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A GEOLOGICAL AND GEOPHYSICAL INFORMATION SYSTEM FOR EURASIA

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Topography and heterogeneous crustal structure have major effects on the propagation of regional seismic phases. We are collecting topographical, geological, and geophysical datasets for Eurasia into an information system that can be accessed via Internet connections. Now available are digital topography, satellite imagery, and data on sedimentary basins and crustal structure thicknesses. New datasets for Eurasia include maps of depth to Moho beneath Europe and Scandinavia. We have created regularly spaced grids of the crustal thickness values from these maps that can be used to create profiles of crustal structure. These profiles can be compared by an analyst or an automatic program with the crustal seismic phases received along the propagation path to better understand and predict the path effects on phase amplitudes, a key to estimating magnitudes and yields, and for understanding variations in travel-time delays for phases such as P_n, important for improving regional event locations. The gridded data could also be used to model propagation of crustal phases in three dimensions. We encourage ARPA and Air Force researchers to contact us about gaining access to our databases at these computer mail addresses: "eric@geology.cornell.edu" -or- "fielding@seismo.css.gov".

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SUMMARY

The topography and heterogeneous crustal structure along seismic propagation paths and at the source and receiver sites are crucial information to understand the excitation and propagation of regional seismic phases (especially L_g and P_n) and other aspects of the problems of nuclear non-proliferation treaty monitoring. We collected and organized available topographical, geological, and geophysical datasets for Eurasia into a digital information system that can be accessed via network connections over the Internet. The work included assembly of available digital datasets, such as topography and satellite imagery, and digitization of available geological and geophysical information on sedimentary basins and crustal structure thicknesses. High-resolution topographic data for all of Europe, western, southern and central Asia, North Africa, and the Middle East have been processed and stored in a "semi-online" optical disk jukebox system. We cooperated with CSS researchers on the development of an X Window System-based user interface that provides effective access to these three-dimensional datasets via Internet connections.

The work has resulted in useful datasets for Eurasia, including digital geologic maps and a first-order Moho and sedimentary basin depth gridded dataset covering all of Eurasia and more detailed maps of depth to Moho beneath Europe and Scandinavia. We have created regularly spaced grids of the crustal thickness values from these maps that can be used to create profiles of crustal structure. These profiles can be compared by an analyst or an automatic program with the crustal seismic phases received along the propagation path to better understand and predict the path effects on phase amplitudes, a key to estimating magnitudes and yields, and for understanding variations in travel-time delays for phases such as P_n, important for improving regional event locations. The gridded data can also be used to model propagation of crustal phases in three dimensions. Numerous researchers have already obtained our datasets. We encourage ARPA and Air Force researchers to contact us about gaining access to our databases at these computer mail addresses: "eric@geology.cornell.edu" -or- "fielding@seismo.css.gov".

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Fielding, E. J., Isacks, B. L., Barazangi, M., and Duncan, C.C. (in press, February 1994), How flat is Tibet?, *Geology*.

INTRODUCTION

Topography and variations in crustal structure along seismic propagation paths and at the source and receiver sites are crucial information to understand the excitation and propagation of regional seismic phases and other aspects of the problems of detection, verification, and estimation of the yield of nuclear explosions. Our objective was to collect and organize available topographical, remote-sensing, geological, and geophysical datasets for Eurasia into a digital information system that can be accessed by display programs running at Internet sites, including other ARPA and Air Force researchers and the Center for Seismic Studies (CSS). We store the data in an information system (GIS) with a network-accessible server to which can connect X Window System clients of ARPA and Air Force researchers and modules of future versions of the Intelligent Monitoring System (IMS) running at CSS. The information system is organized to extract and usefully display the information most relevant to verification and detection, such as maps and profiles of crustal thickness and depth to basement. The work includes assembly of available digital datasets such as topography, satellite imagery, and crustal reflection and refraction profiles and digitization of available geological and geophysical map information on sedimentary basins and crustal thicknesses and other details of crustal structure.

DATASETS ACQUIRED

We have compiled several useful datasets for Eurasia, including a vast digital topographic database and digitization of geologic maps and several sets of crustal seismic structure maps, at scales from 1:15,000,000 for the entire continent to 1:500,000 for selected areas. These include maps of crustal thicknesses (depth to Moho) and sedimentary basin depths (depth to seismic or "metamorphic" basement). We have created regularly spaced grids of the crustal and sediment thickness values from these maps that can be used to create profiles of crustal structure. These profiles can be compared with the crustal seismic phases received along the propagation path to better understand and predict the path effects on phase amplitudes, predominant frequencies, and delay times, which are keys to estimating event magnitudes and yields. The gridded data could also be used to model propagation of crustal phases in three dimensions.

Digital Topography

We acquired an important database of digital topography for Eurasia, North Africa, and the Middle East from the U.S. Defense Mapping Agency (DMA; see Figure 1). We have processed and analyzed a huge volume, about 15 gigabytes (GB), of high-resolution Digital Terrain Elevation Data (DTED—Level 1) that we received. Coverage is complete for Europe; western, central and southern Asia; and most of the Middle East and North Africa. The basic processing of the raw DTED into an accessible format included rotating the data to have east-west

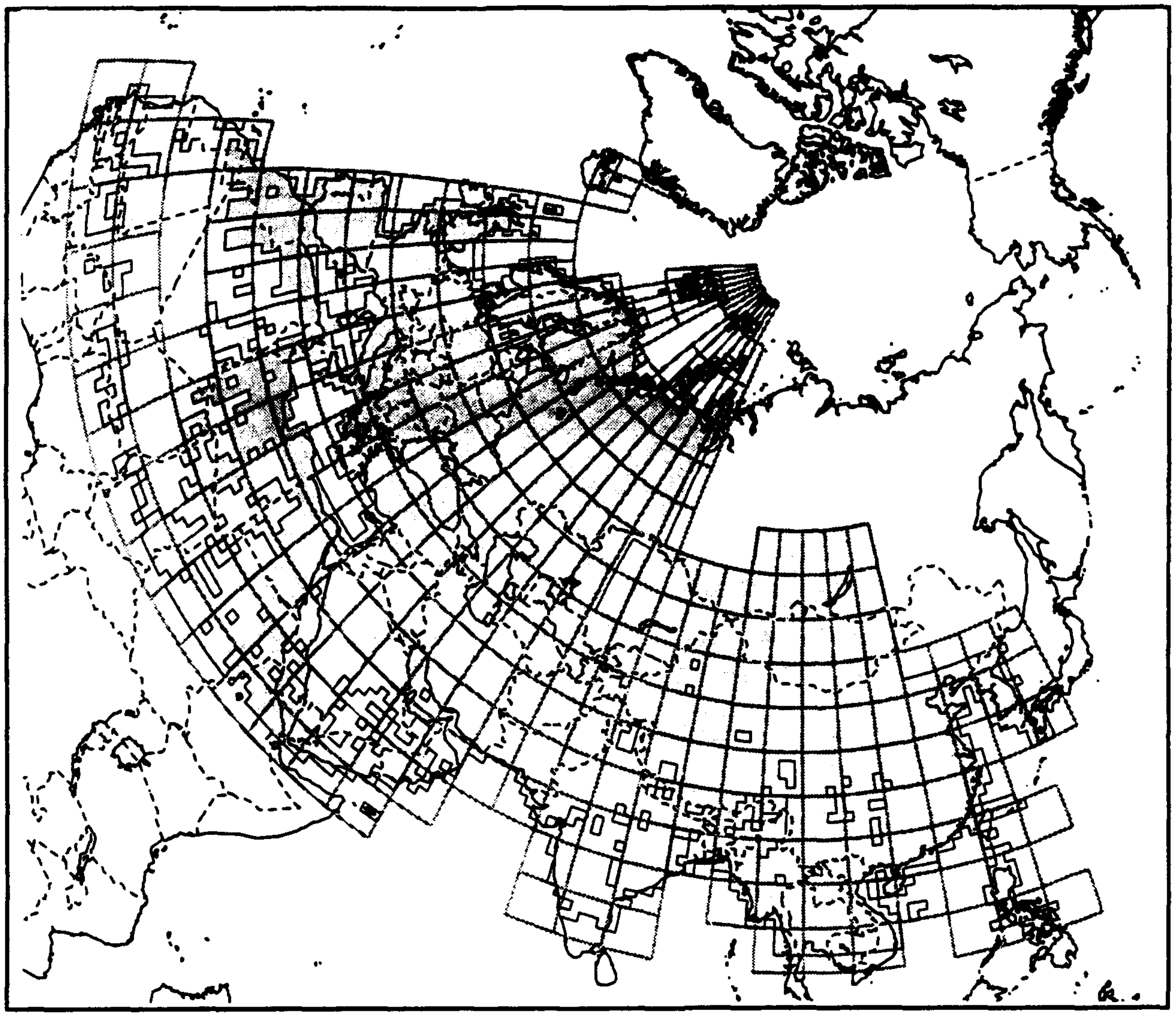


Figure 1. Map of Eurasia, the Middle East and North Africa showing area covered by our present databases of digital topography. Coastlines of oceans, seas, and major lakes are *solid lines* and country borders are *dashed lines*. Acquired and processed DTED cells are *filled light gray* and outlined with a *black line.* Unavailable cells are *irregular white holes*. Blocks 5° by 5° of DTED are outlined with *dark gray lines*. Map is an azimuthal equidistant projection centered in north central Eurasia.

scanlines (as used in most image storage systems), conversion of the unusual negative elevation notation, and the creation of mosaics of the full resolution data for blocks that are normally 5° by 5°, a file of manageable size for manipulation on a workstation and storage on optical media. In some areas, the creation of 5° x 5° blocks would result in files with a lot of "no data" pixels, so some files were created with different sizes to make a more efficient storage. The files are all clearly named by their latitude and longitude bounds. This data is "distribution limited," and only available to Department of Defense and Department of Defense contractors.

