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Design and Development of Information Systems for the Geosciences: An Application to the Middle East

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ABSTRACT

As our understanding grows of how the Earth functions as a complex system of myriad interrelated mechanisms, it becomes clear that a revolutionary and novel approach is needed to study and understand it. In order to take advantage of an ever-growing number of observations and large data sets and to employ them efficiently in multidisciplinary studies aimed at solving earth system science problems, we are developing a comprehensive Solid Earth Information System (SEIS). The complex nature of the solid earth sciences raises serious challenges for geoscientists in their quest to understand the nature and the dynamic mechanisms at work in the planet. SEIS forms a first step in developing a broader and more comprehensive information system for earth system sciences designed for the needs of the geoscientists of the 21st century. In a way, SEIS is a step towards the Digital Earth. Application of SEIS to the complex tectonics of the Middle East shows that information systems are crucial in multidisciplinary research studies and open new avenues in research efforts. SEIS includes an Internet module that provides open access to anyone interested. Researchers as well as educators and students can access this knowledge and information system at http://atlas.geo.cornell.edu.

INTRODUCTION

Currently, one of the greatest challenges facing earth sciences is related to the assimilation, dissemination, and management of the ever-growing quantity of digital information. The chaotic distribution of massive geoscience data sets, their uneven documentation, and the lack of easy-to-use tools for data access and analysis are major obstacles for earth scientists and educators alike. These obstacles limit both scientific productivity and the quality of education. However, the power of having at one's finger tips all available relevant data, information, and knowledge together with data access, modeling, and visualization tools has great potential for improving the quality of scientific research and education.

In order to solve these challenging problems we must change the way information, data, and knowledge are preserved, utilized, and disseminated. The earth science community is in need of systems that not only provide digital data, but as importantly, provide tools that allow users to manipulate, query, select, and cross-reference any part of data sets with efficiency and speed. One of the most promising systems for use by earth scientists is the Geographical Information Systems (GIS). GIS is an organized collection of hardware, software, and data designed to store, manipulate, analyze, query, and display information for decision-making and accurate analysis of any spatial data. Although GIS systems in the geosciences have become increasingly widespread in recent years (Walker et al., 1996; Seber et al., 1997), they have the capacity to be exploited much more fully.

One of the misconceptions about GIS is that it is only a map-making tool. In fact, GIS does much more than simply make maps. It enables a user to analyze, study, search and select databases for a specific purpose. For example, a person studying the seismotectonics of a region can display all active faults in a region, select earthquakes within a certain distance from these faults, and calculate the density of seismic events. Similarly, a user can select a geologic unit and determine its area, its topography, or the number of faults within it. These are simple tasks that can be completed in a few seconds. What GIS provides is a convenient way to expand our abilities to do better research in much less time and to bring interdisciplinary approaches to scientific studies by allowing efficient ways to cross-reference multiple data sets.

Using GIS software allows storage of the data in a spatially registered structure and permits cross-referencing for heterogeneous, multidisciplinary data sets. It manages data sets as layers of information. Geographic features such as rivers and lakes or geological features like faults, sample locations, and ages of rocks are all examples of layers. Each layer is independent from the others, yet all have a common geographic registration and they can be linked with each other using specific identification tags. This provides a convenient way of selecting necessary information from the database and making it ready for further analysis and decision-making.

As a first step in building a comprehensive information system for Earth System Sciences, we are constructing a Solid Earth Information System (SEIS) for research and educational purposes. SEIS includes large volumes of data sets from surface to sub-crustal levels and their related metadata. SEIS also includes easy-to-use tools to access the data sets and manipulate them in a variety of ways. Furthermore, an Internet module built for SEIS allows users access to the data sets and tools over the Internet using Word Wide Web browsers.

SEIS is a regional scale information system, although the goal is to have a global information system. It currently holds regional data sets from the Middle East, North Africa, and the U.S.A. The main purpose of this paper is not to solve a specific problem, but to outline the structure of an effective geoscience information system and give several examples of how it can be used to better study and understand the complex tectonics of the Middle East region.

BUILDING A GEOSCIENCE INFORMATION SYSTEM

Building a comprehensive information system is time consuming and requires significant financial and labor resources. Collecting appropriate data sets, digitizing analog data, and developing customized codes are all challenging tasks and require significant effort. However, the benefits of having a comprehensive information system for research and education greatly outweigh the difficulties. In constructing a geoscience information system the most important issues that need to be considered are the objective, scale, and by whom and for what purpose the information system will be used.

Structurally, an information system will have three main layers.

(1) At the base level is a database that contains all relevant data sets in an organized fashion.
(2) The middle layer is composed of codes that allow communication with the underlying database and help to make user-defined searches, selections, and plots.
(3) The top layer is the user or an analysis / request mechanism.

Data Layer

The database level forms the foundation of the system. After collecting and properly organizing / reformatting the relevant data, the digital files are placed in this layer to be accessed by users. In reformatting the available data, there are several technical issues. The main question is how to get the data into this organized digital system. There are several ways to import existing data into the database. If digital data are available, putting them in this layer requires little time and effort to convert the original format of the data to the database's own format. When digital data are not available, analog to digital conversion must be performed. If the data of interest are in tabular forms, they can be typed in, or files can be scanned and automatically converted to digital format using text recognition software. If the data are in the form of map sheets, two different techniques are generally used: scanning and digitizing. Both of these techniques have their advantages and disadvantages.

Scanning provides a fast and efficient way of putting the data into computers. However, scanned files are large and they are not feature-oriented, that is, no features in the maps can be selected separately.

Digitizing, on the other hand, provides maximum flexibility in feature manipulation, since each object in a map is digitized separately and assigned various identification labels. However, digitizing takes considerable time and it is tedious. The developers must decide between the two techniques according to the needs and uses of the data set.

An important aspect of the database layer is the development and use of metadata. Metadata is information about the data sets: their resolution, accuracy, original sources, quality, and other necessary information. This information is essential for users of the database to learn about the data sets in the system and how they were created. There are already developed standards for metadata, although these standards will certainly be updated as needs arise and more people start using large data sets and start exchanging data among themselves. It is essential for future users that all critical information about the history of the data be kept and made accessible to users regardless of its format.

Software Layer

The middle layer in an information system is its lifeline. This layer is composed of software components that form the communication links between a user and the underlying data sets. Writing codes for data access and manipulation is one of the most time-consuming tasks in system development. However, recent developments in the software industry eliminate some of the major obstacles that might be faced in the code development phase. For example, utilizing commercially available database and GIS software reduces the software development time considerably.

Having commercial software as the main application source also helps in keeping pace with technological advancements as well. As new tools and methods become available they are incorporated into existing software by the software vendors and system developers can take advantage of these new developments. Yet, regardless of the sophistication level of the software being used, developers will have to build additional codes for their specific needs. An efficient system can only be achieved by custom designed tools (i.e., codes) specific for each data set. Developers must determine the needs of users and potential uses of each data set that they include in their information system.

User Layer

The user is an integral part of the system, as users actually control how the system will act based on specific needs. Since the potential number of users of a comprehensive geoscience information system is large and users' background levels vary widely, it is important that they be trained and educated about the advantages of a GIS. On the other hand, a user need not be a person, it could be a computer program or an electronic interface that makes specific requests to the system.

SOLID EARTH INFORMATION SYSTEM (SEIS) AND ITS APPLICATION TO THE TECTONICS OF THE MIDDLE EAST

Solid Earth Information System (SEIS) is a GIS-based information system with menu-driven data manipulation, search, and plotting tools designed to be used by earth scientists in research and education. SEIS has been designed and developed by the GIS group at Cornell University, Institute for the Study of the Continents and Department of Geological Sciences. At the present time, SEIS has variable-scale data sets; the Middle East, North Africa and the U.S.A. are covered at regional scales (~1:1,000,000) and the rest of the world is covered at smaller scales. Currently, SEIS runs on UNIX and NT platforms and requires ArcInfo® commercial GIS software.

SEIS's internal data sets are held in four main categories: Geography, Geology, Geophysics, and Imagery/Grids. Access to data sets is provided through menu-driven tools that eliminate the requirement of being familiar with the ArcInfo® software. A version of SEIS is also accessible via the Internet at http://atlas.geo.cornell.edu. With a web browser, users can access, analyze, and plot any part of the data sets interactively for their own purposes. In the following sections, we present the Middle East component of our ongoing work in developing a SEIS.

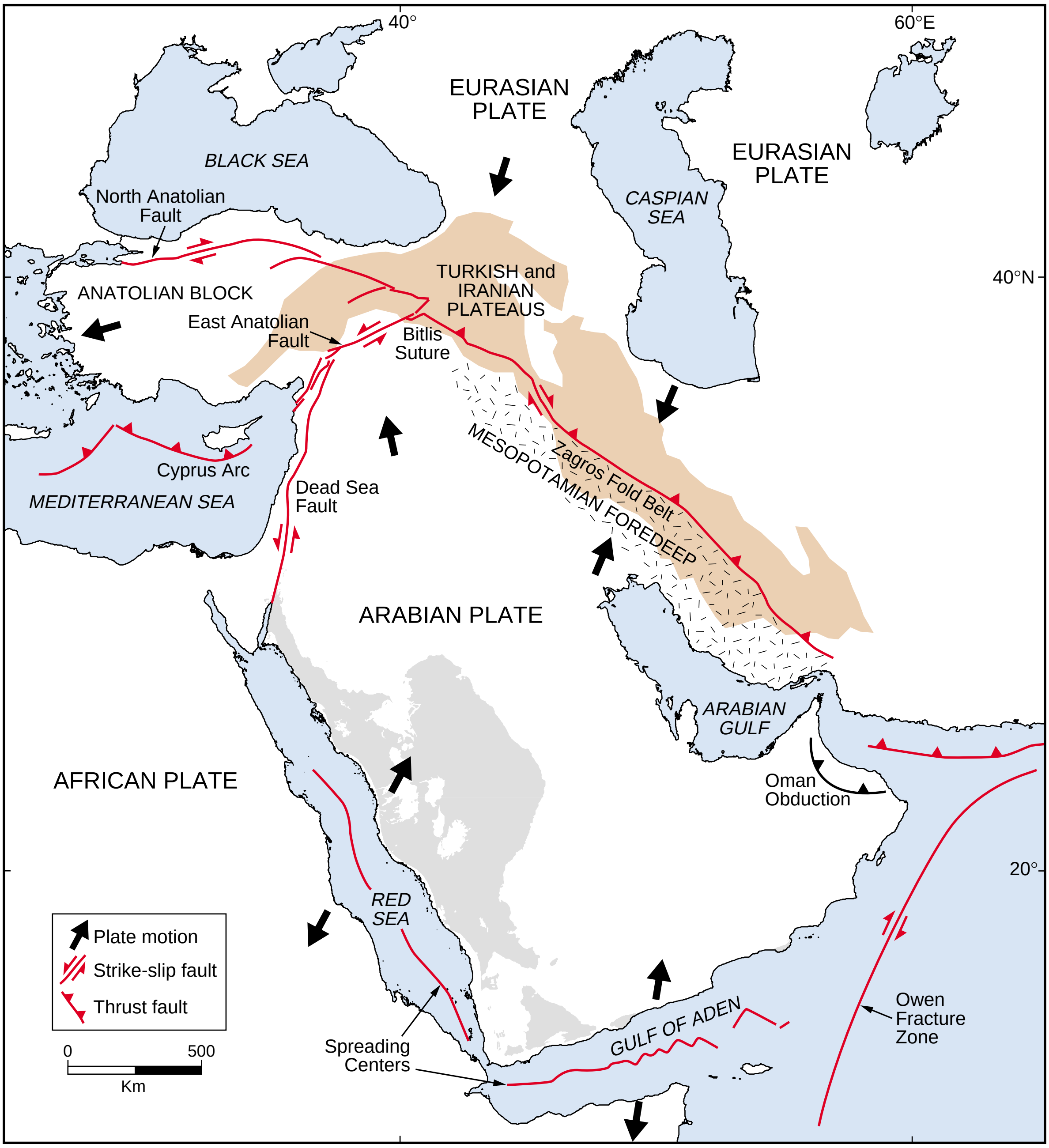


Figure 1: Map showing the simplified tectonic units of the Middle East. Regions with topographic elevation over 1,500 meters in the Iranian and Turkish Plateaus are shaded in brown. Basement outcrops of the Arabian Shield are shown in gray. The large black arrows represent major plate motion directions.

One of the main advantages of having a comprehensive information system is the ability to access and compare several data sets relative to each other quickly and easily. Tectonically complex regions such as the Middle East require such comparative studies. The Middle East encompasses all major types of plate boundary processes, from rifting and mid-ocean ridges in the Red Sea and Gulf of Aden, to subduction and the subsequent continent-continent collision in the Zagros and Bitlis Suture Zones, to strike-slip plate motion along the Dead Sea Fault System and the North Anatolian Fault (Figure 1). This is an ideal region in which to test and validate the potential applications of SEIS.

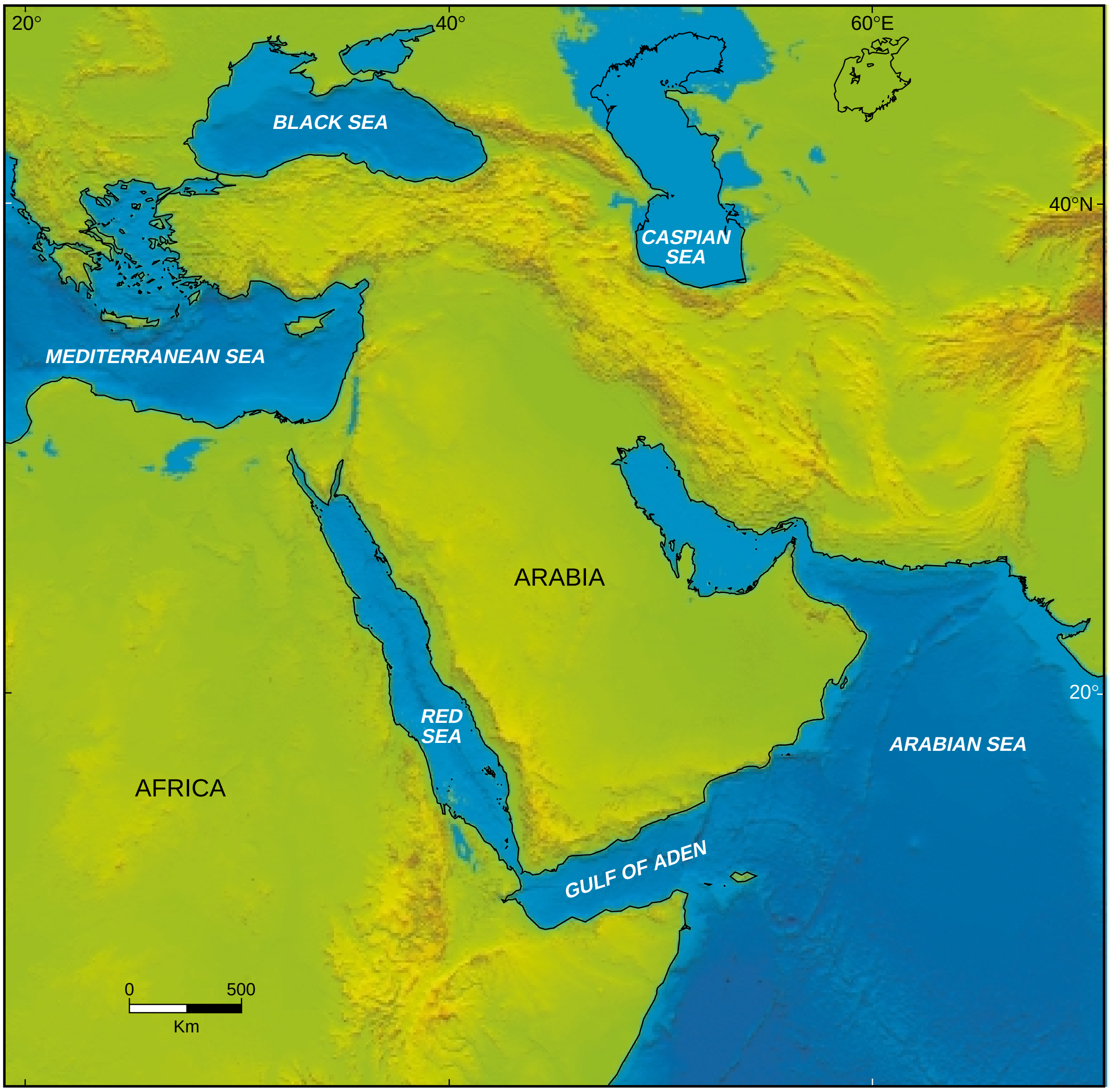


Figure 2: Shaded-relief representation of the topography of the Middle East and surrounding regions. This image was created using a 1-km grid size data set with an artificial sun illumination from the north. Oceans and land areas below sea level are shown in blue.

