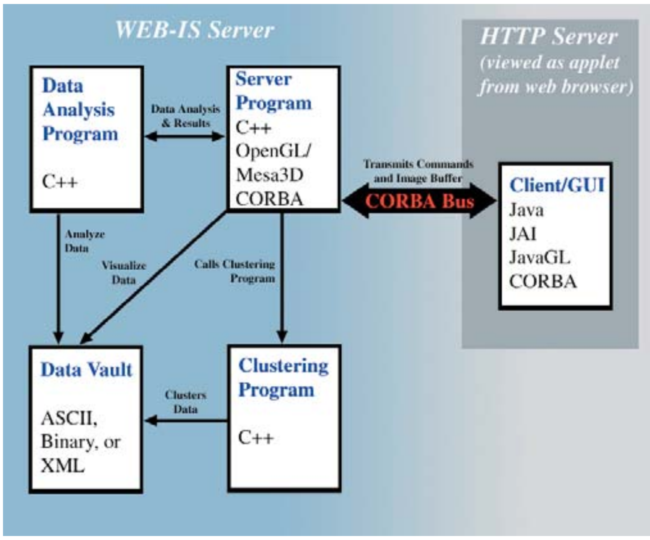

Fig. 4 Functional setup for WEB-IS, which allows remote visualization and data analysis over the Internet. The client interacts with the Java applet and Python script located on the web browser (*right*), which provides an interface to interact with the powerful imaging and data analysis capabilities on the server (*left*)

WEB-IS allows the exploration of worldwide earthquake distributions coupled with the selection of localized regions for local statistical analysis. However, because there are too many earthquakes to be visualized and manipulated smoothly using Java3D over the internet, we use a combination of C++, OpenGL, CORBA, Python, and Java Advanced Imaging to distribute the visualization load between the client and server (Fig. 4). In our setup, the server utilizes off-screen rendering via the Mesa3D graphics library (http://www.mesa3d.org, 2003) to visualize the 3-D data. The practical implication is that the server does not need to open a window in order to visualize the earthquakes (Fig. 5). The client can remotely start and connect to the server via the Internet. Once connected, the client makes requests to the server to move around in the 3-D world. The server subsequently computes the image with respect to the new position, and sends the image data back to the client to be displayed. This setup reduces the processing load of the client, allowing even computers with low processing power, such as handheld devices, to visualize and analyze hundreds of thousands of earthquakes in three dimensions. This setup also promotes collaboration by allowing multiple researchers to connect their client programs to a common server. This permits each user to manipulate the same data and interactively view the same image, allowing users from around the world to work closely together in real-time. We have tested this mobility by accessing our data from various sites around the country (including Florida State University and Indiana University) and even in Japan.

WEB-IS renders the image off-screen on the server-side, which has many advantages. Since it does not need to load a window to render the image, the server can provide visualization and analysis services to multiple users, while simultaneously providing normal functionality for a user logged on at the console of the server machine. In addition, off-screen rendering provides added security for the server, by not sending to the client any information that is visible in a terminal window. Since a user at the console cannot see what is visualized, this offers privacy for the client to conduct his or her visualization and analysis. However, one glaring disadvantage of off-screen rendering is that it does not utilize