All of our topography, including both the reduced resolution mosaics and the full resolution topography blocks, and other archived datasets are being stored in our Epoch-1. The network-based Epoch file server includes an optical disk jukebox system with a library unit that contains 60 GB of "semi-online" storage and unlimited off-line storage of rewritable optical cartridges. The Epoch-1 provides unattended access, usually within less than a minute to any of the disks inside of the library unit. Our server program is able to load any part of the dataset in a short time, when the necessary optical cartridges are available in the jukebox.

We have developed, adapted, and implemented several visualization techniques to aid in the analysis of digital topography at a variety of scales. One technique that works well for black-and-white figures, such as those in this report (Figures 2–6), is shaded relief which shows the local variations in slope and gives the shape of the surface. On a color display, this shading can be combined with a pseudocolor scheme that depicts the absolute elevations to produce a very effective display. Unfortunately color figures are not possible in this report. A special anaglyph version of the shaded-relief images where two images, one with a relief displacement applied, are shown together as red and blue bands of a combined image can also be viewed in stereo on any 24-bit workstation display (such as the International Imaging Systems IVAS or 24-bit Sun and Silicon Graphics workstations at Cornell, CSS, and elsewhere) using red-and-blue glasses to better visualize the third dimension of the data.

The digital topography is stored with "georeferencing" or geographic coordinates, and can be easily projected into a map projection and overlain with other datasets, such as seismic events. Figure 2 shows the full resolution DTED for the nuclear test site at Matochkin Shar, central Novaya Zemlya, portrayed as

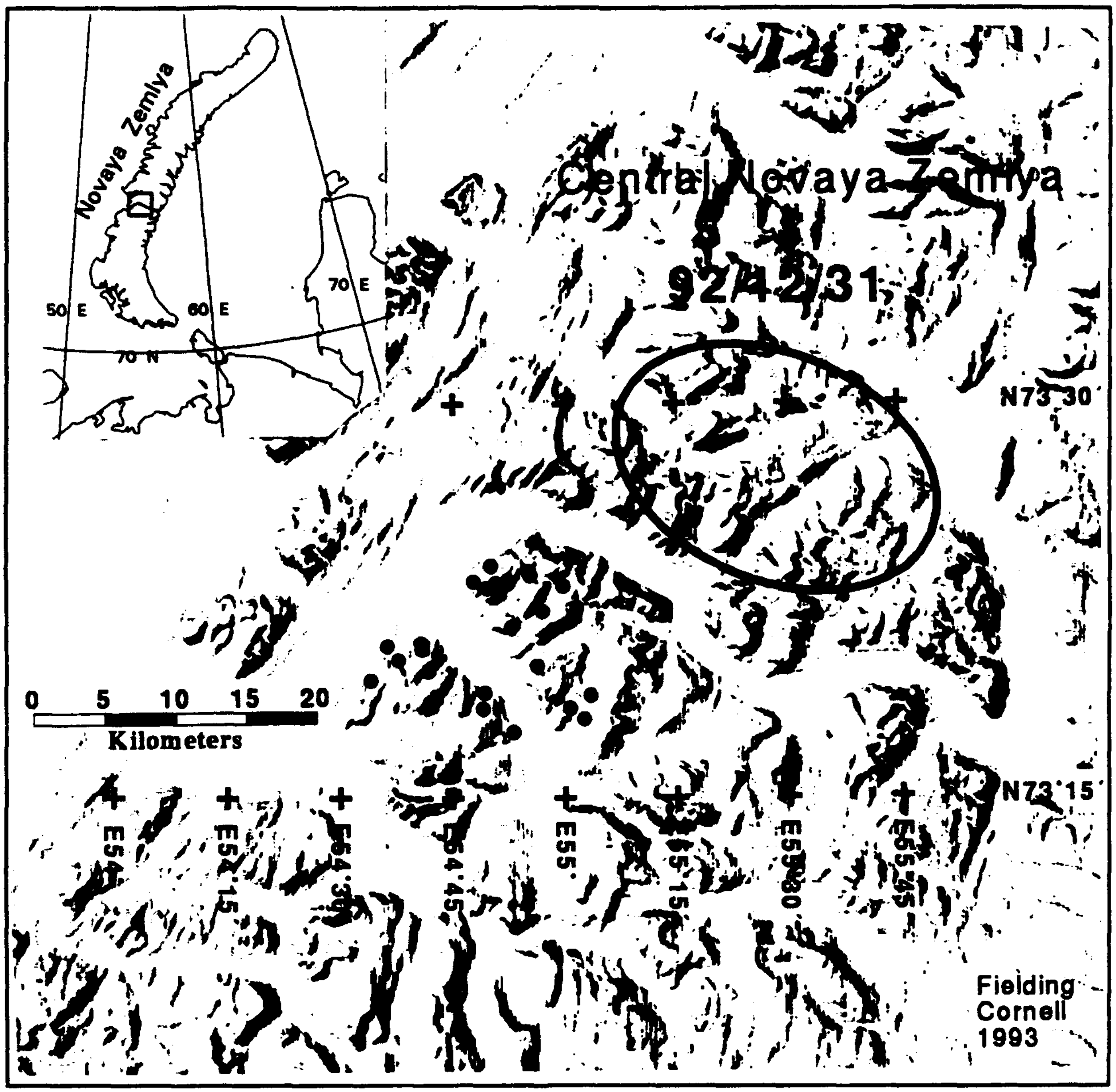


Figure 2. Shaded relief map of the central Novaya Zemlya nuclear test site showing locations of known tests and an enigmatic event on 92/12/31. Known nuclear test locations are shown as *small white circles*, and the error ellipse of the "New Year's Eve" event is shown as a *white outline*. The full resolution topography was shaded with a light from the west-northwest. *White crosses* mark 15 minute latitude and longitude tics. Water of ocean and Matochkin Shar is shown in *white*. Map is in an azimuthal equidistant projection centered on 73°N and 55°N. Inset map shows location *box* of image.

shaded relief, overlain with the locations of known nuclear tests as 250m radius circles and the 95% confidence error ellipse of an event that occurred on 92/12/31(both obtained courtesy of Dr. Hans Israelsson at CSS). The "New Year's Eve" anomalous event is clearly located across the Matochkin Shar from the test site.