Data Sets

Plate Boundary Processes and Digital Elevation Models

The plate boundary processes affect the overall tectonics of the Middle East and are mainly responsible for the structure and kinematics in this region, including the intraplate processes (see Figure 1). In a general sense, the dynamic plate boundary processes in the Middle East are manifested in the present-day topography (Figure 2). Higher topography and relief in the region coincide mainly with plate collision zones such as the Zagros. Distinct topographic features are also observed along the Red Sea coast and also along the Dead Sea strike-slip transform fault system.

With an organized data and information system such as SEIS one can look for spatial relationship among different data sets. Calculating topographic slopes in mountainous regions is a common GIS application. The slope map (Figure 3) calculated on a Digital Elevation Model (DEM) of 1,000 meter

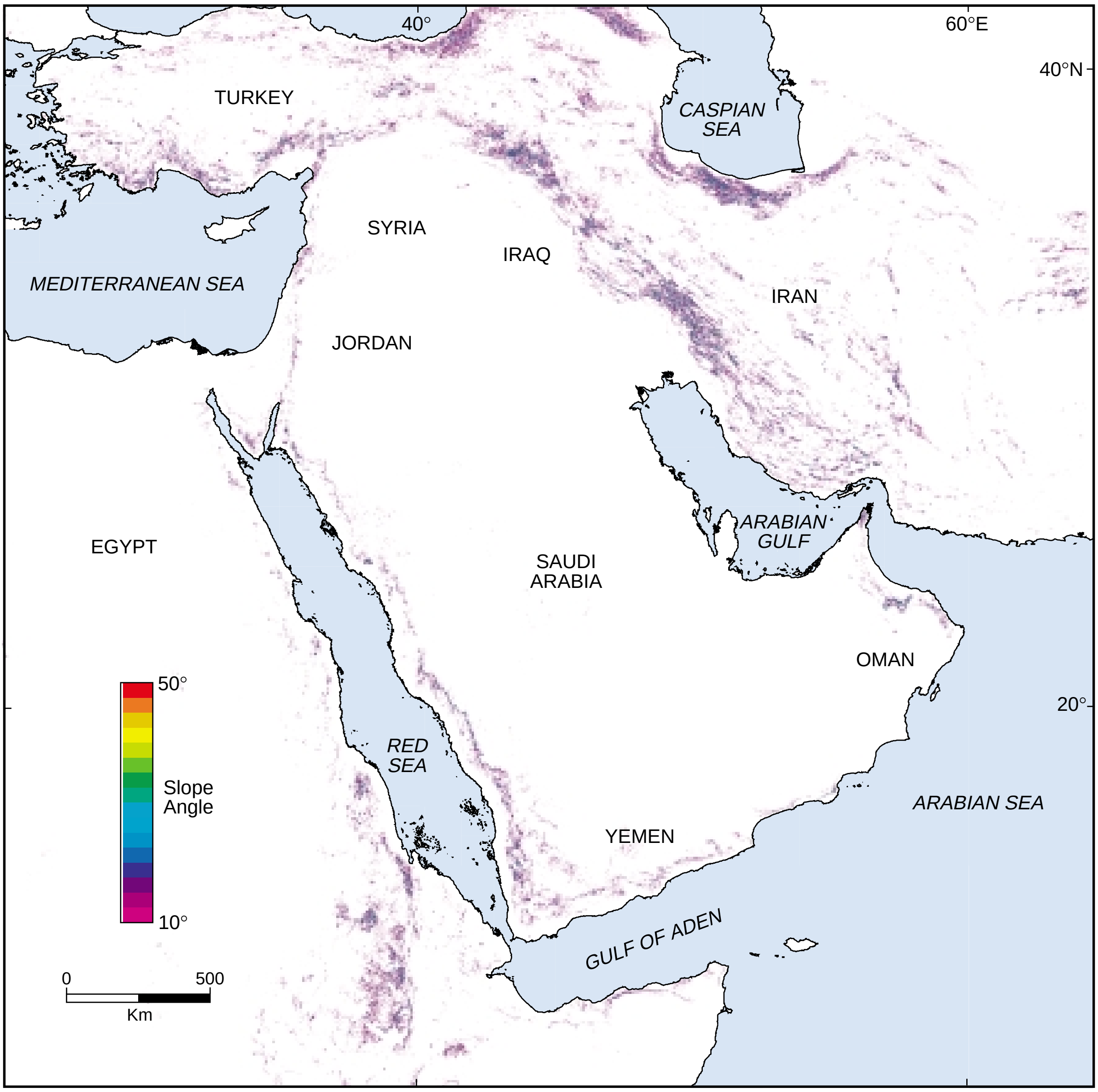


Figure 3: Color-coded slope angles based on data shown in Figure 2. Slope angles less than 10° are not displayed. Slope angles shown vary from 10° to 50°. Higher slope angles are calculated along major plate boundaries and tectonically active regions.

(m) resolution shows that high-angle topographic slopes are mainly concentrated along the plate boundaries. Although a 1,000-m resolution is not sufficient for an accurate slope estimation, it gives a regional picture. There are steeper topographic slopes along the Zagros and Bitlis Suture Zones, the margins of the Red Sea, and in the interior of the Turkish and Iranian Plateaus.

In contrast, the interior of Arabia, Turkey, and Iran are relatively flat. The steep slopes along the Zagros and the Bitlis sutures are a consequence of the collision process of Arabia with Eurasia. The higher slope angles calculated along the Red Sea coast in Arabia are due to rifting and opening of the Red Sea and the evolution of the Red Sea escarpment. Steep slopes are also evident in parts of interior Iran due to island arc volcanism. Similarly, in eastern Turkey away from the Bitlis Suture Zone, the steep slopes are possibly related to active deformation within the plateau. Steep topographic slopes are also calculated along the North Anatolian right-lateral strike-slip fault zone in northern Turkey.

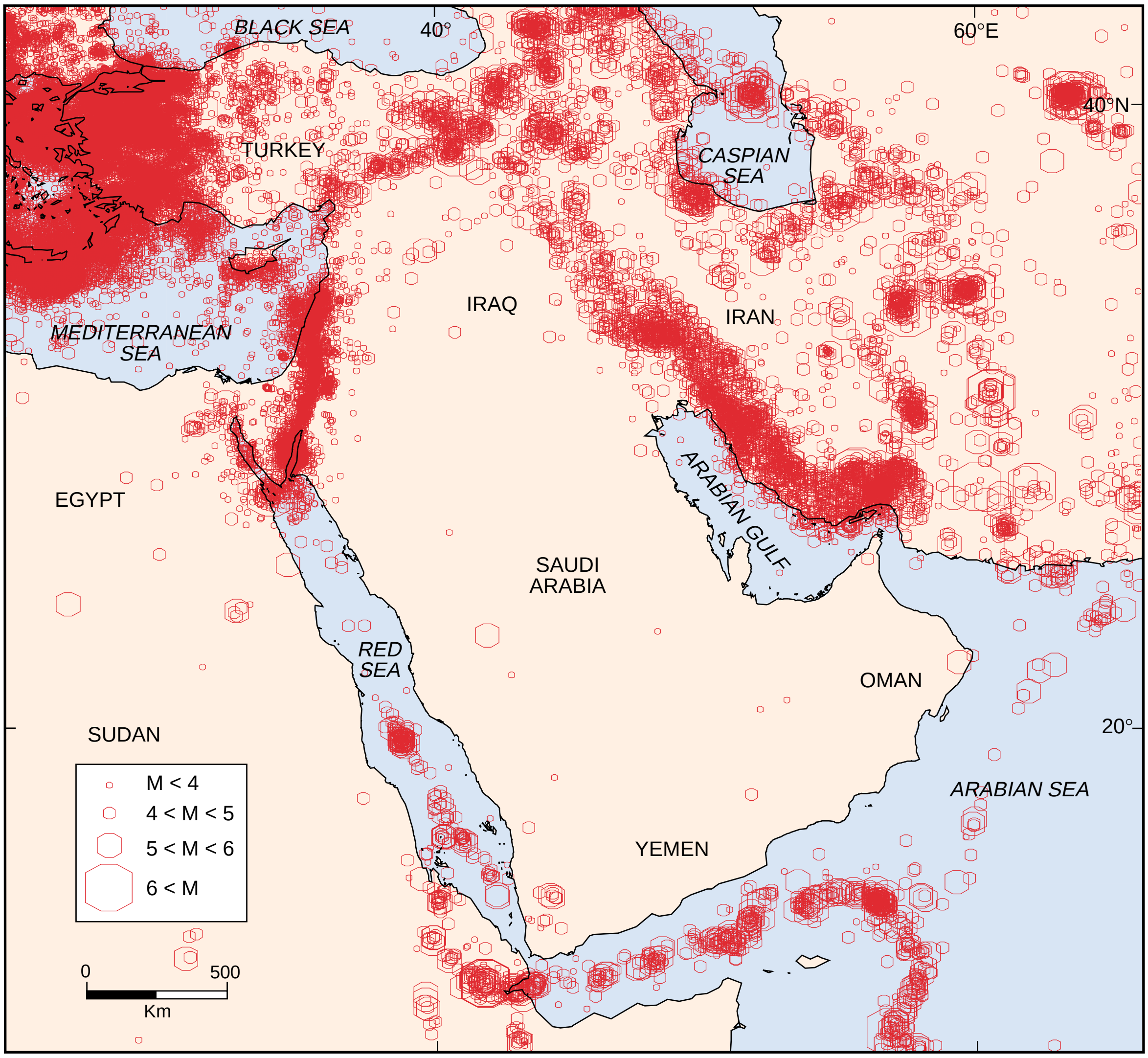


Figure 4: Seismicity of the Middle East region based on the ISC catalog for the period 1964 to 1994.

A comparison of steeper topographic slopes and recent seismicity (Figure 4) in the region indicates that steep slope regions (i.e., high relief regions) coincide with active plate margins. This correlation implies that active tectonism is mainly responsible for the topographic relief in the region. Interpretation of steep slope regions, however, can be challenging, it has been documented that high erosion rates can also be an influence on topographic relief (e.g., Montgomery, 1994). However, these regions of the Middle East are relatively arid and erosional effects in these regions are assumed to be insignificant. Steep slopes calculated along the margins of the Arabian Plate also coincide with the seismic activity in the region. This correlation is best observed along the Zagros Suture. In the central Zagros, a topographic embayment disturbs the overall northwest trend of the Zagros chain (Figure 2). Seismicity also mimics this embayment. One-to-one correlation between the topography and seismicity along the Zagros is quite remarkable. In fact, this correlation is observed in most of the Middle East. The only significant deviation from this correlation occurs in western Turkey where seismicity is very high, but there is no related topographic feature. This could be explained by the dominant extensional tectonics in this region.

Geologic and Tectonic Maps

Tectonic complexity in the Middle East is reflected in the surface geology. In order to make good use of surface geological features in any regional-scale analysis it is necessary to have a digital representation

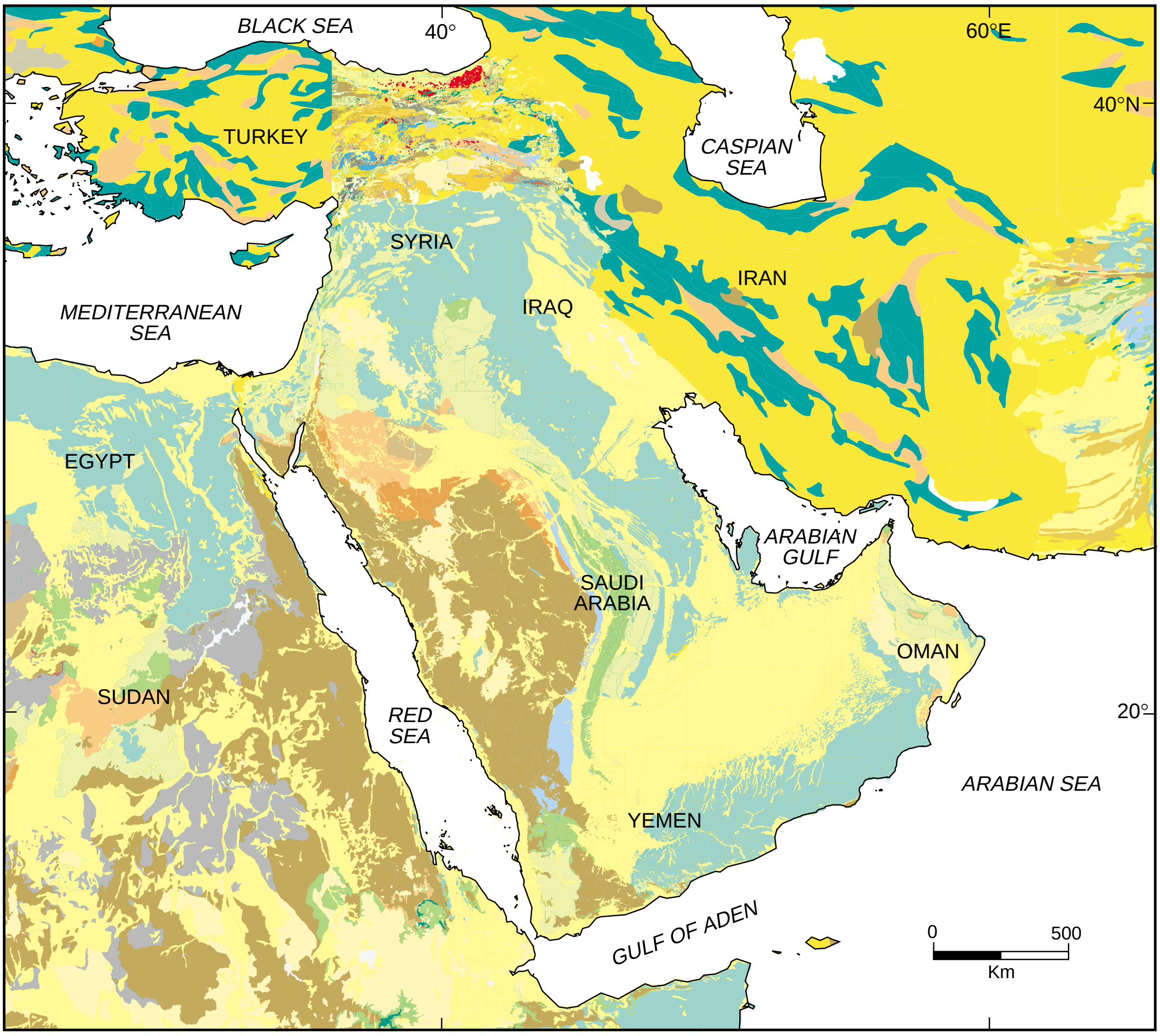


Figure 5: Digital geology map of the Middle East region. High-resolution data are from the United States Geological Survey World Energy Program (Pollastro et al., 1997). Lower resolution data are obtained from the Geological Survey of Canada (Kirkham, 1995). Eastern Turkey data were digitized at Cornell University.