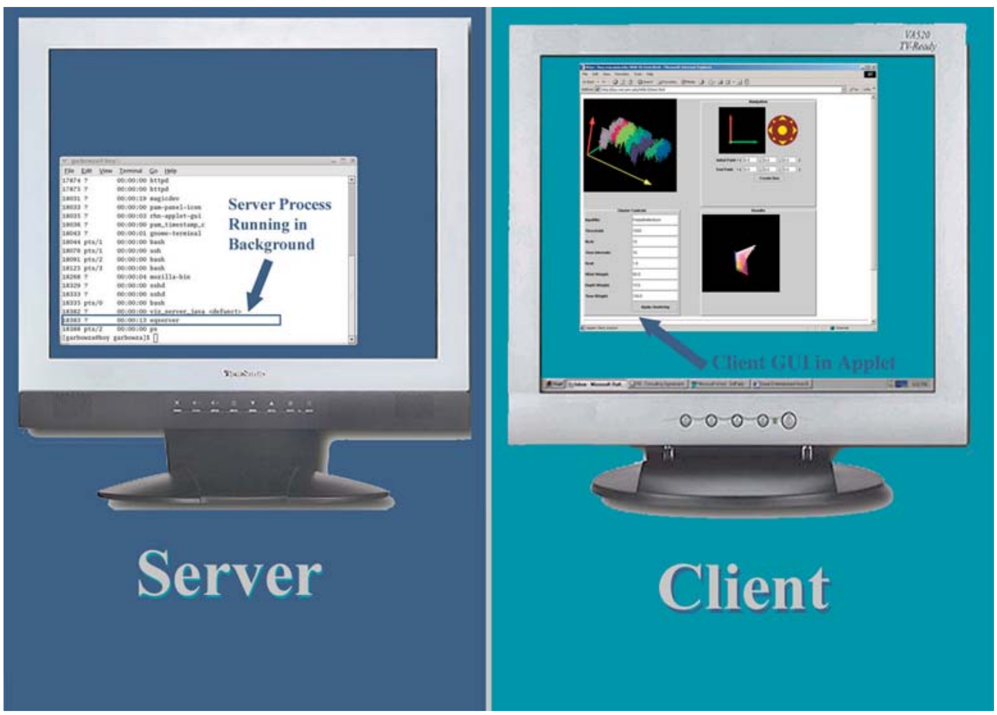

Fig. 5 A screenshot of the client/server setup, which is the framework to be used by WEB-IS for remote visualization of 3-D earthquakes. The client-side (*left*) starts the server via the Internet, and displays the image that is sent by the server. The server (*right*) utilizes off-screen rendering so that no window is required to open in order to perform visualization. The server process is connected to the client, but remains running in the background

the computer's graphic hardware, instead performing the visualization on the main CPU, which is much slower for visualization purposes. Recently, effort has been made to allow for hardware accelerated off-screen rendering (Stegmaier et al. 2002).

Another approach we are considering to provide increased dynamic content to our system is to use the output of a powerful visualization suite, such as Amira (http://www.amiravis.com, 2003), as input into our system. By doing this, we can use the output image from the visualization package in conjunction with the data analysis and web-based capabilities of our software to create more powerful data exploration tools. Additionally, we are creating software to allow Amira to function over the Internet as a web server, providing its powerful visualization abilities to be access via a web browser (Yang et al. 2003; Wang et al. 2003). These two systems, along with other visualization web services, will be combined into a single visualization portal to allow users to seamlessly switch from one service to another in order to extract the strengths of each service and gain multiple perspectives of the same data (Kadlec et al. 2003).

Wavelet toolkit as a problem-solving environment in geological sciences

Geological data is by its very nature multiscalar in character. Spatial scales range from the grain-size of minerals (millimeters), to the fault-size scales (10–100 km). Temporal scales range from a hundredth of a second in the rupture process to tens and hundreds of years for the earthquake stress-transfer, to tens of thousands of years in postglacial rebound due to ice ages. A broad description of the cross-scaling nature of geological processes can be found in Yuen et al. (2000). Earthquakes are not the only phenomenon with multiscale characteristics. Another good example is volcanic eruptions, which are intermittent in time and are intrinsically associated with plate tectonic activities.

Wavelets are very well suited to analyzing data with multiscale characteristics. They are oscillatory functions that permit simultaneous analysis of a signal in the time and frequency or space and wave number space, a property not shared by Fourier transforms. Wavelets have been employed in many fields ranging from data compression (Mallat 1998), visualization (Horbelt et al. 1999), numerical simulation (Vasilyev and Paolucci 1996; Vasilyev et al. 1998), and feature identification (Bergeron et al. 1999), just to name a few. Extensive references can be found in (Kumar and Foufoula-Georgiou 1997; Barth et al. 2002).

Traditionally, wavelet bases arise from the discrete dilation and translation of a single mother wavelet. This defines the concept of first generation wavelets (Daubechies 1988) on infinite or periodic domains. With second-generation wavelets (Sweldens 1998) we now have at our disposal a new class of wavelets that can be defined on general domains and on irregularly sampled intervals. We can construct these wavelets in the physical domain rather than in Fourier space and associate each wavelet with a point in physical space. This last property makes it possible to visualize the density of wavelet coefficients in physical space, making feature identification rather straightforward, given an appropriate scalar or vector function.

A wavelet expansion of a scalar variable defined over a region of interest (ROI), with a threshold operator applied to the wavelet coefficients, automatically provides a reduced representation of the associated coherent features, such as plumes in thermal convection (Yuen et al. 2002). To help understand the relationship between wavelet thresholding and the associated structures captured, we have constructed a specialized user interface within Amira. We can take an arbitrary scalar field, apply a second-generation wavelet transform to it, manipulate its threshold, explore the data via a ROI, and visualize the results interactively. The locations of the wavelets are plotted as small cubes, and serve to identify the local coherent structure. Similar techniques will allow the identification and extraction of faults in earthquake deformation problems.