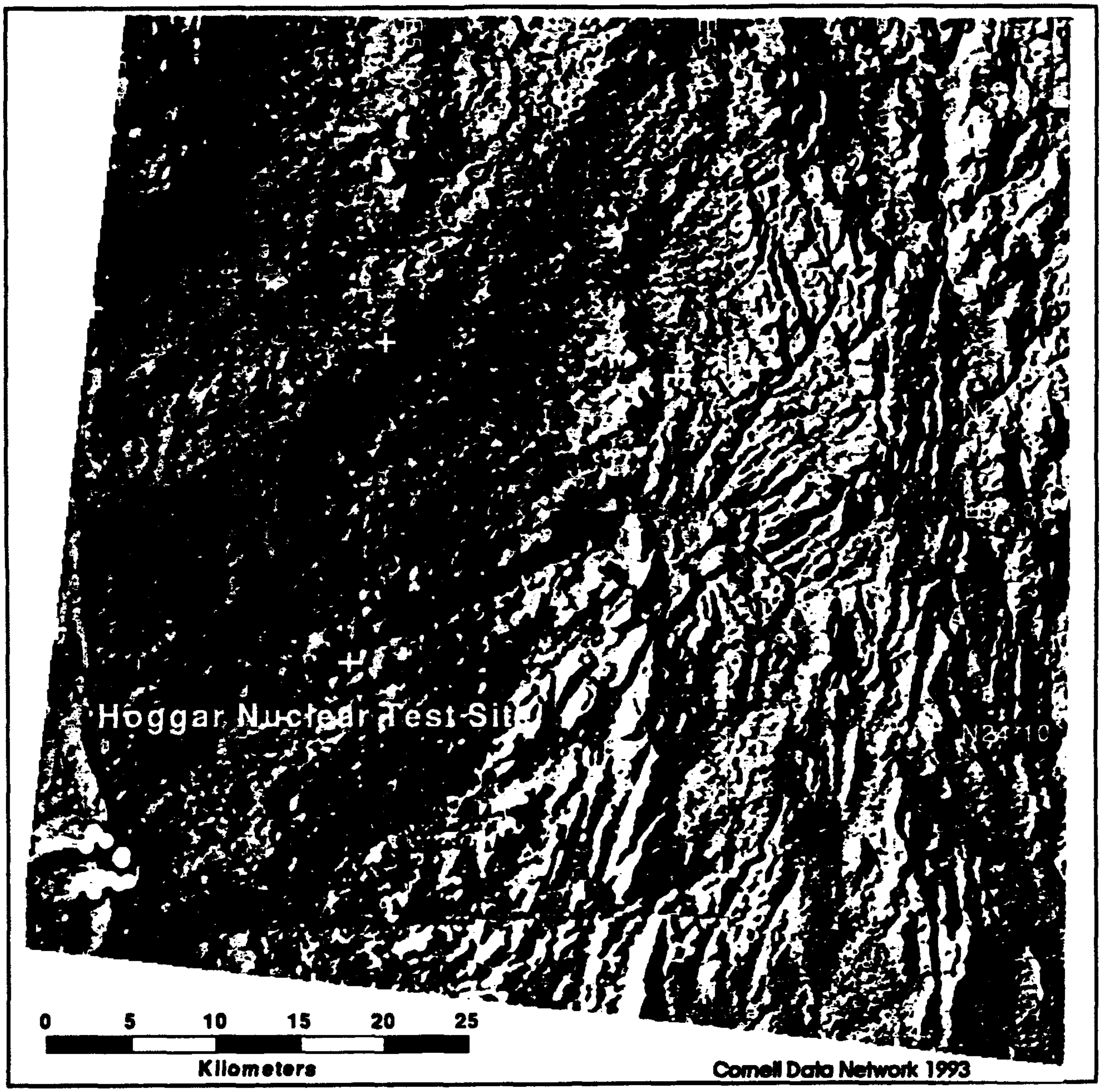


Figure 3. Grayscale shaded rendering of full resolution topography for the Hoggar site of French underground nuclear tests in Algeria. Shading is with a "light" from the upper left of the page. *Small white circles* mark locations of tests extracted from the CSS "explosion" database, and *white crosses* mark 10 arc-minute latitude (N) and longitude (E) tics. The mountain where the tests were emplaced has a maximum elevation of ~1950 m.

As an example of our new DTED from North Africa, we prepared some shaded relief figures showing the "hot-spot" volcanic complexes (Figures 3 and 4). The DTED includes coverage of the Hoggar site close to 24°N and 5°E in Algeria where French underground nuclear tests were conducted in the early 1960's (Figure 3). The explosions were apparently emplaced in a granite mountain that

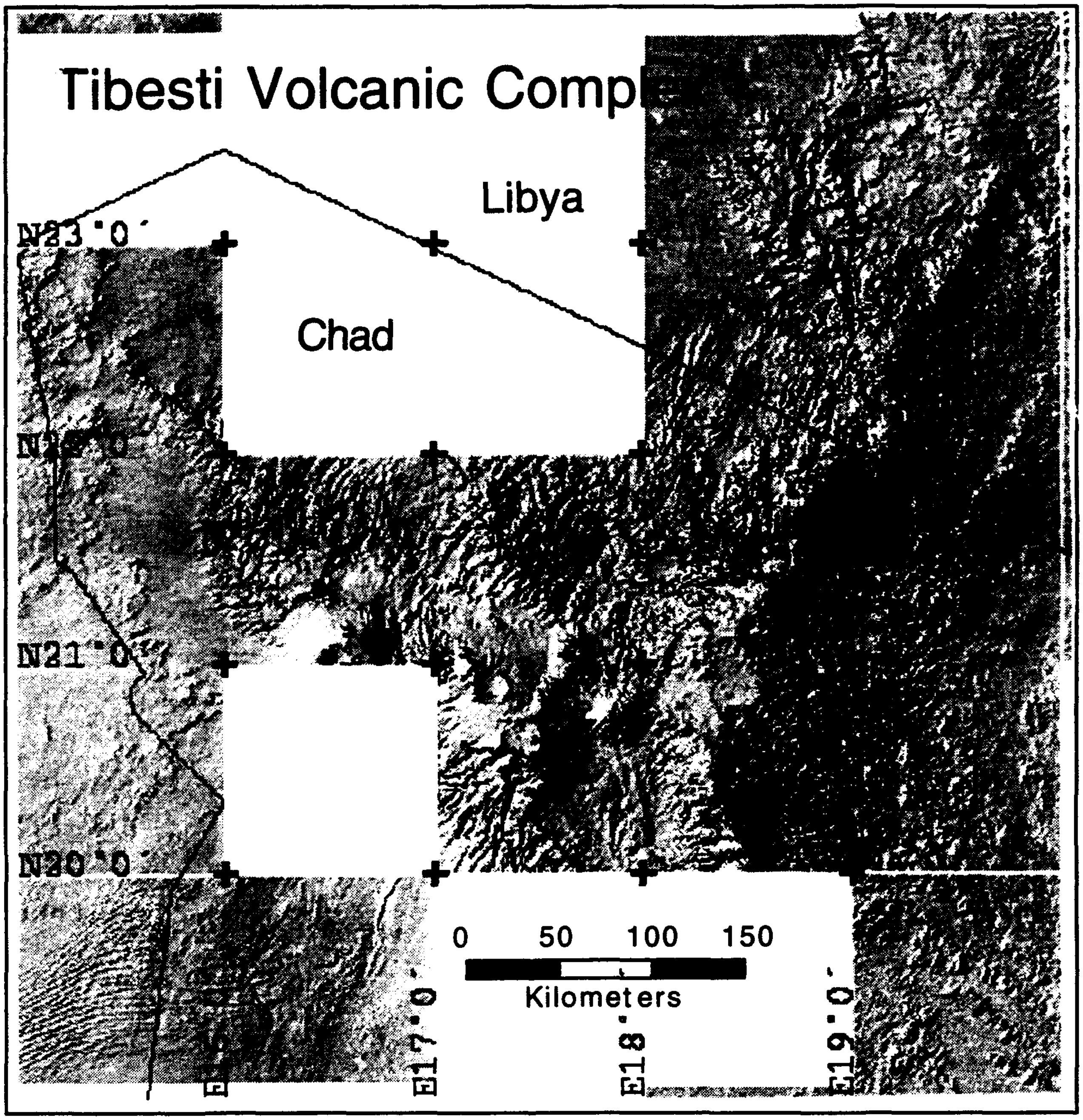


Figure 4. Grayscale shaded rendering of DTED for the Tibesti volcanic complex in Libya and Chad, which is similar to the Hoggar complex in Algeria. *White areas* are areas missing from the available DTED coverage. *Black lines* mark country boundaries, and *black crosses ticks* mark latitude and longitude degrees. The Tibesti complex has a maximum elevation over 3100 m.

is part of one of the large volcanic systems in the central Sahara, called the Hoggar.

Another volcanic complex of similar age and type is exposed to the east in Libya and Chad, called Tibesti (Figure 4). Both of these complexes of Tertiary volcanism in the middle of a Precambrian shield have been attributed to a hot spot in the mantle. The uppermost mantle beneath both of these complexes is presumably still hotter than normal for the North African shield. Some researchers have noted the anomalous nature of some of the seismic signals from the French nuclear tests beneath the Hoggar, and similar effects might be expected beneath Tibesti.

Another important technique that we have developed is combining different topographic datasets into a single merged dataset. For example, we merged the