of surface geology at about 1:500,000 to 1:1,000,000 scale. Unfortunately, digitizing geologic maps is among the most difficult and time-consuming parts of a digital geoscience information system. Several organizations have taken the lead in digitizing different scale geologic maps. The United States Geological Survey (USGS) has made available several medium-resolution digital geologic maps of many parts of the world through its World Energy Project (e.g., Pollastro et al., 1997). Figure 5 shows the surface geology of the Middle East and surrounding regions obtained from the USGS and from the Geological Survey of Canada (Kirkham, 1995). The higher resolution geology map of eastern Turkey was digitized at Cornell University. Digitized geologic maps allow a user, for example, to select certain rock units based on age, type or any other item specified in the data set, and display them separately. For example, the Precambrian units in the Red Sea region can be extracted from the data set shown in Figure 5. These selected units can later be used to estimate the total area of Precambrian rocks, or they can be used to select topography or fault distribution only within these selected regions.

In addition to the geologic map, a new digital tectonic map of the Middle East and North Africa has been compiled at Cornell. The compilation took more than a year and required many data sources to be collected, digitized, and integrated. The scales of maps used in the compilation range from 1:250,000

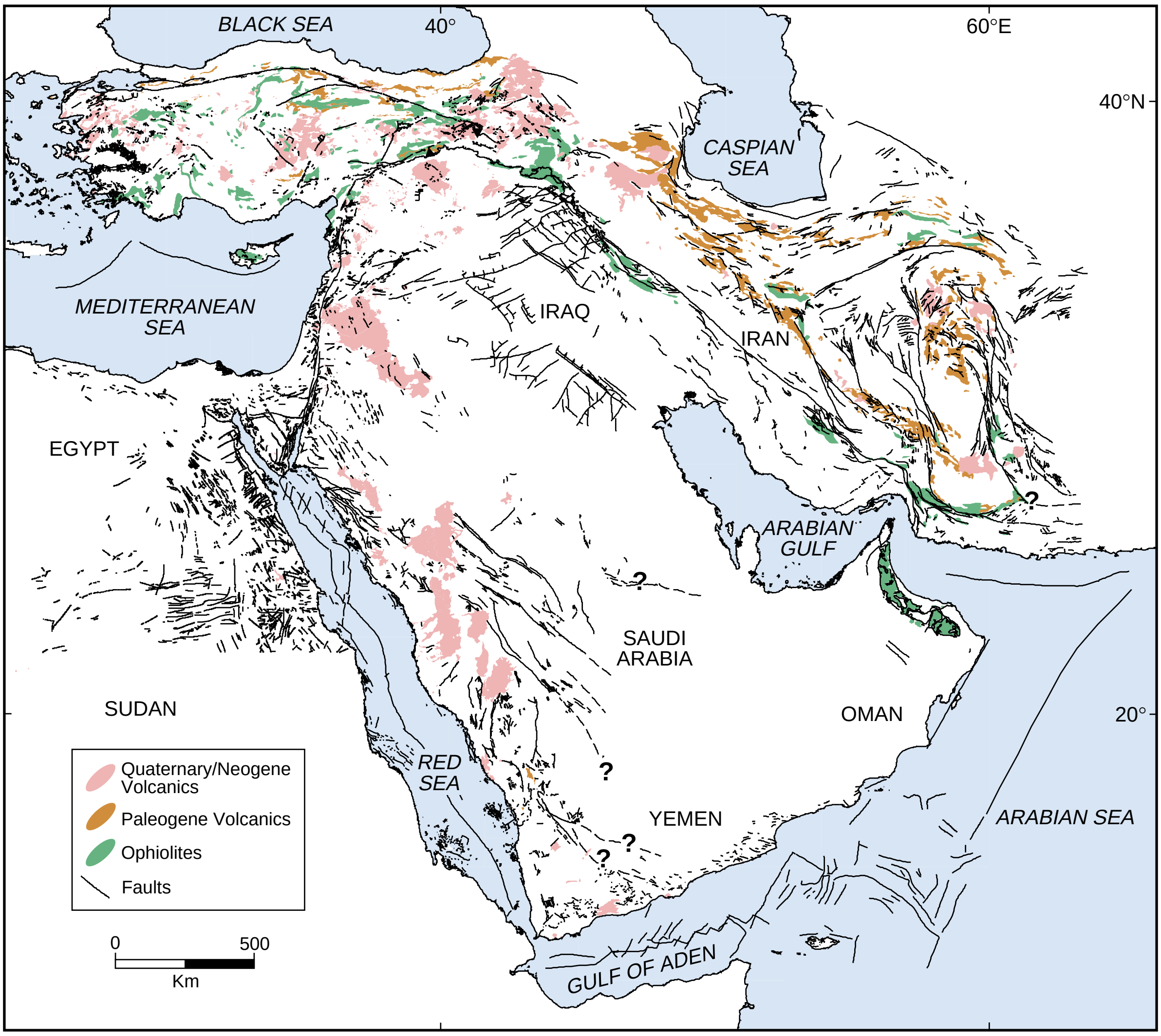


Figure 6: Map showing the tectonics of the Middle East compiled from several sources. Analog maps were digitized and merged to obtain one uniform tectonic map for the region at an average scale of 1:1,000,000.

to 5,000,000. We digitized faults, Neogene and Paleogene volcanics and crystalline basement outcrops. Figure 6 shows our compilation for the Middle East. Each feature in the tectonic map has been assigned all available attribute information such as throw in faults, activity of faults, age of volcanics, and so on.

Earthquakes and Focal Mechanisms

Seismicity (earthquake hypocentral locations) is one of the largest data sets in SEIS. The whole of the International Seismological Centre (ISC) catalog is kept online. It contains global seismic phase readings and attribute data, such as the depth, magnitude, origin time, number of stations used in location, and so on. The data set currently covers the period from 1964 to 1995 and includes information from more than 700,000 earthquakes and millions of associated phase readings. We have developed several tools to access any part of the ISC catalog and select, display, and analyze any event, or select a station and query its recorded events and their phase readings.

Figure 7 shows a sample plot from this data set. Station SHI (Shiraz) in Iran has been selected and all events in the database recorded by the station within the distance range of 0°-10° were chosen using the data access tools. In addition, great circle paths (the shortest distance between station and

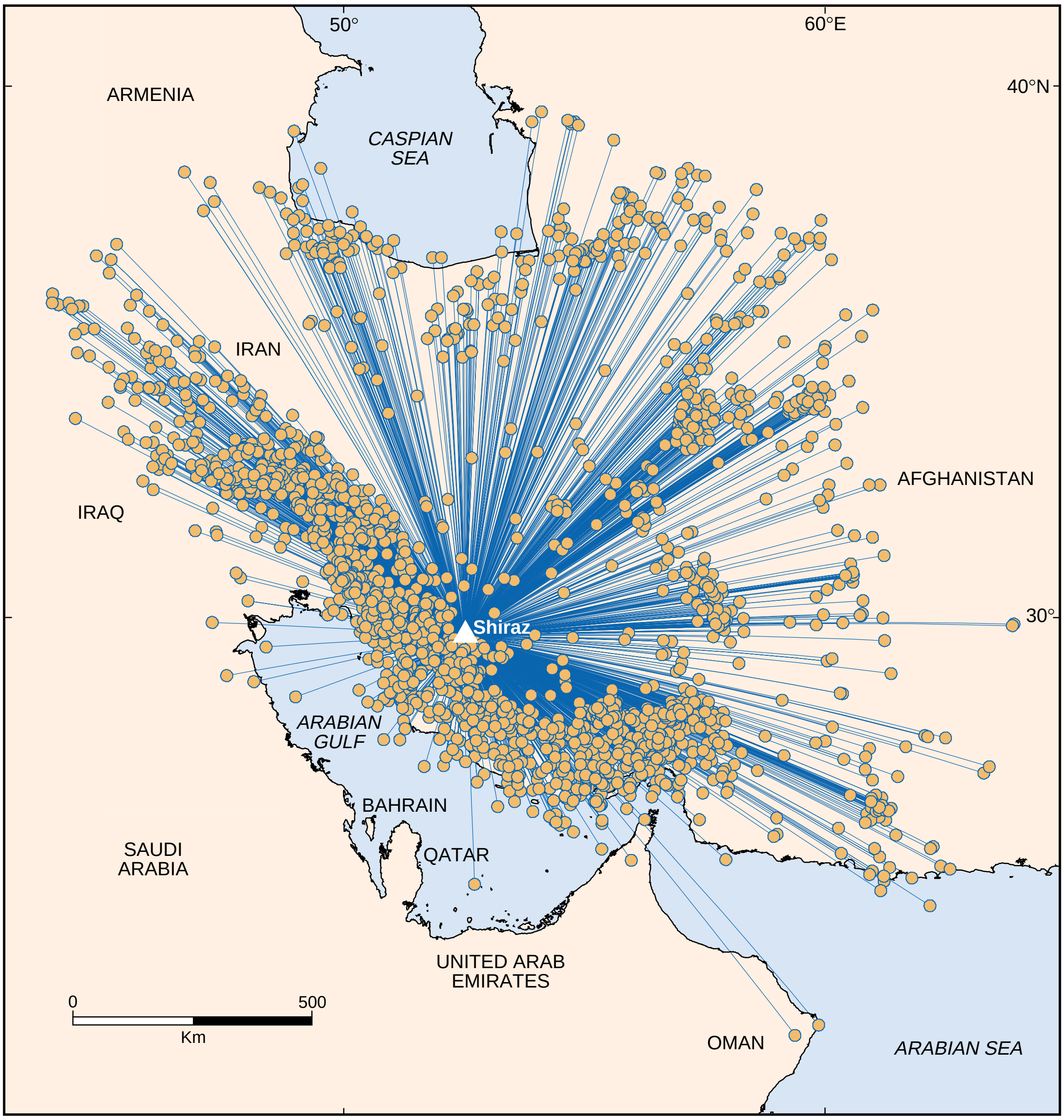


Figure 7: Map showing locations of seismic events (mostly earthquakes) for which phase readings exist from station SHI (Shiraz) in Iran. SEIS allows selection of seismic events based on recording stations' codes. In this selection only those events that are within 10 degrees distance of station SHI are plotted. Calculated great circle paths to each event are plotted as blue lines.

earthquake) have been calculated and plotted. Based on the station location and distance range selected, most of the seismic phase readings are from the Zagros and the Iranian plateau regions. Users can plot the travel-time data from this data set. Since the distance to epicenter is known and all seismic phase arrival data are kept in the database, users can plot distance versus seismic phase arrival times (Figure 8) for the selection. This allows determination of average seismic P and S wave speeds in this region and since the selection covers most of Iran and the distance is limited to 10°, Figure 8 provides an average speed of the uppermost mantle P waves (Pn) beneath Iran. The shear wave (Sn) arrivals in this region are attenuated and reported arrival times of Sn phases are scattered, making Sn speed estimation difficult. The solid lines on Figure 8 represent the average global Pn and Sn speeds as

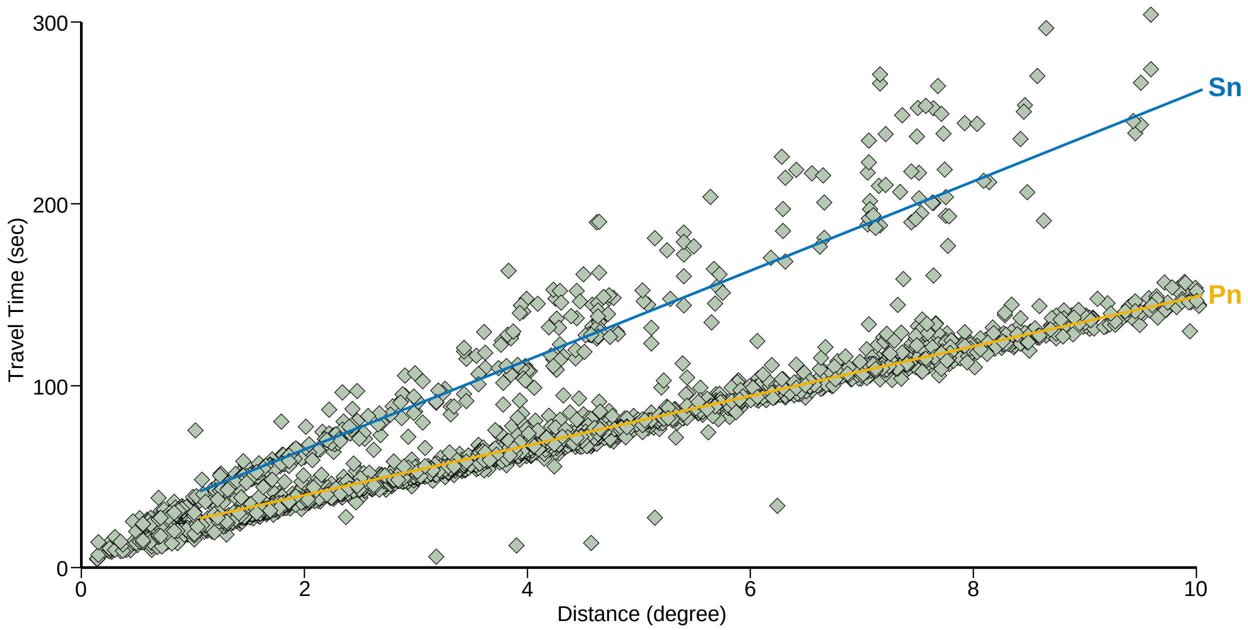


Figure 8: Travel-time plot of recorded seismic phase arrivals at station SHI for events shown in Figure 7. This option in SEIS allows a better analysis of regional seismic wave speeds in this region. Predicted arrival times based on IASPEI 91 velocity model for Pn and Sn phases are plotted for comparison with orange and blue lines, respectively.

provided by IASP-91 travel-time tables. These tables are also a part of SEIS and can be used for comparative studies of regional seismic phase speeds in any part of the world. The users have the option of limiting their selection further by adding new criteria such as the depth of the event, azimuthal coverage, and date.