The sheer amount of data in the geosciences vastly exceeds our ability to perform comprehensive analyses. To this end, we have constructed a prototype system using high-resolution convection data, stored on a server, as a series of maps (Garbow et al. 2001, 2002, 2003). The user queries the data either in its entirety or in ROIs. The user interacts with the statistical data through histograms and selected numerical data (average, standard deviation, median, etc.). Users select and download one or more images based on a variety of criteria and have a slew of analysis tools at their disposal. The tools currently address the needs of computational scientists, but their flexible nature permits easy modification to address any specific requirements.

Our web-based map framework accommodates both with PCs and handheld devices over wireless networks (see Fig. 3) (Garbow et al. 2003). A wireless interface makes information located on the server readily accessible to geologists, firefighters, etc., working out in the field. Figure 6 depicts this setup. The onboard computers are the main processing units, and play the role of a multi-processor server, which has at its disposal software tools for wavelet analysis, cluster analysis, identification of dominant adsorption bands and correlation calculations. Users on Earth interact with the system via clients (handheld devices or PC's) that permits interactive querying of the data. Judicious use of ROI further reduces the computational effort.

Feature extraction of region of interest (ROI) using continuous wavelets

By virtue of their locality in space and time, wavelets are well suited to examine data at multiple scales at a single location or over a spatial neighborhood at a given scale.

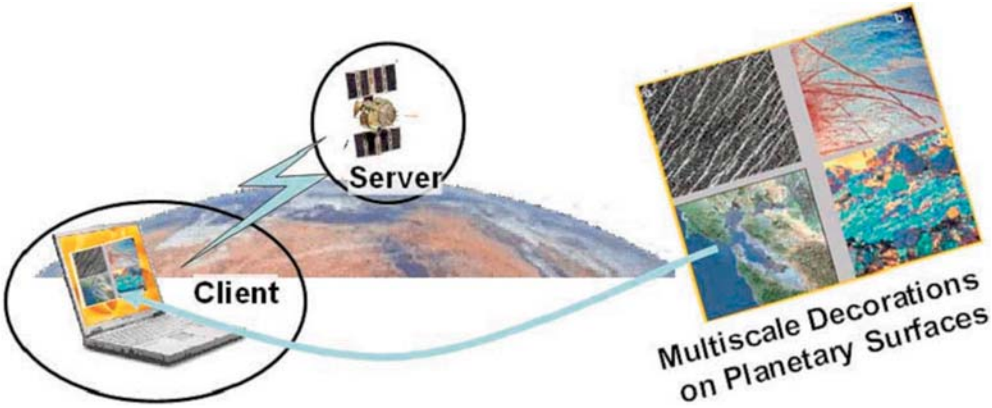

Fig. 6 Onboard processors are responsible for feature extraction and identification of ROI. Users guide tasks on the ground working from client PC's and handheld devices. Multiscale decorations represent four different geological examples that best exemplify the multiscale nature of expressions on planetary surfaces

Figure 7 shows examples of physical phenomena over a wide range of scales, which continuous wavelets can help compress and analyze. Singularities are usually associated with the presence of many scales at a single point, or along a curve. The location and properties of these singularities are identified through the variation of the wavelet coefficient as a function of scale at a fixed position in space. This defines local wavelet spectra. Wavelets have been used to detect features within geoid fields in the presence of substantial random noise (Yuen et al. 2002; Vecsey et al. 2003). Certain properties of wavelet spectra, such as the maximum amplitude and its associated local wave number, can enhance the feature extraction process (Bergeron et al. 1999; Yuen et al. 2000). Figure 7 shows such regions of interest involving shear zones, which are the hallmark of plate tectonics and geological processes.

Shear zones can develop over many scales from the micro (grain-size) scale at the bottom right in Fig. 7, to the San Andreas Fault on the bottom left panel. The top panels unveil the multiscale features of global faults developed on the Venusian surface (top left) and the tantalizing fracture zones caused by interior dynamics on the icy Jovian moon Europa (top right). We see clearly the pervasive presence of bifurcating features because of both microscopic forces due to dislocations on the nanoscale and tectonic forces operating over hundreds to thousands of kilometers from elasticity, viscoelasticity and plasticity. In all of these cases, the data is provided over a high-resolution grid (5×10^4 by 5×10^4 points) greater than from both satellite imagery and high-resolution electron microscopy. This type of imagery will become more pervasive as new satellites like the ECHO come on line and better data acquisition and microscopy techniques are developed and implemented.