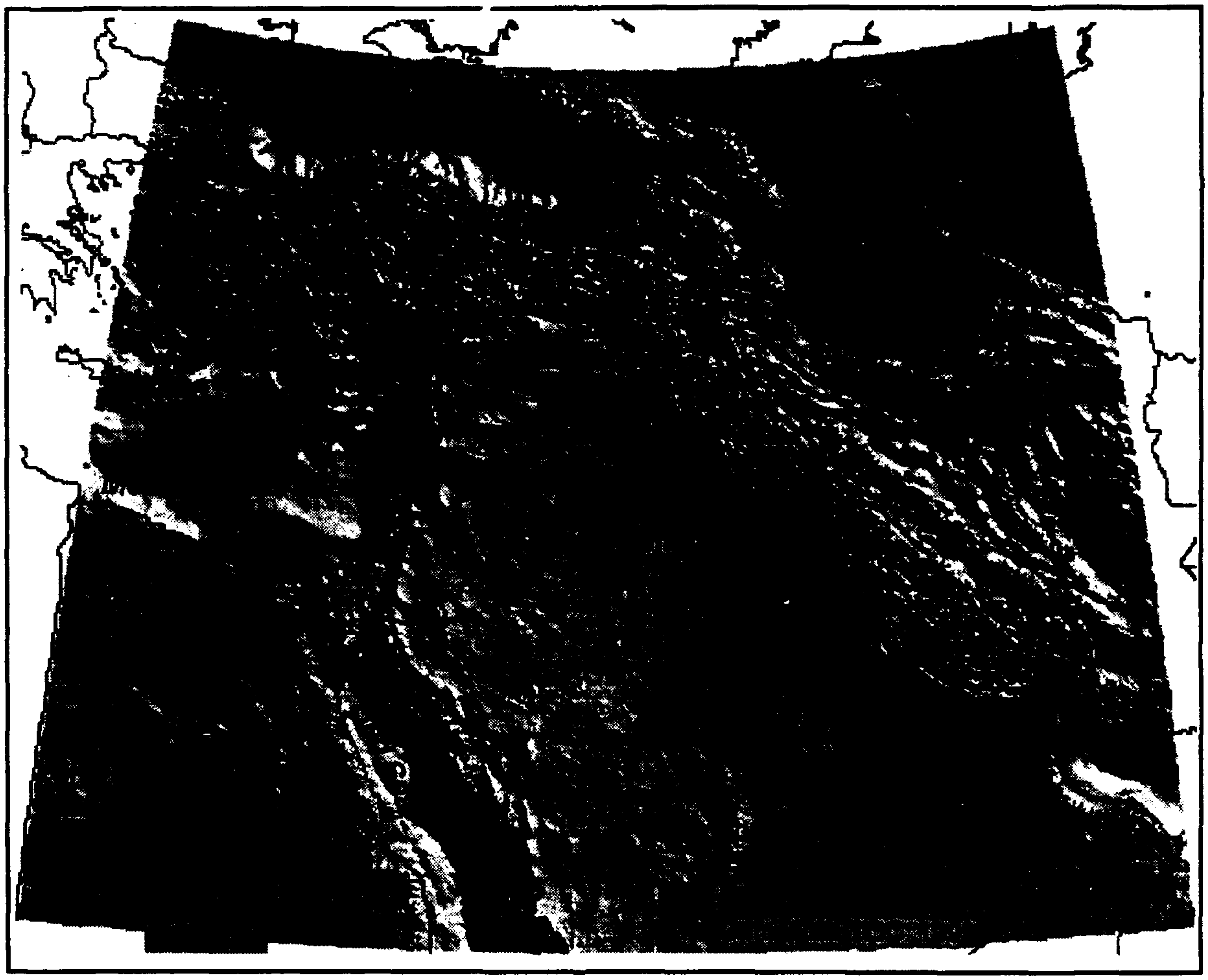


Figure 5. Shaded relief rendering of Transverse Mercator projection combined ETOPO5 and DTED dataset of topography and bathymetry for northern Middle East. *Solid lines* mark coastlines of seas, major lakes, and country borders.

much lower resolution ETOPO5 dataset with a reduced resolution DTED mosaic to produce a ~500 m resolution mosaic without holes for the Middle East (Figure 5). The ETOPO5 dataset (also called DBDB5) is a public domain topography and bathymetry database distributed by NOAA and covers the whole globe on a 5' (12 x 12 points per degree) grid. The data sources for ETOPO5 outside of North America, Europe, and Australia were on a 10' grid, so in most places the resolution is poorer than the grid spacing. Despite the lower resolution, the complete global coverage and the bathymetry of the oceans and sea provide data that is unavailable from the DMA DTED.

A preliminary 1/5 resolution (240 points per degree) mosaic of the DTED for a portion of the Middle East was combined with the ETOPO5 bathymetry for the depths of the seas and then projected into a Transverse Mercator map projection at 500 m resolution. The resulting combined dataset was then shaded with a synthetic light from the northeast to produce Figure 5. This mosaic is an accurate representation of the topography and bathymetry at the scale that can be presented in this paper (or on a color X Window System display) and shows the major topographic features of the Middle East. The shallow Persian/Arabian Gulf over part of continental crust of the Arabian Plate is clearly different from the deeper waters of the oceanic crust in the Black, Red, and Mediterranean Seas.

Figure 6 shows another combined dataset. We merged the much lower resolution ETOPO5 dataset with a Digital Chart of the World (DCW) grid and our 1/5 full resolution DTED mosaic to produce a ~500 m resolution mosaic without holes for central Asia (Figure 6). The DCW dataset is a public domain digital version of the topographic contour lines and other data from the Operational Navigation Charts (ONC) distributed by DMA and the USGS and covers the whole globe on four CDROMs. We extracted the topographic contour lines and then interpolated to create a regular grid at a 500 spacing. Since there are still a few holes in the DCW topographic contours in the Himalayas and nearby areas of Central Asia, we have used the ETOPO5 to "fill in" the remaining holes to produce a triple-merged dataset. The resulting mosaic shows some join lines where the elevations of the three datasets do not match exactly, but it provides a "best available now" approximation of the topography at this resolution. Finally the merged dataset was projected into a Lambert Conformal Conic projection. Figure 6 shows a shaded relief rendering of the merged dataset.

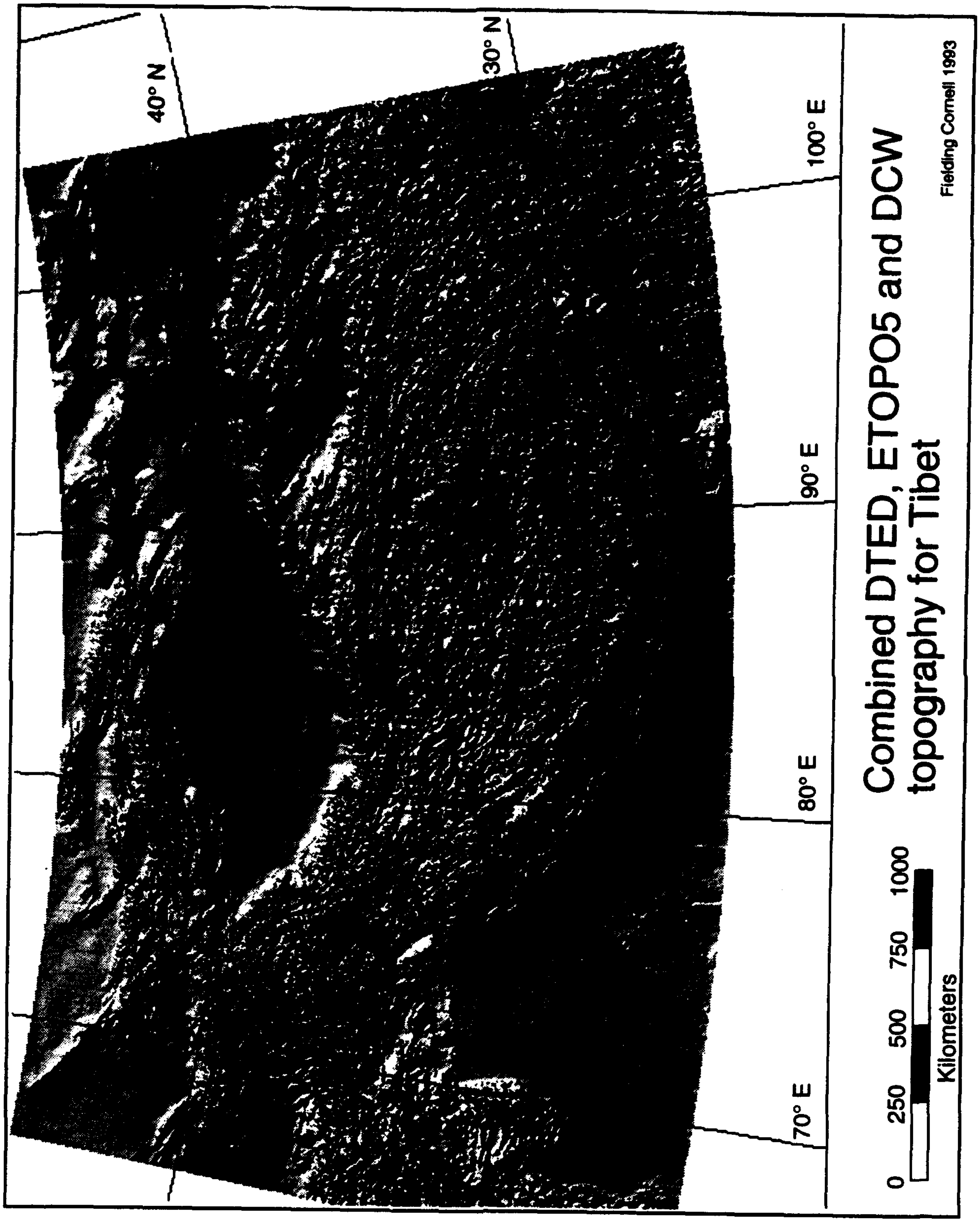


Figure 6. Shaded relief rendering of merged topography datasets for Tibet and surrounding areas. We have used DCW and ETOPO5 databases of topography to fill in the holes where high-resolution DTED is not yet available. The resulting merged dataset has an approximate resolution of 240 x 240 points per degree, and was projected into a Lambert Conformal Conic projection at ~500 m.

To enhance access to the voluminous database, we have written a subroutine library to easily read and write files in the "BIL" (Band Interleaved by Line) image format with their accompanying text georeferencing files. Building on this subroutine library, we have created a program that will "cut out" a patch of topography given the latitude-longitude limits of the area required and another that will stitch together the pieces of data if the area requested crosses one of the 5° latitude or longitude boundaries between the topography files. We have already used this system to supply areas of topographic data to ARPA and Air Force researchers at the CSS, Pacific Sierra Research, Teledyne Geotech, USGS, Lamont, University of Wisconsin, SMU, Institut de Geodynamique/CNRS and SUNY Binghamton. We have enhanced the extraction program to use averaging to reduce the resolution of a patch as it is extracted. Again, any ARPA and Air Force researchers are welcome to request patches of topographic data for their research from us. We must emphasize, however, that this topographic data, even at reduced resolution, is "distribution limited" and restricted to use for ARPA or Air Force research only. We have been requested to verify a contract or get permission of the ARPA or Air Force program manager before supplying the data. The subroutine library is also available upon request.

In addition to the mean elevations, maximum and minimum elevations have also been calculated from the full resolution data for different sized moving windows. The calculations maintain the full range (maximums and minimums) of values in the original data but result in a more manageable dataset that can be easily stored on-line and manipulated for the whole area of coverage, *e.g.*, to generate topographic profiles along great-circle paths (Figure 7). These derived datasets can be used for the interpretation of surface roughness on a variety of scales for comparison to the propagation paths of Lg and other regional phases.