Earthquake focal mechanisms are also an important data set. Several organizations calculate focal mechanisms of major seismic events (Mb>5.5). Harvard University's Centroid Moment Tensor (CMT) solutions are an example. We have collected all the solutions from the Harvard catalog and included them in our database with all available attributes. In addition to geology, fault maps, and seismicity, fault plane solutions provide insights about the kinematics of the region. Since the data sets are registered and are accessible by way of menu-driven tools, users can plot focal mechanisms of either all or selected events in a region. Figure 9 shows Harvard CMT focal mechanism solutions in the Middle East. The continent-continent collision in Zagros is delineated by predominantly northwest-oriented thrust-type focal mechanism solutions along the Zagros Mountain chain. In contrast, the Gulf of Aden and Red Sea regions are dominated by mostly extensional focal mechanism solutions. The North Anatolian Fault Zone is dominated by strike-slip type solutions, and western Turkey is dominated by mostly east-west oriented extensional focal mechanism solutions.

Unfortunately, CMT solutions are available only for major seismic events. To make up for the gap in focal mechanism solutions of lower magnitude events and those that occurred prior to the CMT catalogue, we have made an exhaustive literature search to determine earthquake focal mechanisms for the Middle East and North Africa. Our search resulted in finding more than 450 focal mechanism solutions. These focal mechanism solutions are mainly based on first-motion analysis and waveform modeling. Figure 10 shows these focal mechanisms for the Middle East. The quality of the focal mechanism solution vary. In order to take into account the quality variations in the data set, we added special items and comments for each of the focal mechanism solutions. Users can easily access all this information and include or exclude certain types of events from their analysis.

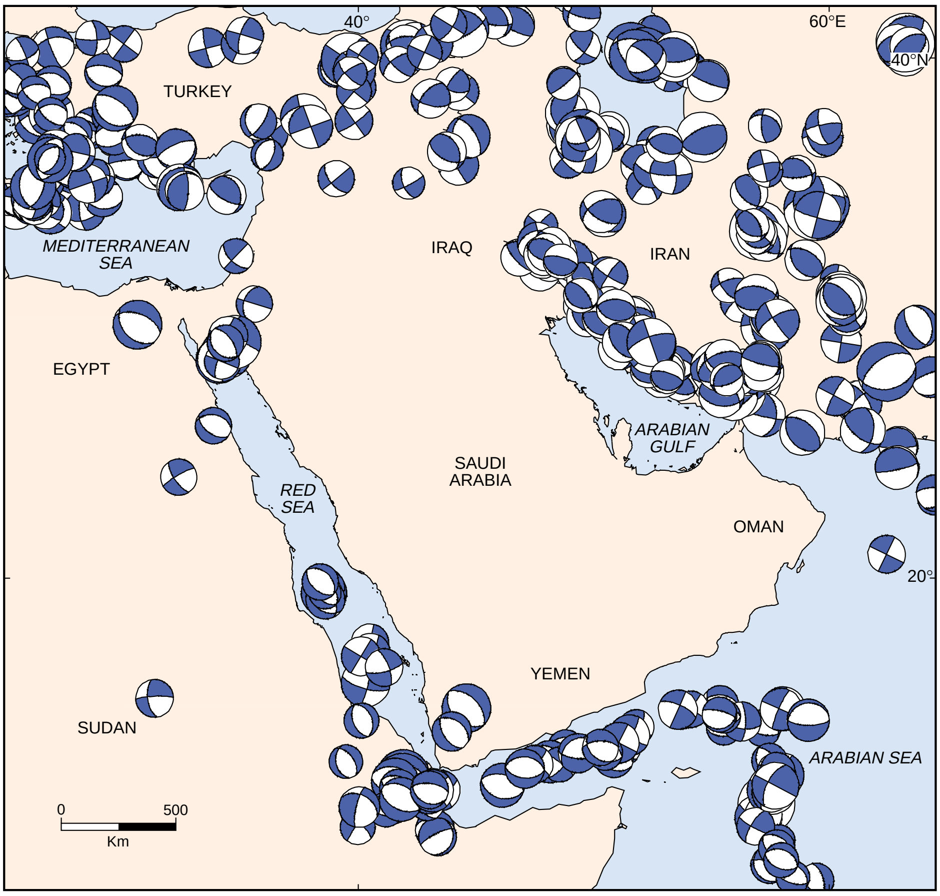


Figure 9: Focal mechanism solutions of large events (Mb>5.5) in the Middle East. The solutions are from the Harvard CMT catalog for the period 1977 to 1996.

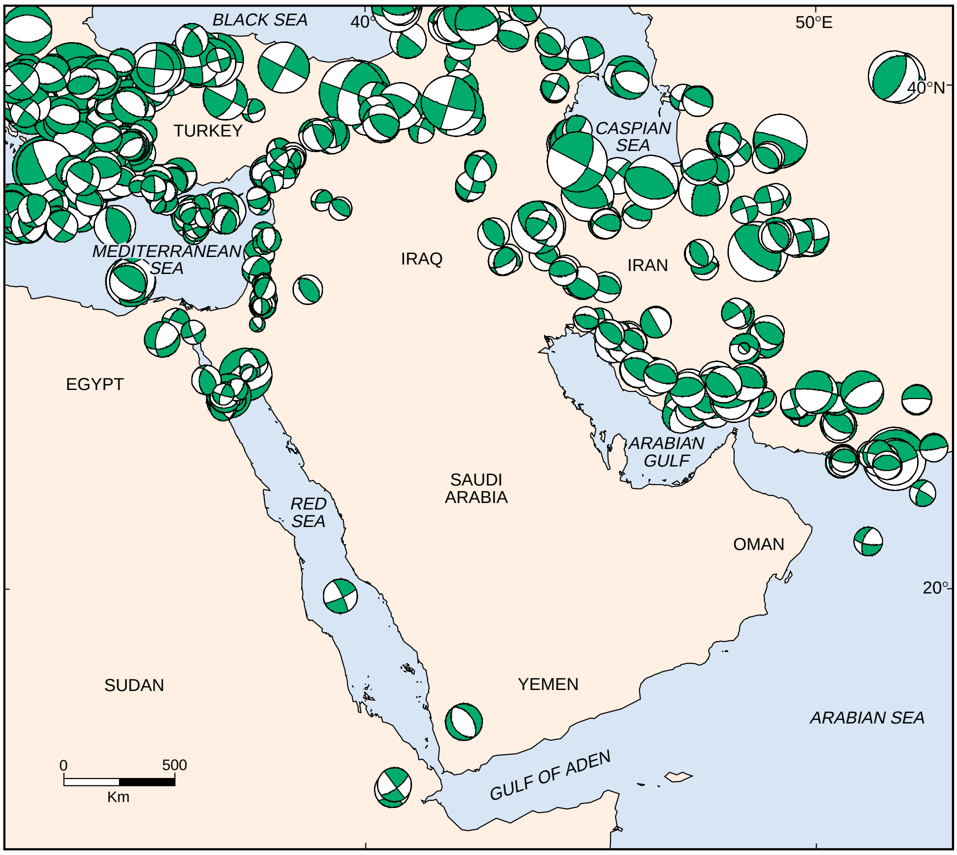


Figure 10: Focal mechanism solutions for events smaller than Mb<5.5 as well as for events pre-dating the CMT catalog. About 450 focal mechanism solutions were obtained from an extensive literature search. This data set is used to complement the CMT catalog shown in Figure 9.

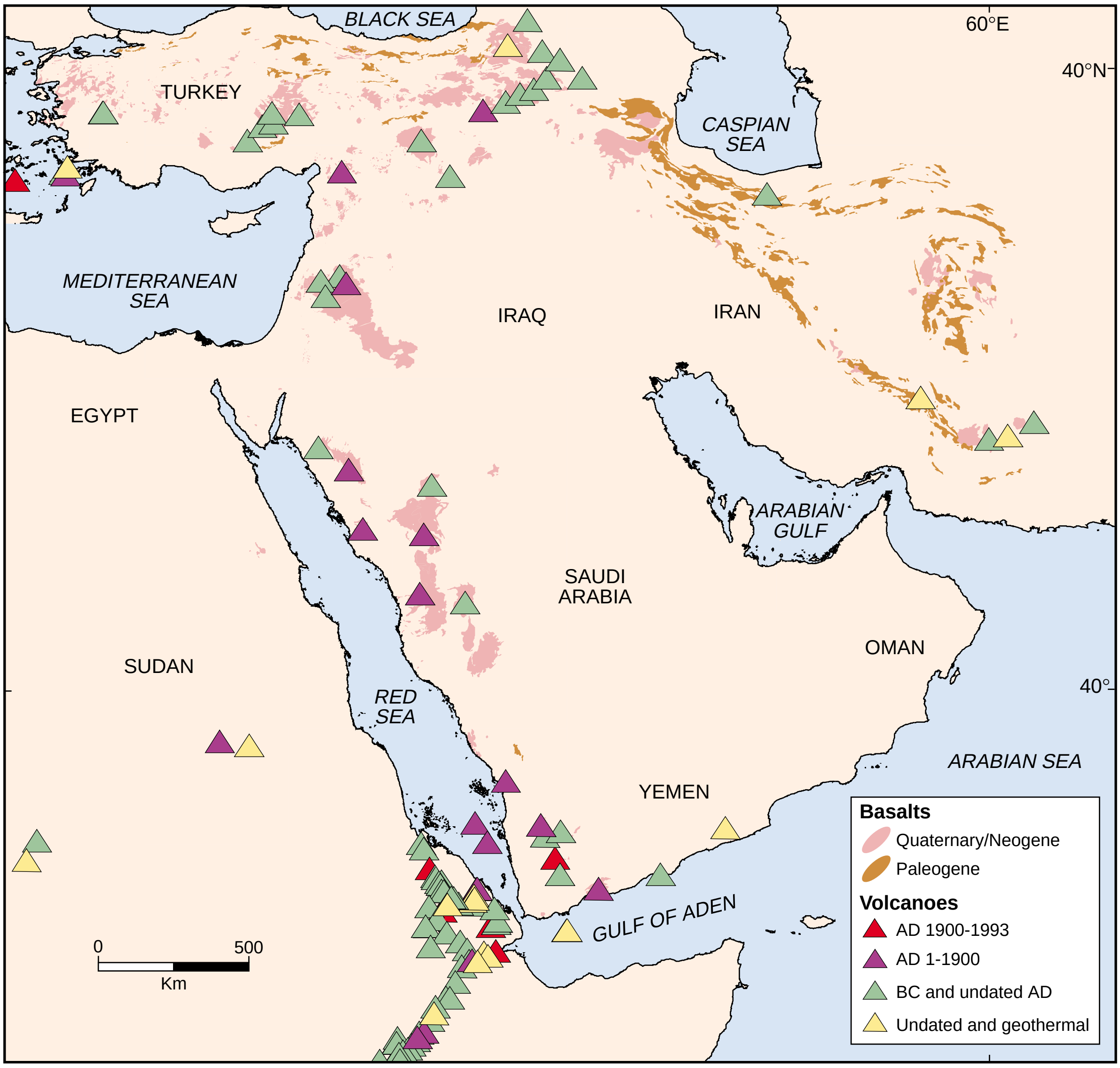


Figure 11: Map showing distribution of volcanic activity in the Middle East. Only Neogene/ Quaternary and Paleogene volcanic fields are shown. Holocene volcanoes obtained from the Smithsonian Institution are also shown colored based on their age groups. The majority of the Neogene/Quaternary fields are in western Arabia and Turkey, whereas the majority of Paleogene volcanics are in Iran.

Active Volcanoes

An important data set in the Middle East is the distribution of Cenozoic volcanoes and volcanic rocks. Cenozoic basaltic rocks are widespread in the region, but a concentration is present in the western and northern parts of the Arabian Plate, Turkey, and northwestern and eastern Iran. Historically active volcanoes in the region show a similar spatial pattern (Figure 11). The Smithsonian Institution active volcano data set (Figure 11) shows that the majority of historically active volcanoes is located in the Red Sea and Afar Triangle regions as well as in Turkey and northern Arabia. Each volcano in the data set (Figure 11) includes items such as volcano type, eruption status, and elevation. Users of SEIS can access the entire data set or select one or many of the volcanoes by their type, elevation, or any other item that is defined in the data set.

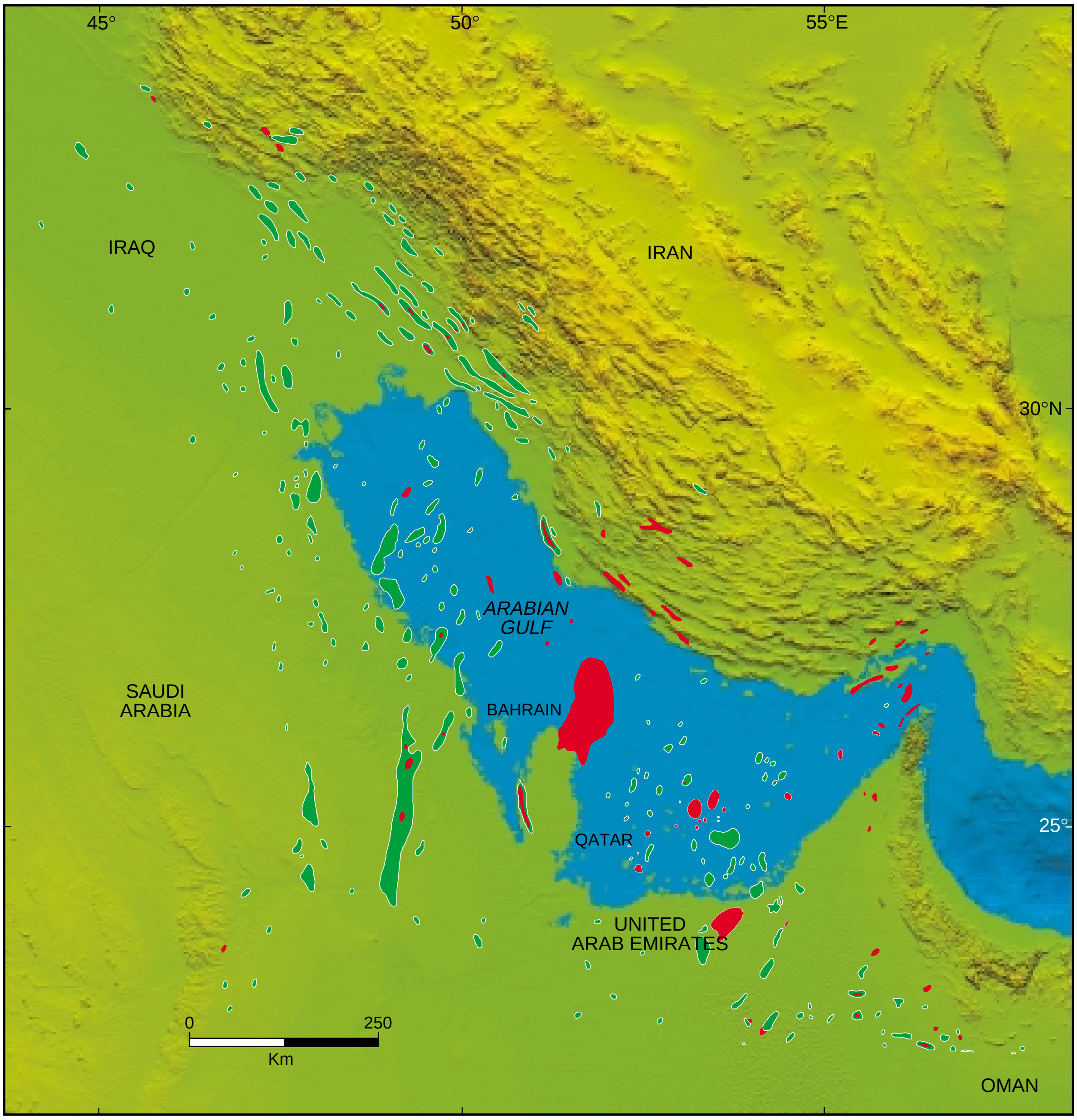


Figure 12: Map showing distribution of oil and gas fields in the Arabian Gulf. Red represents the gas fields and green the oil fields. A shaded-relief topography image in the background shows the Zagros fold belt. Two major orientations in oil and gas fields are apparent from this image: fields in the Zagros fold belt follow the main southeast (Zagros) trend; to the south, however, the trend is north-south, indicating that the structure controlling these fields is different from that of the Zagros trend.