Faults, small coherent features, or clusters all occupy a small fraction of the entire volume. Geoscientists are interested in their spatial distribution, their morpho-

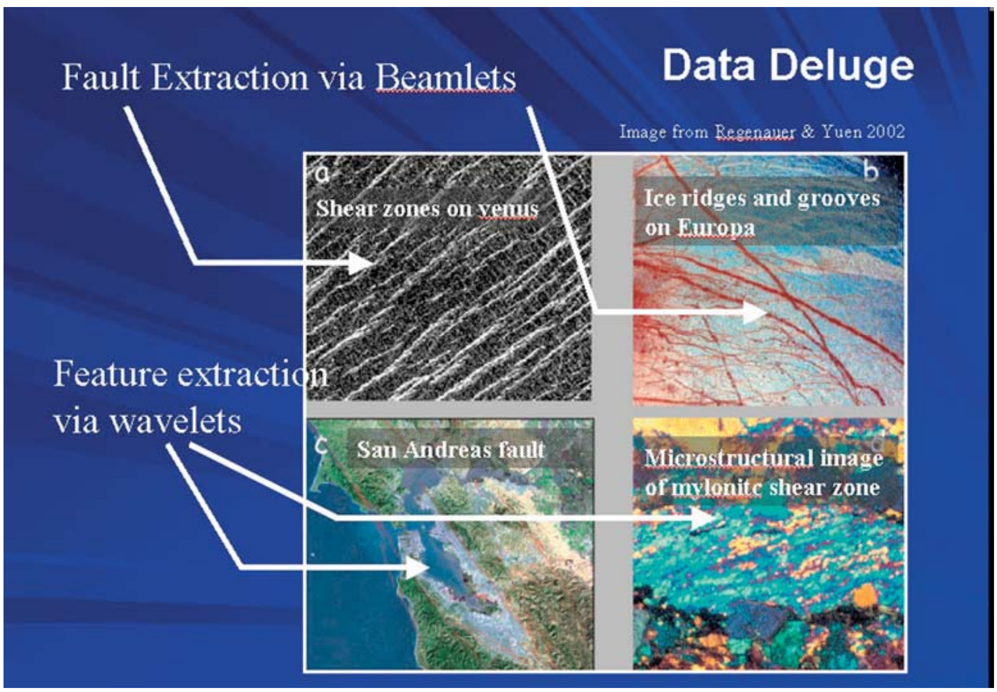

Fig. 7 The multiscale nature of shear zones. *Top left*, Venus, equidistant wrinkles covering large parts of the surface; *top right*, Jovian moon Europa, ice ridges and grooves forming a criss-cross structure; *bottom left,* Earth, The San Andreas Fault; *bottom right*, microstructural image of a shear zone found in a mylonite crystal

logical properties and their dynamics. Second-generation wavelets can offer the potential to extract only the relevant information. Additionally, it is possible to use wavelets to analyze correlations in space and time between multiple signals (Piromallo et al. 2001). Spatial and temporal correlations between adjacent scales often provide new physical insight into cross-scaling processes in geological sciences (Yuen et al. 2000).

Problem solving environment with web-based maps and wavelets

A PSE makes available to users a set of intuitive tools to solve problems without the need to understand many of the underlying details. We currently have at our disposal three capabilities: (1) user selection of 2-D slices from a 3-D dataset and statistical information of subsets of these slices, (2) examine data in physical and wavelet space, with or without thresholding, and (3) clustering techniques (Hastie et al. 2001), currently applied to earthquake events.

The combination of these three capabilities within a common framework leads to an initial data analysis and visualization portal. Such a portal brings together a collection of tools that allow the user to visualize, transform, and query datasets through a uniform user interface. The combination of the three aforementioned capabilities will enable the use of wavelets to identify, analyze, and visualize potential regions of interest and their statistical properties.

In the future, we expect to apply clustering techniques to construct connected regions that bound areas where the wavelet coefficients are dominant. The use of wavelets isolates regions of interest which will allow users to perform multiscale exploration of data without sacrificing network interactivity.