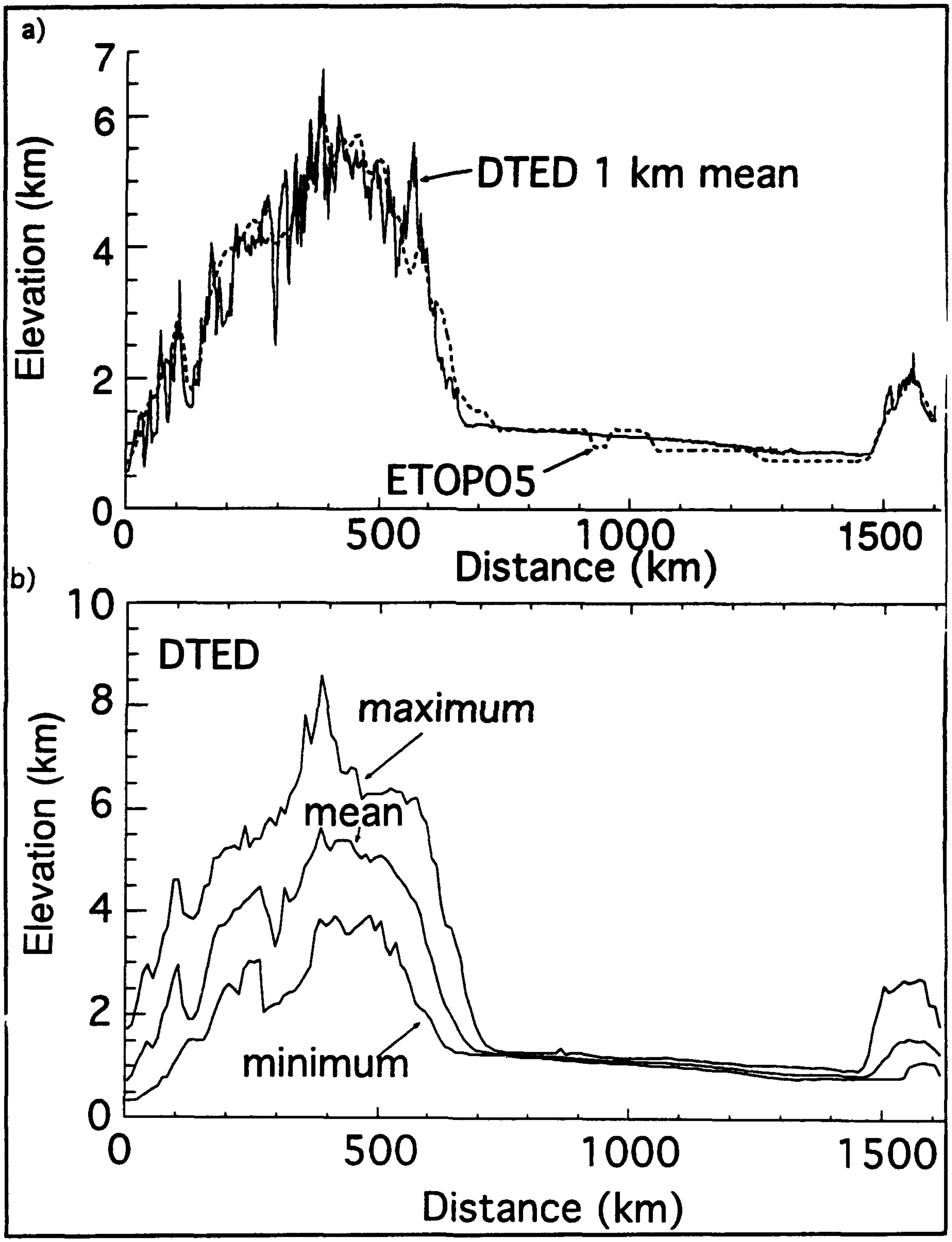


Figure 7. Comparison between low-resolution ETOPO5 topography and medium-resolution (~1 km) mosaic from DTED along the same great circle path between station NIL in Pakistan and the Chinese test site at Lop Nor that is shown in Figure 13. a) single profile lines of 1 km DTED and ETOPO5. b) Maximum, minimum, and mean elevations from DTED within a 100 km wide swath centered on the great circle path showing local variation in topography portrayed by 1 km resolution mosaic.

Satellite Imagery

We have created stereoscopic images from the limited number of stereopairs panchromatic SPOT imagery that were acquired for several key sites in Central Asia, including the Garm IRIS/IDA station, and South America and also processed a Landsat Thematic Mapper (TM) image for the Kazakhstan test site to analyze the utility of these SPOT and TM images for the interpretation of topographic and geologic features and for the identification of active mines and related activities. Digital topography and satellite imagery are the main types of "raster" or gridded data input for our GIS. Some of our raster data processing at Cornell has been done with routines from a commercial image processing packages, the IIS System 600, that was in use at CSS, while some processing has been strengthened by the development of special programs running on our Sun workstations. We purchased an advanced image processing system that runs on Sun workstations with a very effective graphical user interface, called ER Mapper from Earth Resource Mapping. This system can access our "BIL" format files directly without conversion, and our subroutine library writes out the necessary "header" files to provide ER Mapper with georeferencing information.

The high-resolution topographic information of stereo SPOT scenes can be used to determine the relief of features that are too small to detect on the DTED data. The 10-m resolution of the panchromatic SPOT imagery also allows the detection of fairly small man-made disruptions of the surface, such as the building of roads or digging of quarries or mines. Unfortunately, the SPOT Image Corp. has a very restrictive copyright which makes it very difficult to share the data with other researchers.

Crustal Structure

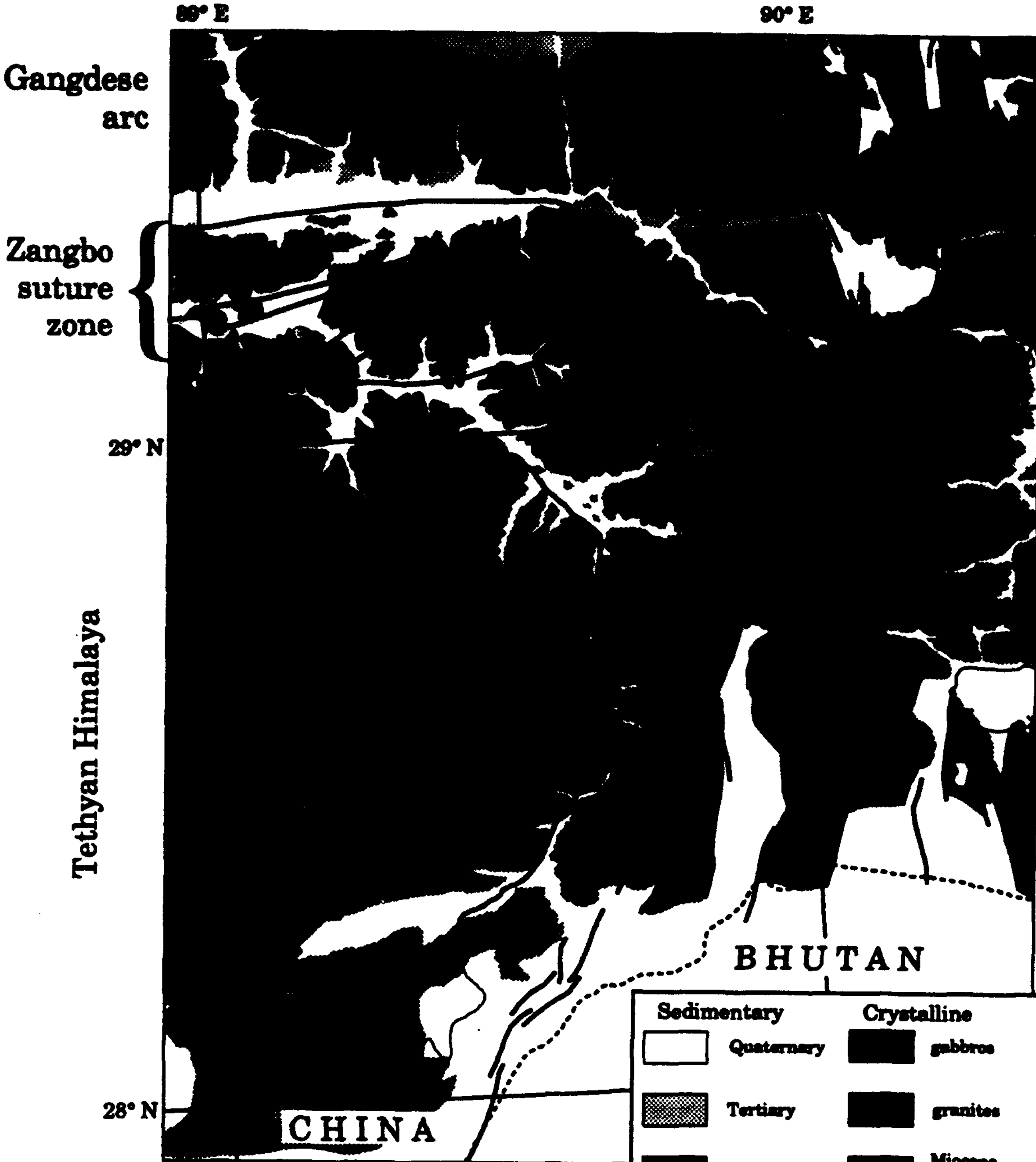
To organize other types of geologic and geophysical data that consist of points, lines, or polygons (such as earthquake catalogs, fault locations, and geologic maps, respectively) we adapted one of the leading commercial geographic information systems (GIS) called Arc/Info from ESRI (Environmental Systems Research Institute). Programs have been written to convert existing earthquake catalogs, such as the one available from the ISC, into Arc/Info format with all of their associated attributes, including the location, depth, origin time, number of stations, and body wave and surface wave magnitudes. Another database that we have incorporated into Arc/Info is the USGS table of locations, names, elevations of seismic stations around the world. We have developed a set of "macros" in the Arc Macro Language (AML) to aid in the digitization of maps and in the production of output maps.