Oil and Gas Fields

The distribution of oil and gas field in the Middle East region is also an important data set in SEIS. Fast on-line access to all oil and gas fields in the Middle East has important research implications. We have taken an initiative to compile all oil and gas fields in the region with their attribute information. These attributes include the name, depth, area, trap-type, and production level. Figure 12 shows the oil and gas fields in the Arabian Gulf region. This figure shows two distinct trends in the spatial distribution of oil and gas fields in this region. One trend is the same as the Zagros trend, and the other is a more north-south trend in the southern part of the Gulf. Undoubtedly, these trends are structurally controlled. More detailed studies must be performed to draw a clear boundary between the two

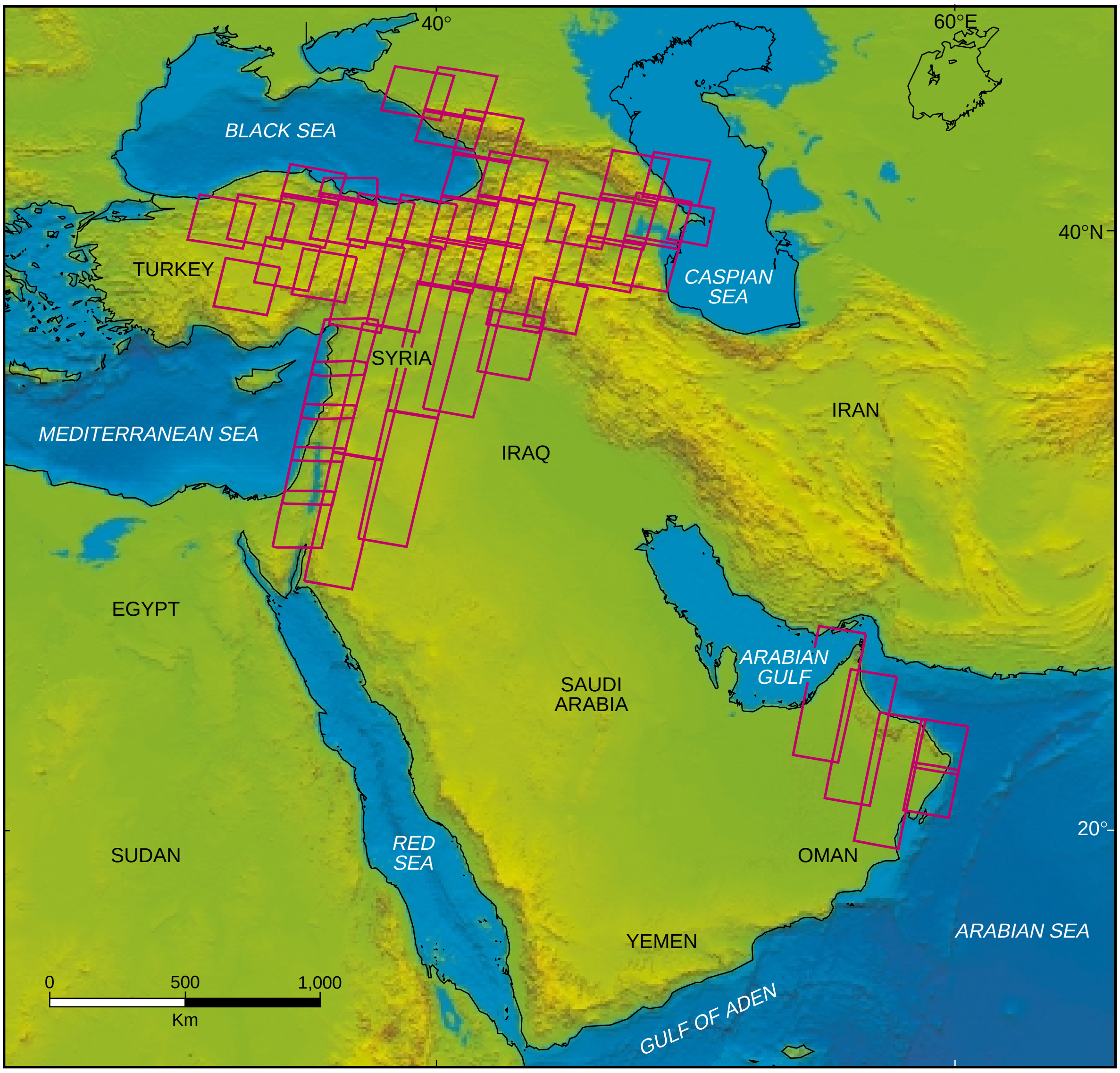


Figure 13: Locations of the TM satellite imagery that are held in SEIS. Satellite imagery are used in many different studies, and they are a significant part of SEIS.

trends and determine the factors that influence this distribution. Note that the majority of the oil fields in the Zagros region are located in the topographic embayment region, whereas they follow the trend of the Zagros folding. As the elevation increases along the same trend of the Zagros towards the south (Fars region) the number of oil fields is dramatically reduced.

Satellite Imagery

Satellite imagery such as Landsat TM (Thematic Mapper) or SPOT provide valuable information about regional surficial features. More advanced satellite imagery such as Synthetic Aperture Radar (SAR) and Landsat 7 provide even more information. SEIS has been designed to take advantage of these types of data as well. Currently, SEIS holds about 120 Landsat TM scenes covering various parts of the Middle East and North America (Figure 13). In the near future SEIS will include additional scenes to cover the majority of the Middle East.

The imagery is not only used for mapping and geomorphologic analysis. Images are also valuable sources for innovative visualization. Visualization is increasingly important in geoscience research. The availability of powerful, fast computers and software have made what once was a painful task of

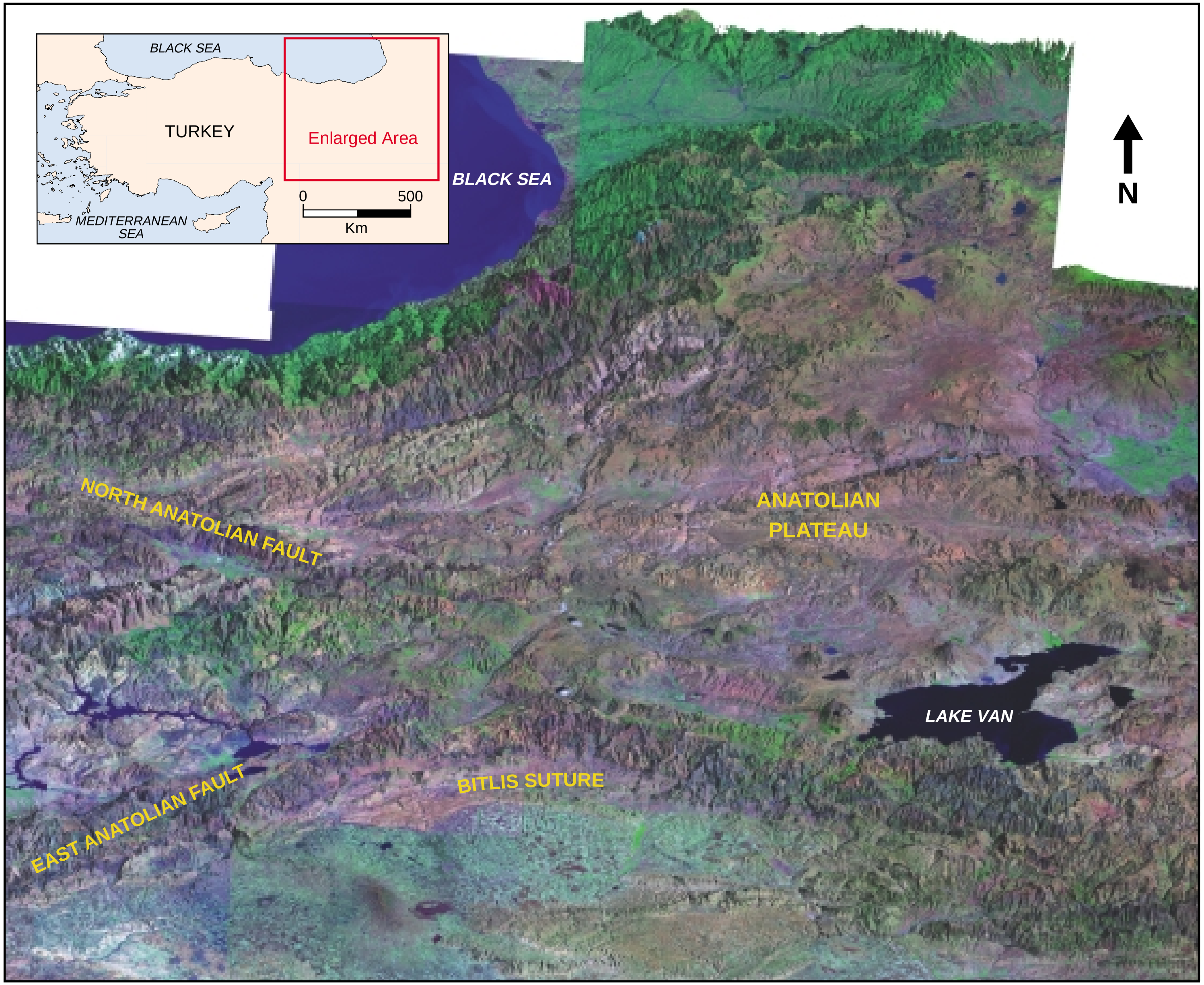
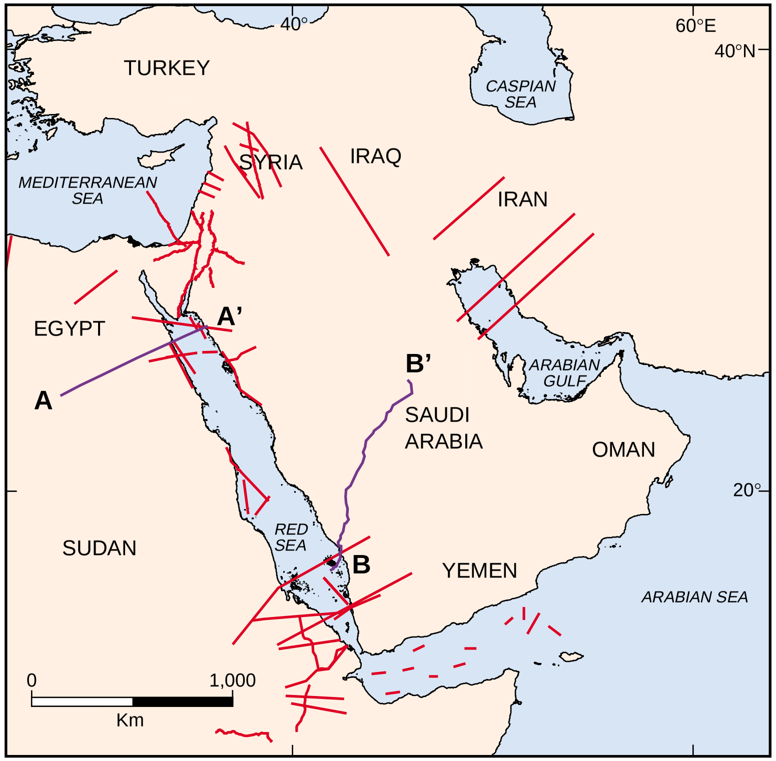


Figure 14: A perspective view obtained using about 12 TM scenes draped over the topography of the eastern Turkey region. The inset map shows the approximate location of the area shown.