Concluding remarks

Without a doubt, the GRID concept of computing will soon hit the geosciences due to the very nature of the discipline, which involves a geographically distributed collection of geoscientists working on problems covering the entire globe. In addition to standard computing resources, many other services must be provided to users in the earth sciences to facilitate their interactions with the Grid system and with each other. These services can take many forms. They include visualization services with wavelet toolkits (Erlebacher and Yuen 2002a) capable of handling multidimensional and multivariate data sets, registration services to allow merging of data from multiple sources into a common framework, data mining services with visualization, video creation services, and various classes of collaborative tools to allow remote access to large datasets stored in remote dataservers. We summarize these concepts in Fig. 8. Geoffrey Fox (pictured in the inset) has been a constant proponent in promoting grid services for the Earthquake community (Fox et al. 2002; Fox 2003). WEB-IS, which utilizes off-screen rendering to allow the server to

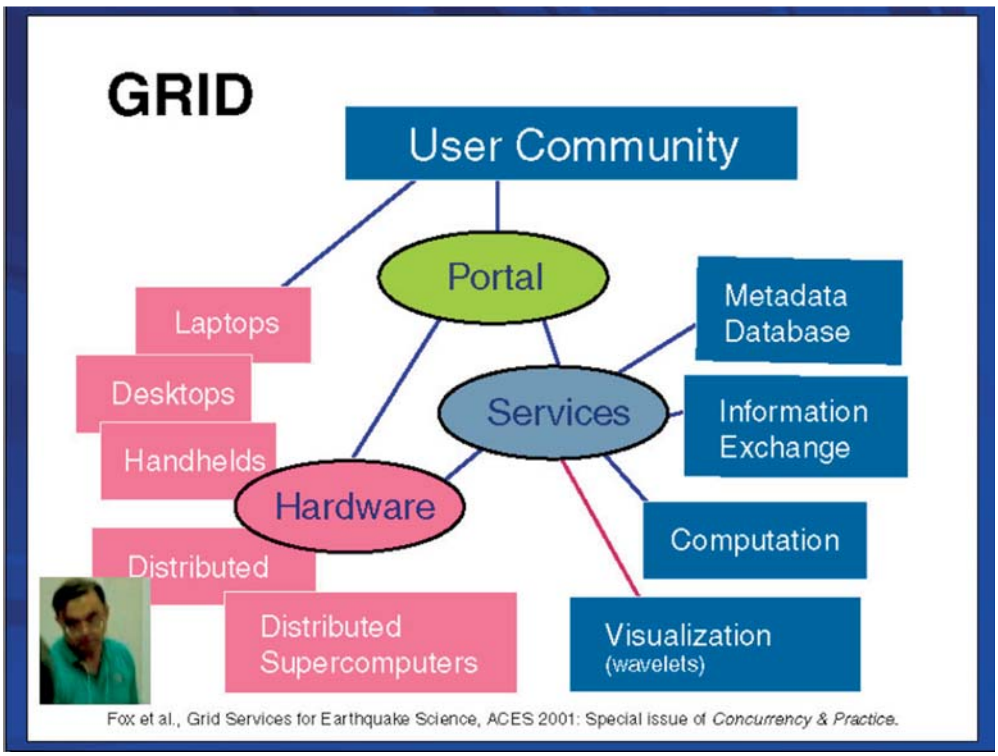

Fig. 8 The grid concept. The user community communicates with a wide range of hardware devices (*left of the figure*) and desires to reach a variety of services, through the web or some other media (*right of the figure*). The user interface comes through a Portal, which may be wireless

perform the intensive visualization and analysis, is a service ideally suited for the GRID. Increased spatial resolution should also be possible using the GRID by considering new strategies of dataset distribution. Since the WEB-IS server sends only the image data to the client, this visualization load could be distributed on a GRID, with each server application visualizing a portion of the image, allowing the client to collect these image pieces from each server and put them back together. This would permit much larger datasets to be efficiently visualized over the Internet. Efficient strategies for visualizing extremely large-scale datasets in parallel are being explored for the Earth Simulator, the world's most powerful supercomputer, located in Japan (Matsui et al. 2002; Chen et al. 2003).

We maintain that the current information-technological forces, unleashed by the oncoming data tsunami, will give rise to new solutions for the entire spectrum of tasks faced by the geoscientists, including simulation, data analysis and data mining, feature extraction, visualization and communication. Only after transformation into toolkits, transparent to the earth scientists, can wavelets play an effective role in this vision, along with the concept of web-based maps. WEB-IS is the first step towards a regional visual network, aimed at providing the infrastructure for the next generation of large-scale data exploration and collaborative visualization.

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