Geological datasets

We expanded our Arc/Info database by the digitizing of geologic, tectonic, and geophysical maps for Eurasia. The data are organized into a hierarchical database of information from different resolution sources. In addition, "metadata" was collected about existing maps to create a database about what areas each map covers and where the hardcopy map is located.

We have digitized some of the available geophysical, geologic and tectonic maps for Eurasia. The polygons that enclose geologic units are not straightforward to digitize, so considerable effort has gone into defining a methodology for doing the work. An example of a digitized geologic map is shown in Figure 8. The Arc/Info system provides a powerful "toolbox" for selecting and combining the various types of data and overlaying them on top of raster imagery. One can easily select features, such as geologic polygons, by their assigned attributes, such as rock type or age.

One of the a geologic maps that we digitized covers one of the major crustal boundaries of Central Asia, the Indus-Zangbo suture zone between the Indian and Tibetan plates in southern Tibet. This is a relatively detailed geologic map, published by J. P. Burg in 1977, that we can combine with the digital topography that we have for the area. We digitized both the geologic units and faults from the 1:500,000 scale map (Figure 8). Polygons are assigned a code value within Arc/Info via their labels that encodes information on the interpreted age and type of rock for the unit. The faults similarly have attributes indicating the fault type (e.g., normal) and interpreted age (e.g., Neogene). These attributes allow one to select rock geologic units or faults of a certain age and then color or otherwise mark the different units on a workstation display or on a hardcopy map. Both Arc/Info and ER Mapper can display these geologic vector dataset overlain on raster images including topography, satellite imagery or the geophysical datasets described below.



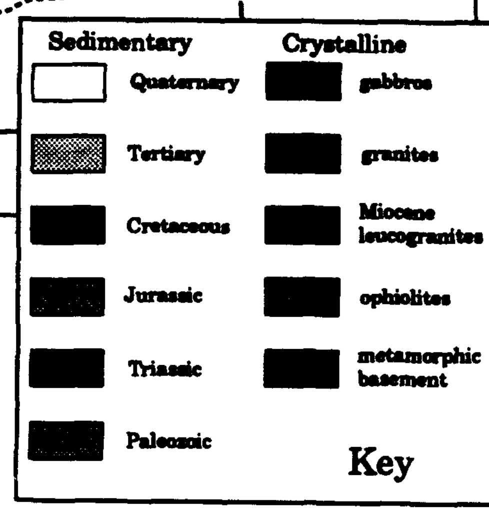


Figure 8. Example of a digital geologic dataset showing a portion of a geologic map of the Indus-Zangbo suture zone between Indian and Tibetan lithosphere in southern Tibet. Unfortunately, color is not possible here to fully portray units. Digitized from J. P. Burg's map of southern Tibet (1977). See box on Figure 13 for location.

Geophysical datasets

We began our digitization of lithospheric structure with a set of crustal seismic structure maps of Eurasia. These include 1:15,000,000 maps of depth to Moho and depth to seismic (metamorphic) basement (Kunin and others, 1987). Using the attributes capability of Arc/Info, we recorded which contours are dashed (inferred or interpolated) and which are solid. We also digitized other information about the data reliability from the maps such as the locations of the seismic refraction and reflection lines used, if they are recorded. Arc/Info was used to edit the resulting databases and project the unusual projection data into latitude-longitude coordinates. Some maps have "faults" or discontinuities in the Moho, and these were digitized as well. We then created regularly spaced grids of the crustal and sediment thickness values from each of these digitized maps, including the offsets of "faults". An example of a portion of the gridded basement depth dataset is shown in Figure 9. This is only a part of the full dataset.

We have evaluated of the accuracy of the databases derived from the IPE maps. We also investigated ways of updating the databases with new information while maintaining a database of what data comes from what source. We consulted with ARPA researchers at SAIC in San Diego about the accuracy of these maps, especially in Europe. There may be a bias in the depth of the Moho beneath Italy, where Prodehl (1984) and Meissner (1987) show somewhat different values (that were probably unavailable to the IPE group when they made their map), but the overall shape of the Moho seems to be substantially correct. The locations of features are probably not exact due to the small scale and strange projection of the map. We also found that some improvements can be made in the interpolation of the values from the contour lines, using the new functions in the latest versions (6.0 and higher) of Arc/Info. We are also searching for digitizable versions of the data published by Meissner (1987), to improve the database for Europe.

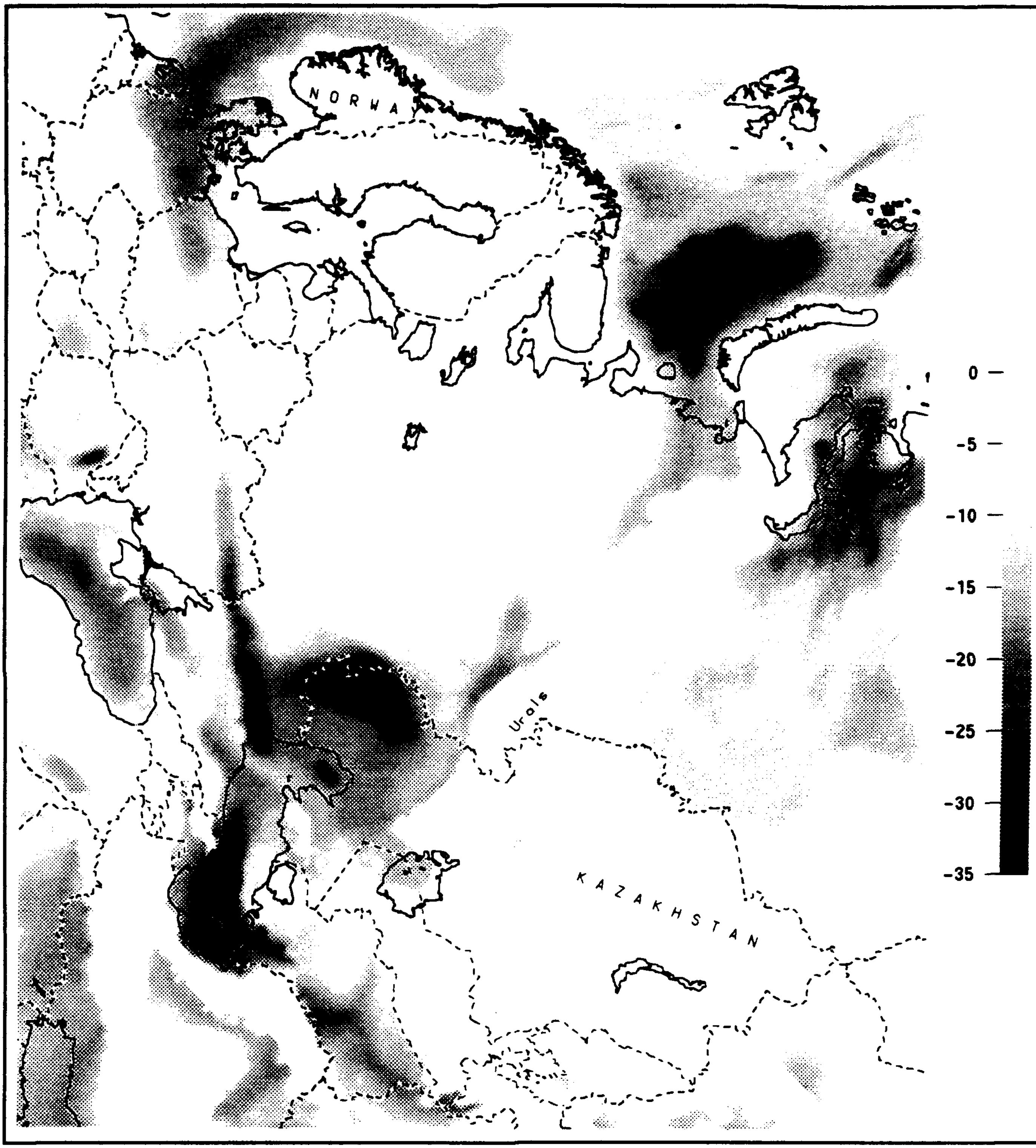


Figure 9. Map of a portion of the gridded database of depth to "seismic basement" showing eastern Europe, northern Middle East and west central Asia. Dataset was digitized for all of Eurasia, the Middle East and North Africa from a map by IPE, Moscow. *White areas* are areas of basement at the surface on the map. *Gray scale* shows depth in km. This gridded dataset, along with similar dataset of depth to Moho can be used for three-dimensional modeling of crustal phase propagation. *Solid black lines* mark coastlines and major lakes. *Dashed lines* mark country boundaries and former USSR republic borders. Map projection is the same as in Figure 1.