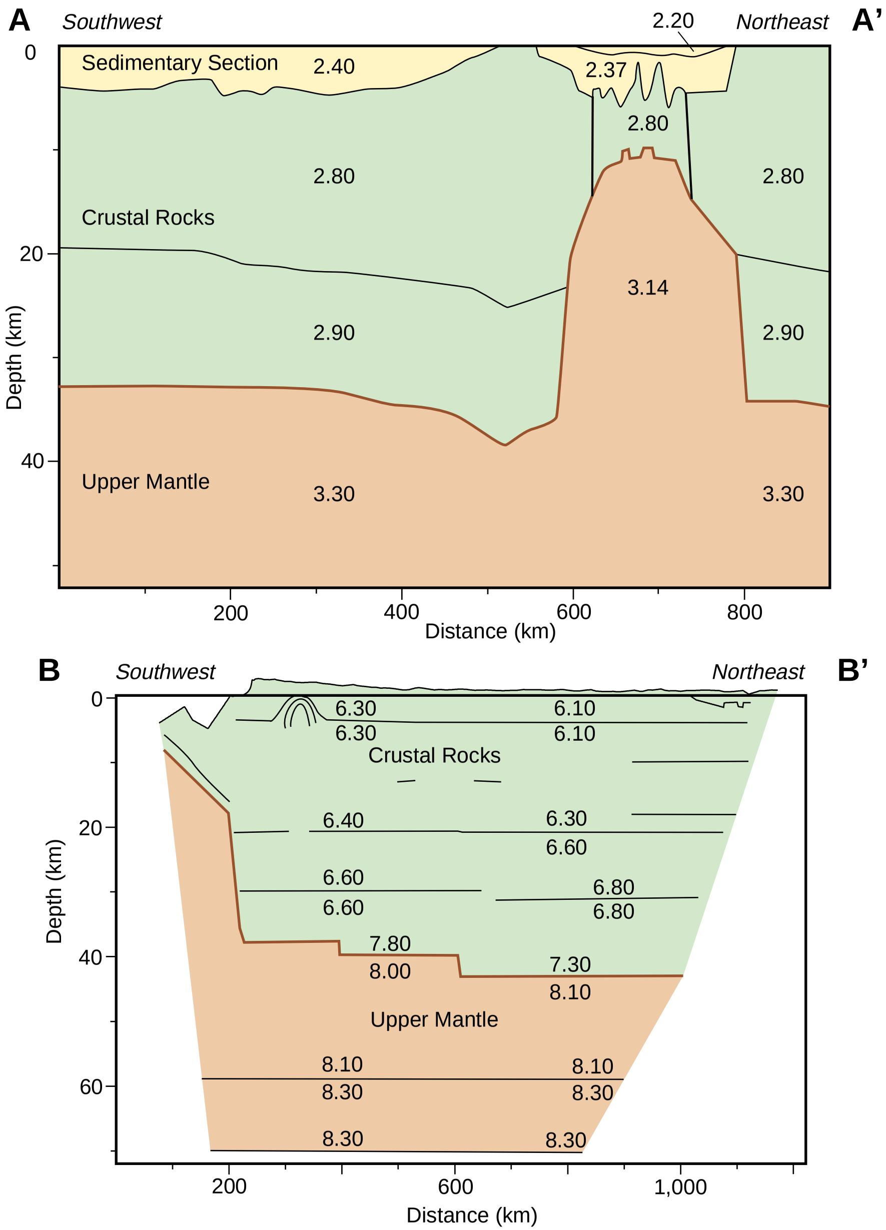


Figure 15: ***Left*** **- map showing crustal-scale profiles available in the Middle East. Interpretations of these profiles have been digitized and entered into SEIS.** ***Right*****: Users can select any of the profiles from a computer screen and display the cross-sections. Two cross-sections marked A-A’ and B-B’ on map are shown. Profile A-A’ is based on gravity modeling and values shown represent density information in g/cm^3. Profile B-B’ is a velocity model and values shown represent P wave speeds in km/s.**

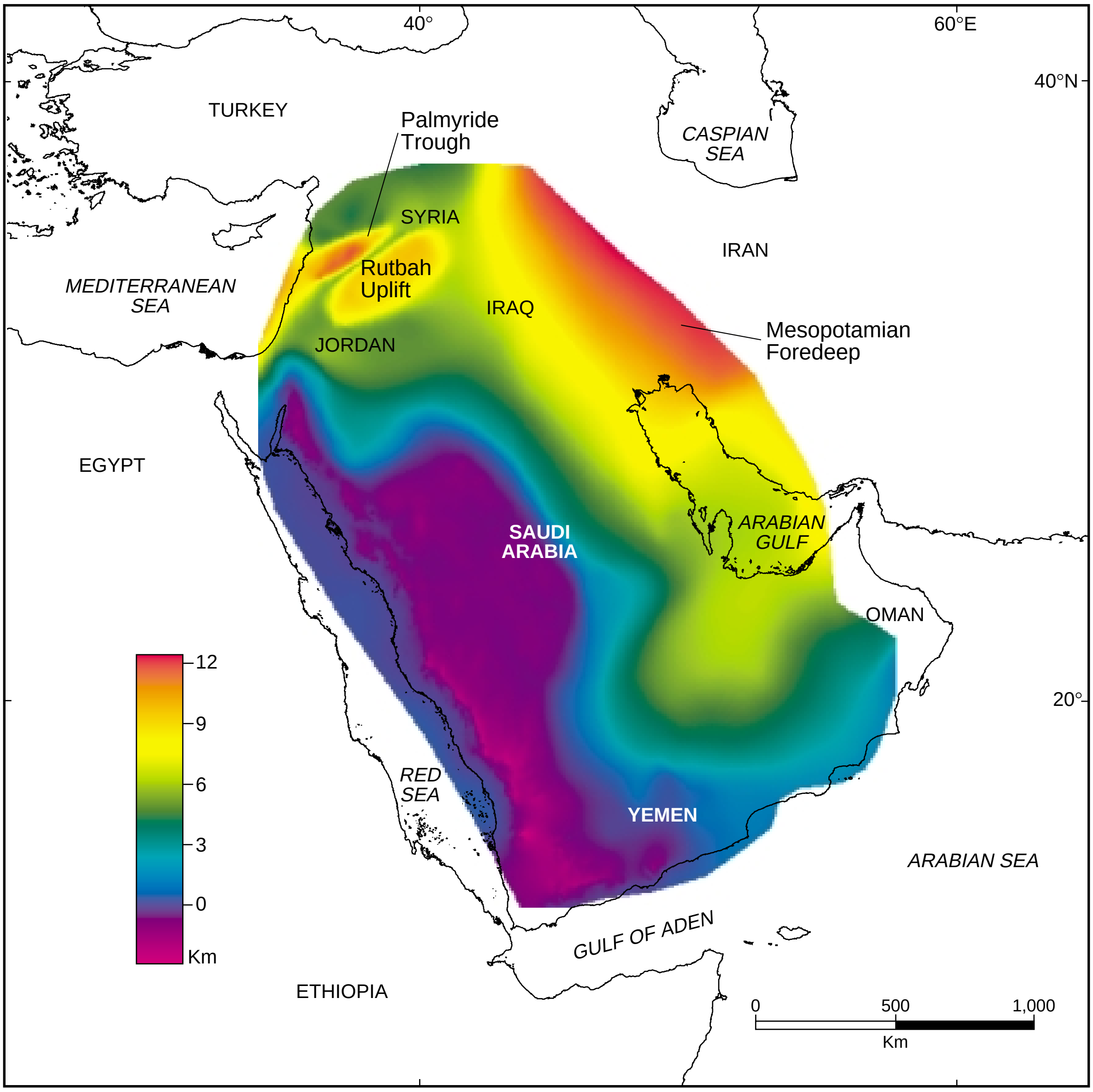


Figure 16: Depth-to-metamorphic basement in the Middle East. This map was obtained primarily using the profiles shown in Figure 15. Basement-sediment contacts from these profiles were selected and gridded to obtain this map.

creating advanced visualizations now a routine task. Figure 14 shows as an example a perspective view in eastern Turkey where the Arabian Plate collides with the Anatolian Block. Twelve mosaiced TM images are draped over the topographic data to obtain this image. The Bitlis Suture and major faults as well as the young volcanoes of the region are easily identified from this image.

Additional Sub-surface Data Sets

A well-designed geoscience information system must include sub-surface structure in addition to various types of data sets as described above. Data sets such as basement depth, Moho depth, depth distribution of seismicity, seismic wave speeds, attenuation, and so on, are essential information in geoscience research. SEIS includes such data sets. In order to obtain accurate basement and Moho depths data for the Middle East, we have collected the locations and interpretations of over 60 crustal scale profiles in the Middle East region (Figure 15). Some of these profiles are interpretations of refraction

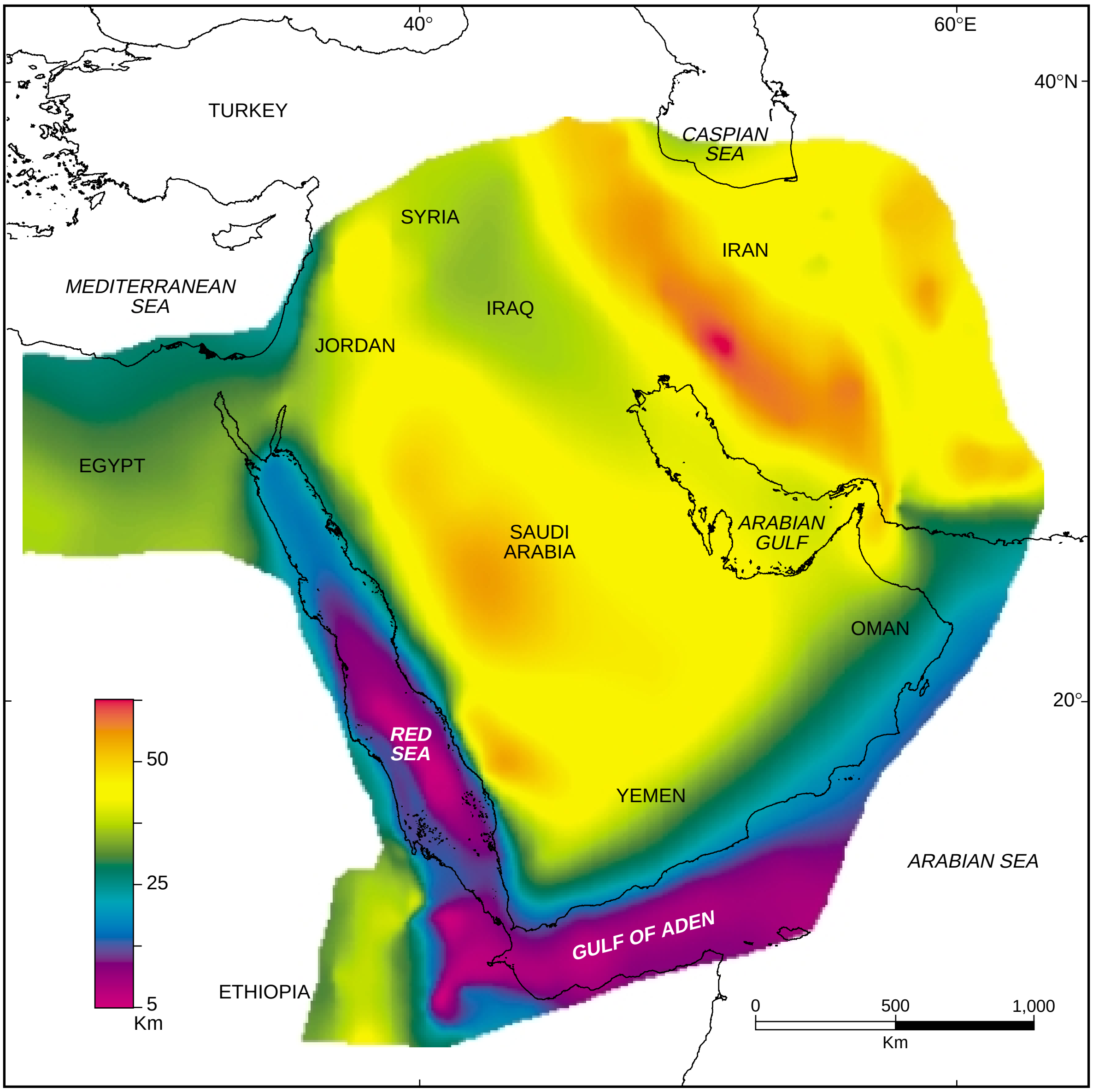


Figure 17: Depth-to-Moho map in the Middle East. This map was obtained primarily using the profiles shown in Figure 15. Moho depths in each interpreted profile were selected and additional data such as receiver function and surface wave tomography results were also used prior to gridding.

data and others are inferred from gravity modeling. Within SEIS we have developed tools to access interpretations of these profiles by simply clicking on a computer screen.

Figure 15 also shows interpreted cross-sections of two profiles marked A-A' and B-B'. In each profile, specific layers such as sediment-basement contact and basement-Moho contacts are highlighted by different attributes. This allowed us to construct basement and Moho maps for the Middle East as a whole by selecting only the basement (or Moho) layers from each profile and contouring the values obtained from these profiles. For both Moho and basement maps, additional information from data sets, such as reflection data, and surface wave and receiver function analysis results from the broadband seismological stations in the region, were also used in the compilations. The resultant depth-to-basement and depth-to-Moho maps are shown in Figures 16 and 17, respectively. The basement map shows that the thickness of sediments in the Middle East varies from zero on the Arabian Shield to about 15 km in the Mesopotamian Foredeep. The Palmyride Trough in Syria and the Rutbah Uplift region in northern

Arabia are other regions with thick sedimentary cover. Triassic rifting in the Palmyrides is thought to be responsible for this deep basin (Best et al., 1993). The estimated thickness of sediments along the Palmyrides fold and thrust belt reach about 12 km in the southwestern part (Seber et al., 1993). The Rutbah sediments are separated from the Palmyrides Trough by a narrow ridge. The estimated thickness of sediments in the Rutbah region is more than 8 km.

Similarly, the Moho depth map in the Arabian Peninsula shows that the Moho varies from about 5 km deep in the southern Red Sea region to about 55 km in the central Zagros Mountains. Depth-to-Moho variations in Arabia are relatively constant with an average depth of about 40 to 45 km whereas Moho depths in Iraq and Egypt are shallower. One of the significant changes in Moho depth occurs across the Oman Line. A change of about 10 km in depth-to-Moho from the Zagros to Makran region is inferred from gravity interpretations (Dehghani, 1981). The Oman Line also marks a region where the strike of faults change, topography shows a lineament, and seismicity is terminated abruptly, all indicating that the Oman Line is a structure of lithospheric scale.

The shallowest on-land Moho in the Middle East region is in the Afar Triangle region. At this locality the estimated Moho depth is about 8 km (Sandvol et al., 1998). A simple geometrical relationship on

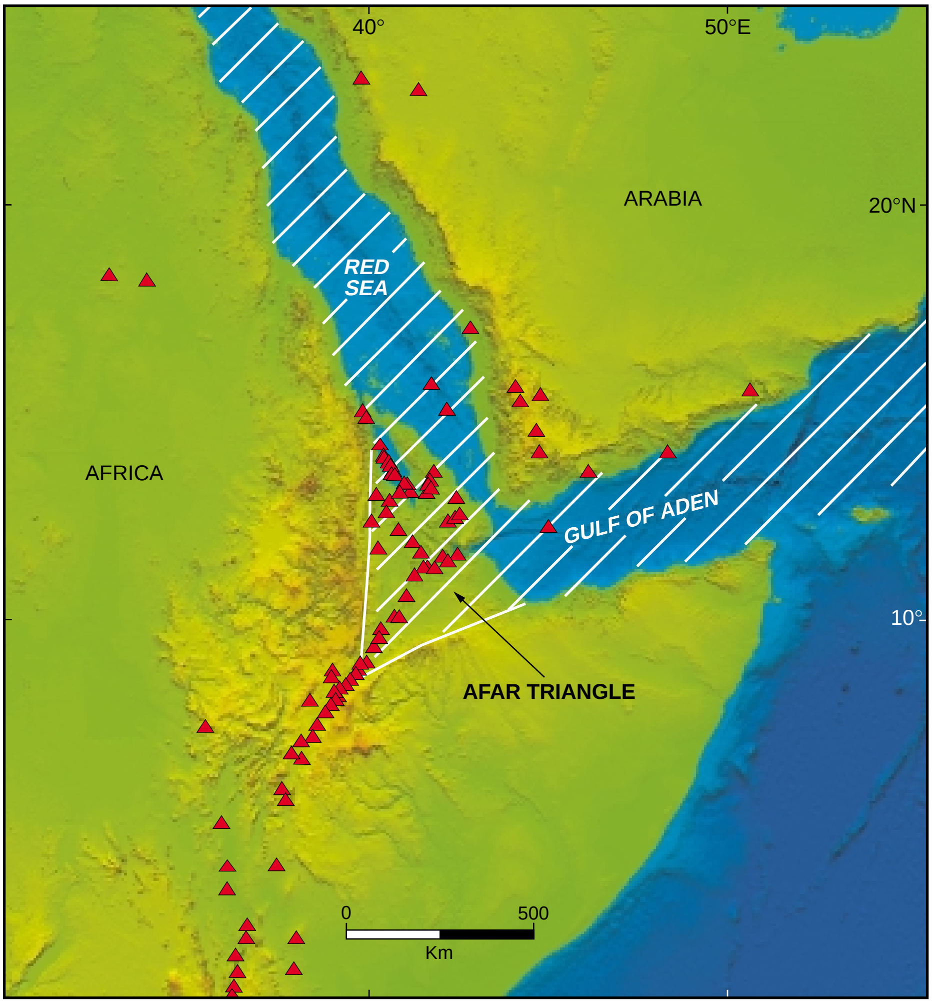
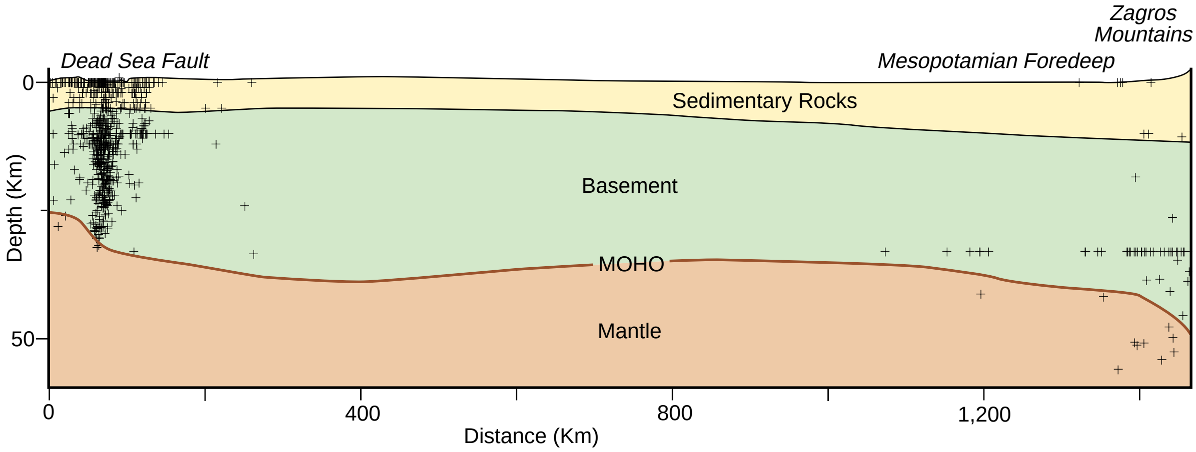


Figure 18: Topography of the southern Red Sea and Afar regions. The escarpments on each sides of the Red Sea mark approximate rifting locations. The hatched zone indicates possible amount of opening due to Red Sea spreading center. Holocene volcanoes are plotted as solid triangles. The Afar Triangle, with a very thin crust (see Figure 17), is assumed to be underlain by newly formed oceanic-type crust.



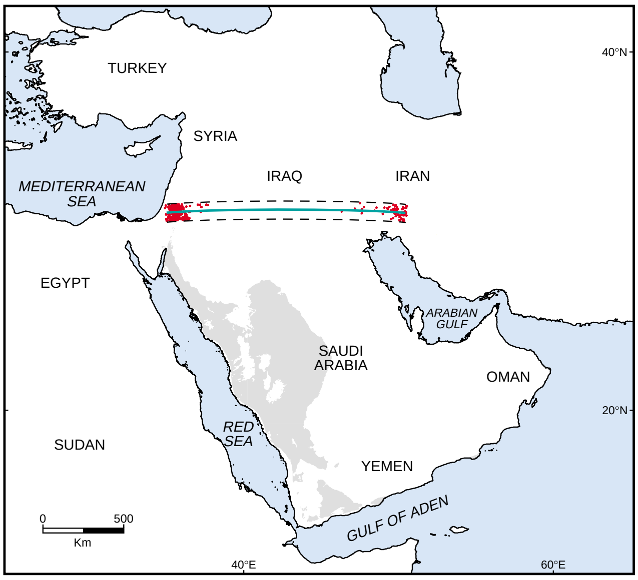


Figure 19: Map and a cross-section showing the results of the Profile Maker tools available in SEIS. The Profile Maker tool is used to extract a cross-section between two arbitrary points from any gridded data set. In this cross-section, an east-west profile in northern Arabia is selected and seismicity from the ISC database is projected onto this plane. This tool allows studying cross-sectional structures in any region where data sets are available. The dashed lines on the map represent area where earthquakes are projected on the cross-section.

both sides of the Red Sea suggests that the Afar Triangle has filled the gap that was opened by the rifting of the southern Red Sea. The topographic escarpments on each side of the rift mark the approximate location of the initial rifting. The shaded area in Figure 18 can then be considered a region of recent opening along the Red Sea rift. The least constrained Moho depth in our compilation is in the southeastern corner of Arabia where information is very limited.

To take advantage of these new Moho and basement maps and to give SEIS users a tool to make crustal-scale sections between two arbitrary points, we have developed a Profile Maker tool. This interactive tool allows users to extract profiles from any of the gridded data sets in SEIS. Users simply select layers such as topography, basement, and Moho, mark the two endpoints of the profile, and extract a crustal-scale profile between the two points. Figure 19 shows such a crustal-scale cross-section. SEIS allows users to create ASCII files of these extracted cross-sections. Later, they can be used in other modeling programs such as gravity modeling or seismic modeling to better understand the sub-surface structure in the region. In addition to crustal sectioning, the Profile Maker tool in SEIS allows the projection of earthquake hypocenters within a user-specified distance from the profile onto the cross-section. This allows more a comprehensive view of the seismicity in any region.

Other sub-surface data sets in SEIS are seismic Pn speed variations in the Turkish and Iranian Plateaus, seismic Lg wave attenuation, and hypocenter distribution of seismic events.

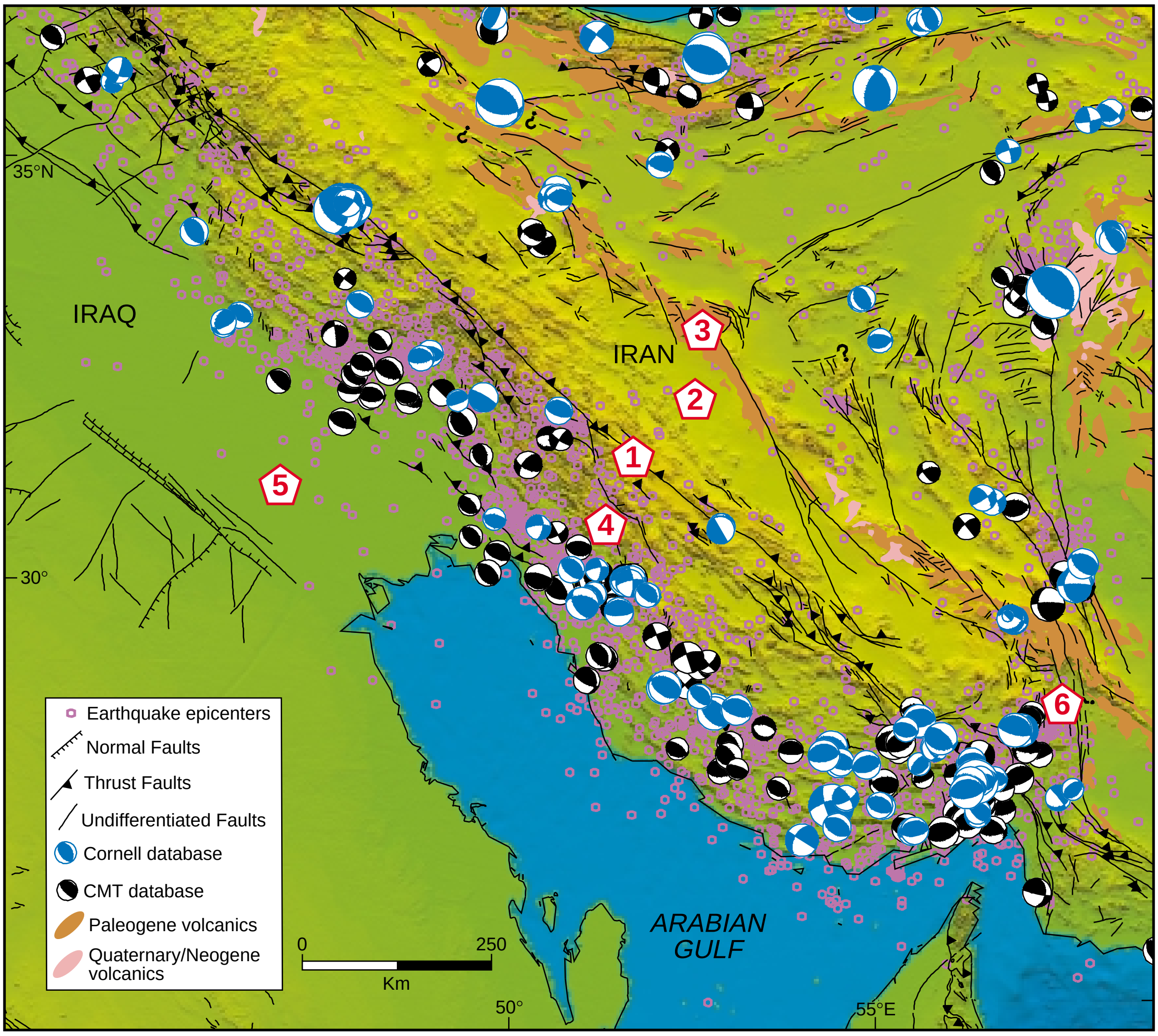


Figure 20: Southern Zagros tectonic map showing major faults, volcanics, and focal mechanisms of CMT and Cornell (MENA) catalog. The majority of seismic events show thrust type fault plane solutions with main compression axes perpendicular to the Zagros trend. The numbers represent (1) Zagros Suture; (2) Fore-arc Basin; (3) Volcanic Arc; (4) Fold belt; (5) Arabian Platform; and (6) Oman Line.

Tectonic Applications

As discussed in the building of a GIS system, data sets can be used as individual entities or more effectively they can be used in a multidisciplinary analysis of a region. For example, by utilizing some of the data sets one can look at the tectonics of the Zagros Mountains (Figure 20) and Anatolia (Figure 21).

Zagros Mountains

Topographic data viewed as a shaded relief image provide an easy way to visualize the entire mountain chain, with its fold axes, fore-arc basins, and volcanic arc. Overlaying seismicity data on top of the topographic map indicates that only the frontal margins of the Zagros fold belt are seismically active. The southeast trend of seismicity along the Zagros Mountain belt makes a bend in the topographic embayment area and trends east-west for about 250 km. Then, it continues in the general southeast trend until it reaches the Oman Line in southwest Iran. At the Oman Line, the Zagros seismicity stops abruptly, indicating that a major deformational change takes place at this boundary. The topography mimics these changes. The focal mechanisms solutions in the Zagros Mountains have nodal planes consistent with the fold axes and indicate that the folds are still active as the Arabian Plate pushes into the Eurasian Plate.

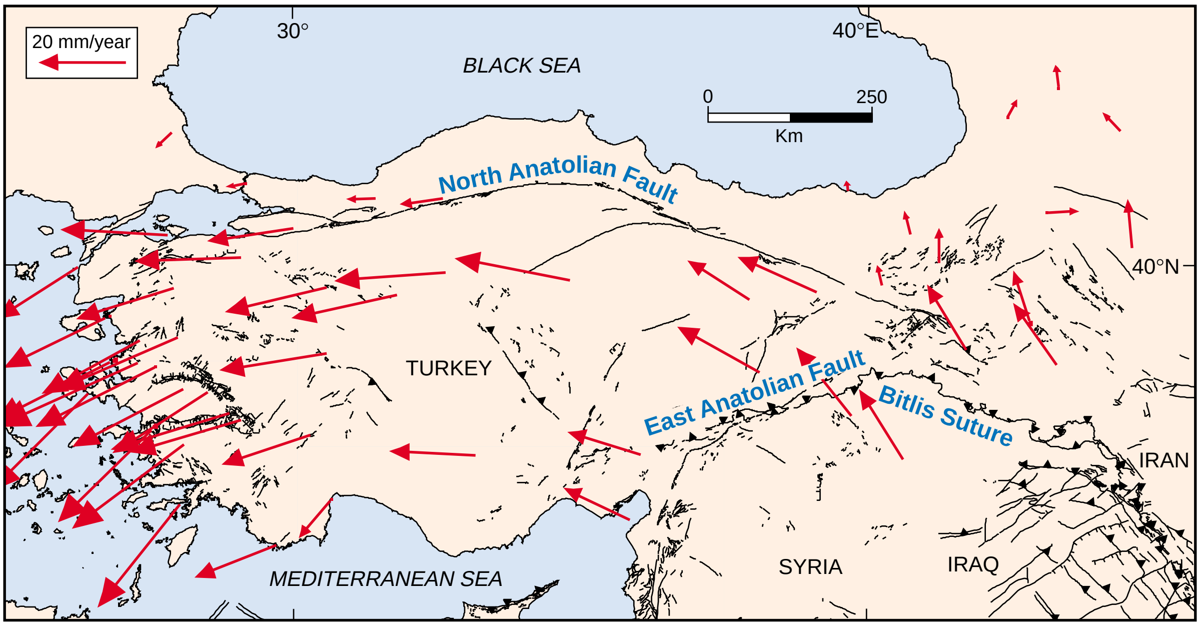


Figure 21: Global Positioning System (GPS) displacement vectors in and around Turkey obtained from Reilinger et al. (1997). GPS vectors indicate counter-clockwise rotation of the Anatolian Block and shortening in eastern Turkey. The North Anatolian Fault marks a region where magnitudes of GPS displacement vectors change significantly due to this fault's right-lateral motion. Along the Bitlis Suture shortening does not seem to be significant. The majority of the shortening occur farther north in northeastern Turkey and in the lesser Caucasus.

Anatolia

In the northern part of the Arabian Plate the collision between Arabia and Anatolia is occurring along the Bitlis Suture and the East Anatolian Fault Zone. Some of the deformation resulting from this collision is taken up internally within the Turkish Plateau to form the high topography in eastern Turkey. A component of the convergence is accommodated by the westerly escaping Anatolian Block. This escape takes place along the North Anatolian and East Anatolian Faults (Figure 1). Recent geodetic measurements based on Global Positioning Systems (GPS) in Turkey and the surrounding regions determined both the internal shortening and the escape directions and rates (Reilinger et al., 1997). We included these GPS results in SEIS and developed tools to analyze the data. Figure 21 shows the GPS vectors in Turkey and surrounding regions. The GPS displacement vectors indicate counter-clockwise rotational movement of the Anatolian Block relative to Eurasia. They indicate that not much shortening occurs along the Bitlis Suture Zone as relative motions both to the south and to the north of the suture zone show similar values. However, significant variations in GPS vector directions are observed north and south of the North Anatolian Fault. Another important conclusion from the analysis of GPS and surface faulting is that in the western part of Turkey the amount of displacement increases towards the Aegean Sea where Aegean extension dominates the regional tectonics. This is interpreted to be a result of the extension in western Turkey and subduction in the Aegean.