The IPE maps provide a first-order database of crustal structure for all of Eurasia at a moderate resolution, but the data may not be correct in detail for every area. To improve our datasets, we have digitized more detailed maps of crustal structure that are available in some areas, beginning in Europe, where the most detail is available. We digitized a much more detailed map of Moho and sedimentary basin depths for Hungary, Austria and Czechoslovakia. These maps at 1:1,000,000 and 1:500,000 scale, respectively, provide great detail on the regional crustal structure of the very deep Carapathian sedimentary basin area.

A map of a new gridded dataset of depths to Moho for the Baltic area is shown in Figure 10. This map is the result of a collaboration with Dr. Vlad

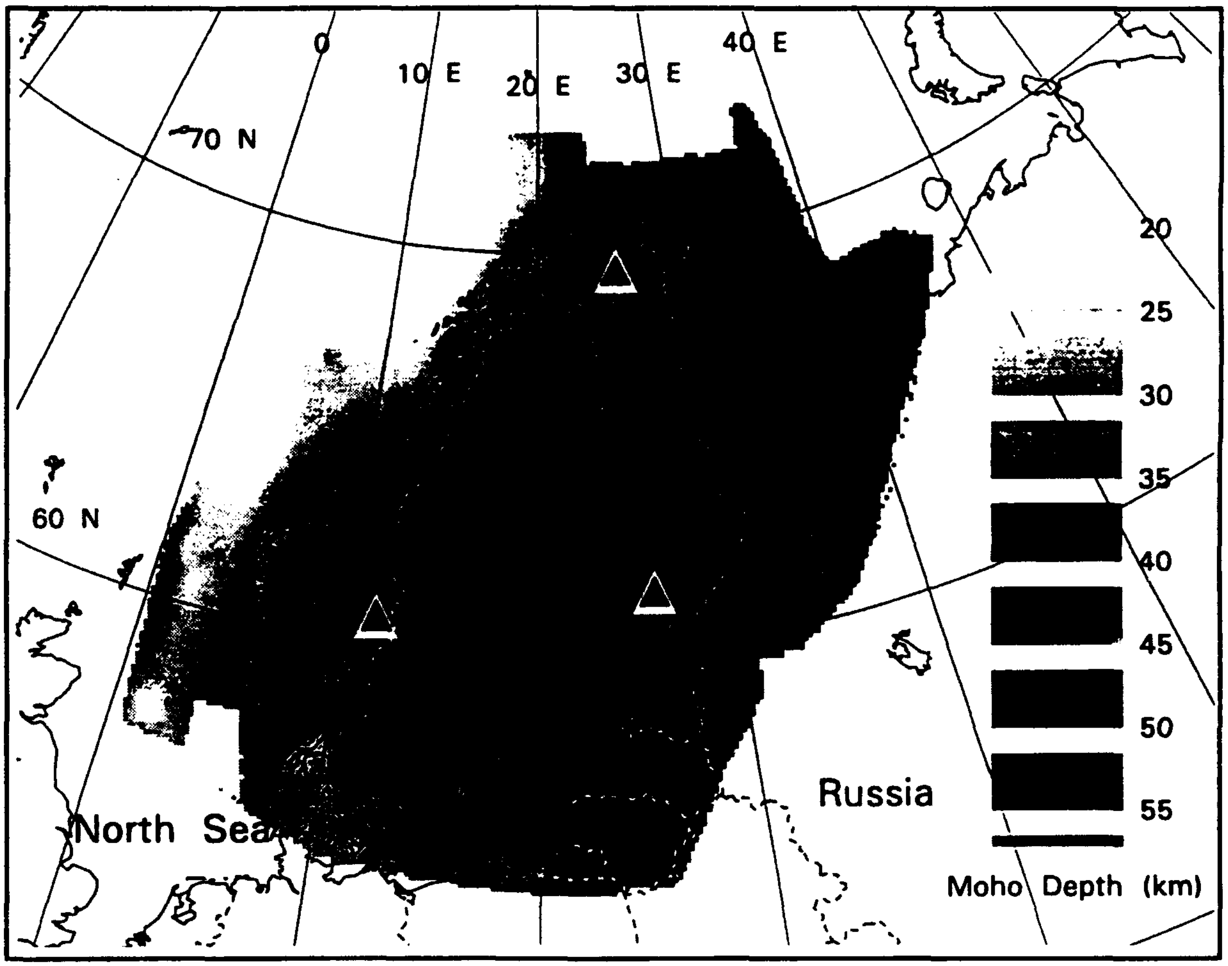


Figure 10. Map of the gridded database of depth to Moho beneath Baltic area. Dataset was digitized from a combination of maps (see text). *Gray scale* shows depth in km. This gridded dataset, along with similar datasets of depth of sedimentary section can be used for two- and three-dimensional modeling of crustal phase propagation and P_n travel time delays. *Solid black lines* mark coastlines and major lakes. *Dashed lines* mark country boundaries. Locations of NORESS, ARCESS, and FINESA arrays are marked by *black triangles with white borders*. Map projection is Lambert Conformal Conic.

Ryaboy at CSS. We digitized two previously published Moho maps of area around the Baltic (Kinck and others, 1992; Sharov, 1991) and then plotted them at the same scale and map projection. Vlad then used these two maps and other information (Ryaboy, 1990; BABEL, 1993) to produce a new combined map that we digitized and converted into a gridded database. These gridded data can then be used to calculate grids of source-specific station corrections for P_n travel times using an empirical equation relating travel-time delays to the depth to Moho beneath the source (at each point of the grid) and the receiver (each of the three arrays NORESS, ARCESS, and FINESA) as described by Suteau-Henson and others (1993, this volume). The locations of the arrays are marked. These kinds of travel-time corrections may greatly improve the locations of regional events. This and all of our completed crustal structure datasets are available over the network from our raster server and via ftp.

Another map of depth to Moho has been recently published as part of the European GeoTraverse (EGT; Giese and Buness, 1992). We have completed the digitization of this map which runs from the Arctic Ocean across central Europe to Tunisia, shown in Figure 11. The map includes several "faults" or discontinuities in the Moho, in the Alps and Apennines of Italy, where the Moho changes depth by up to 20 km over distances of a few dozen km horizontally, marked on the map. Several of these faults can be also seen as sharp changes in depth of the Moho in the cross-section of Figure 12 below. The gridded version of this dataset has a point spacing of about 10 km.

Crustal Profiles

The gridded datasets of depth to Moho, depth to seismic basement, and topographic elevation described above can be used to construct crustal profiles, which usually done along a great circle path corresponding to the propagation path of a seismic phase. These profiles can be compared to anomalous phase amplitudes for sources and receivers located along the section to see whether the crustal structure may explain propagation variations. We have written software to extract swath profiles along great circle paths through gridded datasets, as shown in Figure 7 with a topographic swath. A swath profile projects data within a given distance of the central great circle path into the section and finds the amount of variation as represented by the maximum, minimum and mean elevations (or depths) of the surfaces. In the case of the depths to Moho and seismic basement, the datasets are much smoother since the resolution of the data is much lower, so swath profiles are less useful.