The right-lateral strike-slip motion along the North Anatolian Fault is evident from the relative GPS velocity vectors. In the western part of the North Anatolian Fault near the Sea of Marmara, the fault splits into two main segments (Figure 22). The GPS data, topography, and local seismicity collectively indicate that the northern strand is more active than the southern one. This observation has significant implications for seismic hazard studies as the most populated city in Turkey, Istanbul, and much of the country's industry are located within a few tens of kilometers of this fault. The two most recent earthquakes that occurred on August 17 and November 12, 1999 (Mw=7.4 and Mw=7.1, respectively) confirm the conclusion that the northern strand is more active and capable of producing large earthquakes (Figure 22). These earthquakes produced significant damage and loss of lives.

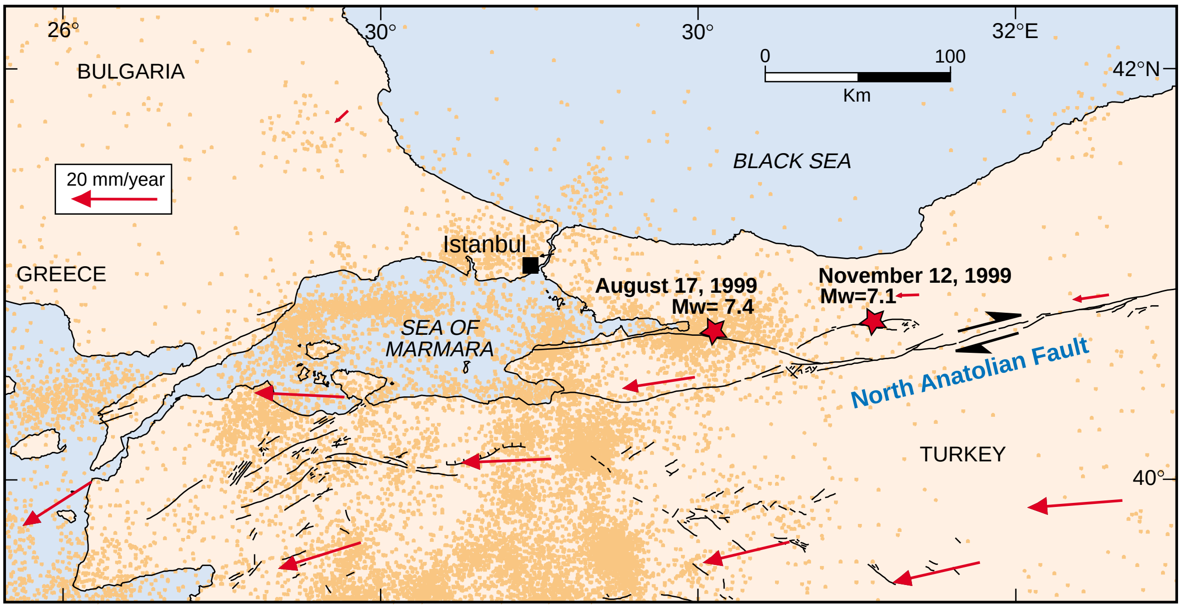


Figure 22: Map showing active faults, GPS displacement vectors, and seismicity (orange dots) in the Sea of Marmara region of Turkey. The North Anatolian Fault splits into two segments about 150 km east-southeast of Istanbul. The GPS results indicate that the northern strand is moving faster.

It is clear that seismic hazard mitigation studies in the region need to be re-evaluated once comprehensive information systems are developed. Other seismically active regions of the Middle East, such as the Dead Sea Fault System and the Zagros Mountain belt, can also benefit from such comprehensive information systems. Not only seismic hazard, but also other natural hazard studies will benefit significantly from organized information systems.

OPEN ACCESS TO SOLID EARTH INFORMATION SYSTEM (SEIS) VIA THE WORLD WIDE WEB

One of the most important aspects in developing a successful information system is its accessibility. Users should be able to access the information easily and efficiently. Today, the Internet provides unprecedented opportunities to build such open systems. We have developed SEIS as an efficient and sophisticated application to be used in WWW browsers for accessing and plotting data and information. This application not only provides access to data sets in SEIS, but also allows users to register their own data sets and combine them with those of SEIS.

The WWW address for accessing SEIS is http://atlas.geo.cornell.edu. The application starts in a web browser as shown in Figure 23. The web interface enables users to create and display maps interactively. The map area in the application is dynamic and receives input from the computer mouse or access buttons; users can also zoom in on any region by drawing a box on the map area. Users can select any data sets that they would like to see in a given region, change the plotting parameters of each data set, and identify features and view attribute information on maps directly from their web browsers. The web site includes a detailed users' guide.

Similar versions of most of the figures shown in this paper can be duplicated from the WWW application. For example, if a user would like to combine the geologic data shown in Figure 5 and tectonic information shown in Figure 6 near the Dead Sea Fault region and northern Arabia, by selecting proper data sets from the web application the user can obtain the map shown in Figure 24. The map extent, data sets to be plotted, and other plotting parameters are all user-defined and can be changed at any time during the analysis of data sets. This efficiency and availability make SEIS a powerful tool for researchers and educators.

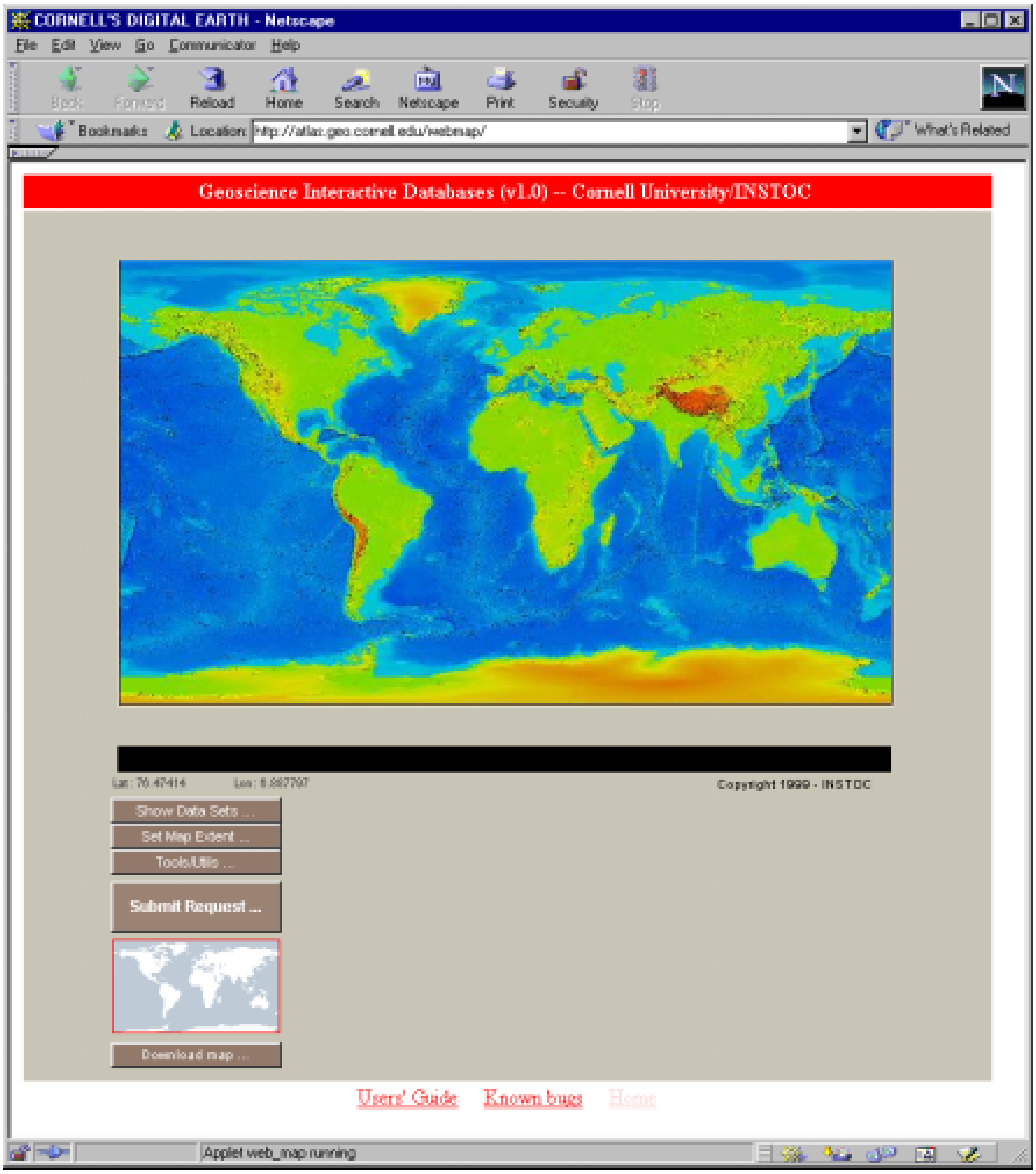


Figure 23: Recently developed web page for SEIS. Users anywhere with an Internet connection can access SEIS via this interface and make their own maps and analyze data sets. The address for accessing this page and relevant documentation is http://atlas.geo.cornell.edu.

CONCLUSIONS

The need for comprehensive geoscience information systems in research and education is overwhelming. Examples shown in this study provide detailed explanations about an information system that will lead to better and more efficient research studies in many parts of the world. Application of SEIS to the Middle East tectonics has already shown that using organized information systems in geoscience research has a significant return. The success of future geoscience research relies on how efficiently and effectively researchers can access multidisciplinary and voluminous data sets in their

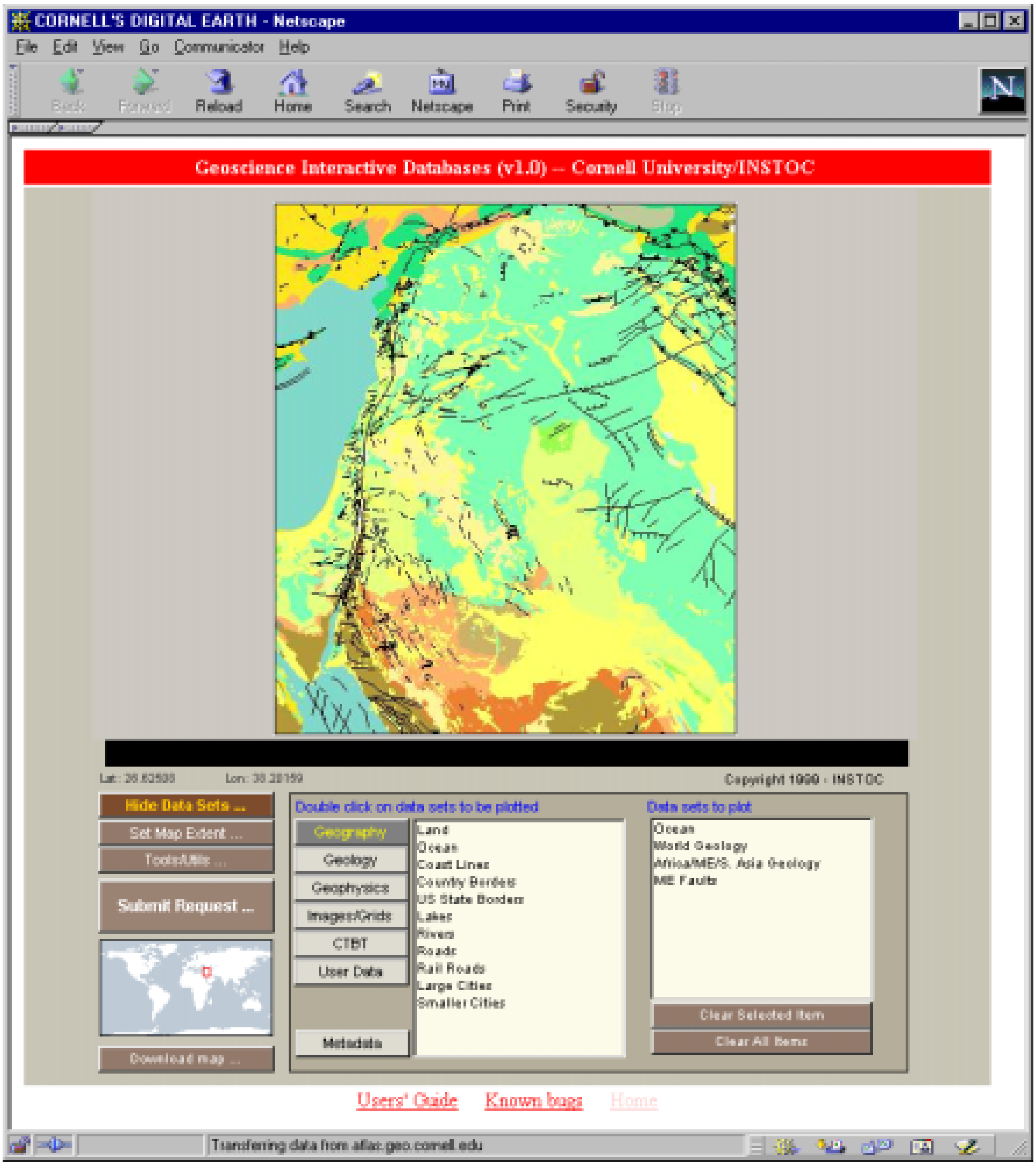


Figure 24: The web server allows interactive access to majority of data set in SEIS. Users can select any data set(s) and a region and display their selection. The web application also allows users to identify features displayed in maps and upload their own data to be plotted with existing data sets in SEIS. Selected "geology" and "ME Faults" are shown in this web page.

analysis. As our understanding of the Earth increases, it is becoming clearer that cross-disciplinary techniques must be utilized to achieve a higher level of understanding. For this it is unavoidable that similar information systems must be developed not only in the geosciences, but in other scientific fields as well. It is no longer a scientific fantasy to think about developing unified information systems that encompass the natural, physical, biological, and social sciences to better understand the workings of our home planet.

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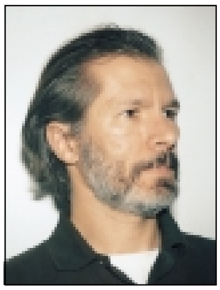

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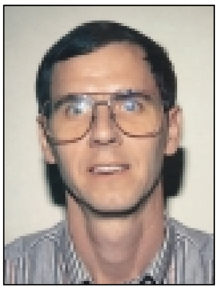

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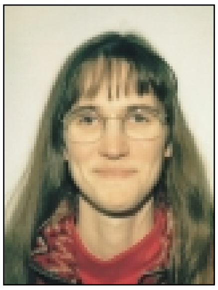

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