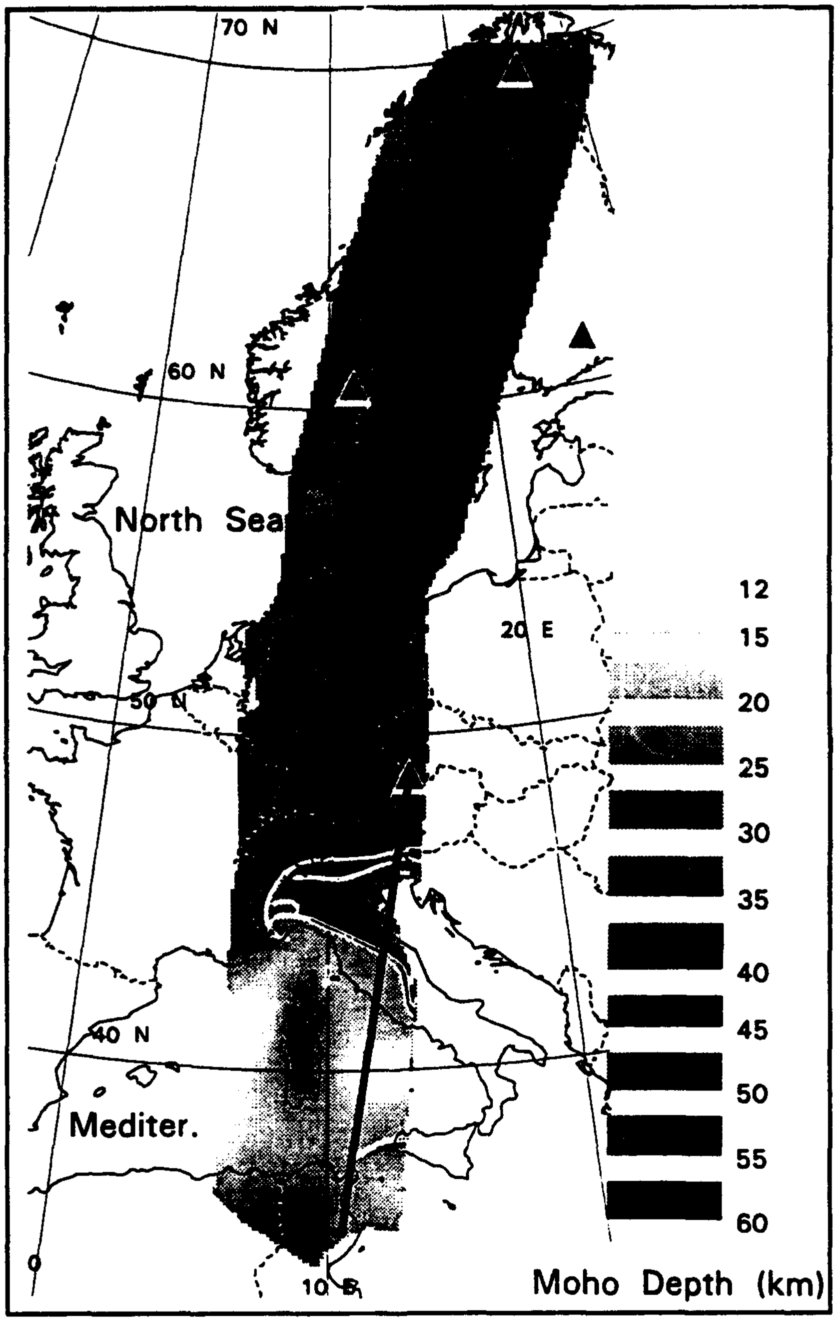


Figure 11. Map of depth to Moho from European Geotraverse. *Gray scale* shows depth in km. This gridded dataset, along with similar datasets of depth of sedimentary section can be used for two- and three-dimensional modeling of crustal phase (L_g) propagation and P_n travel time delays. *Solid black lines* mark coastlines and major lakes. *Dashed lines* mark country boundaries. *White lines* mark "faults" in Moho. Locations of NORESS, ARCESS, GERESS, and FINESA are marked by *black triangles with white borders*. *Thick black line* shows location of profile of Figure 12. Map projection is Lambert conformal conic centered in central Europe.

We present in Figure 12 a simple profile through the EGT Moho database. This was extracted from the 10 km gridded dataset by interpolating depth of the Moho every 10 km along a great circle path from the GERESS array to the south along the line marked on Figure 11, using the Arc/Info software which allows the extraction of profiles along arbitrary lines. The very deep Moho roots of the Alps and Apennines are each bounded on the south by sharp discontinuities. The shallow Moho of the probably oceanic crust between Italy and Tunisia is also shown. These large variations in crustal thickness have major effects on the propagation of crustal phases (L_g appears to be blocked by the Alps and Apennines according to Harjes and others, 1992) and should also affect the delay times of other phases passing through the crust.

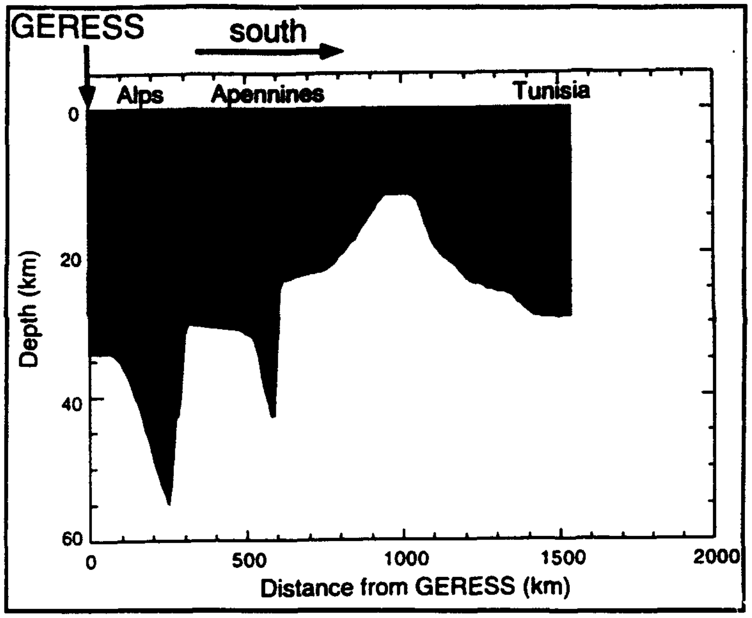


Figure 12. Profile of Moho database along great circle path from GERESS towards the south. Note the extreme variations in crustal thickness that will affect the propagation of crustal phases, such as L_g. No L_g is observed for events more than 500 km from the GERESS array in this direction (Harjes and others, 1992). Location of profile shown on Figure 11.

To get the full crustal structure, one can combine sections of more than one dataset along the same profile. The two depth datasets of Moho and depth to seismic basement were combined with our topographic dataset to produce Figure 13 which shows the crustal structure along a great circle path from station NIL in Pakistan and the Chinese nuclear test site at Lop Nor. This type of profile of crustal structure can be compared by an analyst or an automatic program with the crustal seismic phases received along the propagation path to better understand and predict the path effects on phase amplitudes, a key to estimating magnitudes and yields. The high and rough topography of the Karakoram (see Figure 7) in the middle of this path with its deep (roughly 70 km) crustal root appear to block the propagation of L_g in this direction.

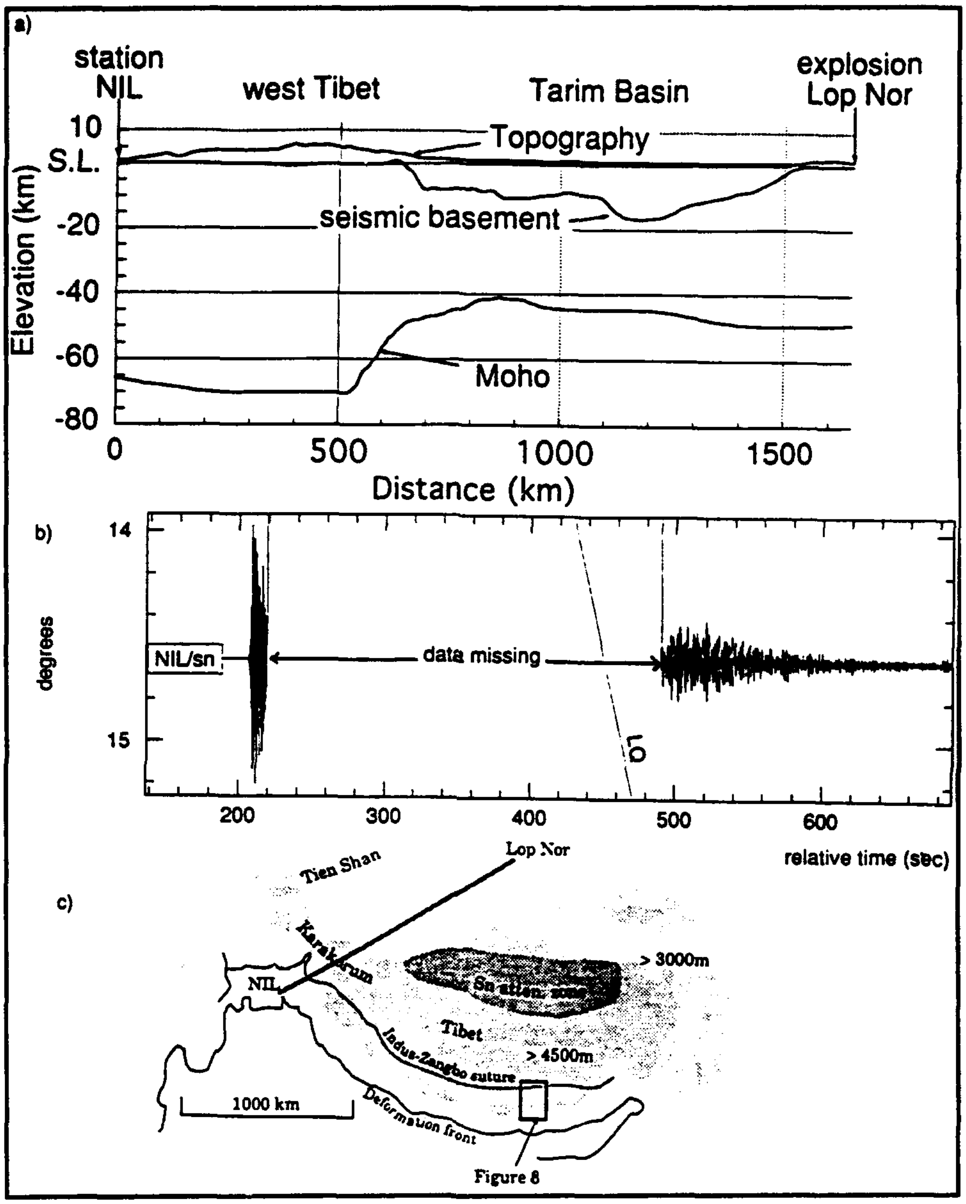


Figure 13. a) Profiles of topography, basement depth, and Moho databases along great circle path from station NIL in Pakistan to the Chinese nuclear test site at Lop Nor. Note the extreme variations in topography and crustal thickness that will affect the propagation of L_g. b) Seismic recording stored at CSS of large Chinese nuclear explosion on May 21, 1992 from station NIL, shown for reference only, as there was an unfortunate interruption of the recording for five minutes including the expected arrival time of the L_g phase. Seismogram was plotted using the IMS program Geotool. c) Map showing great circle path *(thick curve)* and location of geologic map of Figure 8 *(black outline box)* with geographic and major tectonic features.

The two crustal datasets and topographic dataset were also used to produce Figure 14 which shows the crustal structure along great circle paths from the GERESS array of Germany in the four cardinal directions (North, East, South

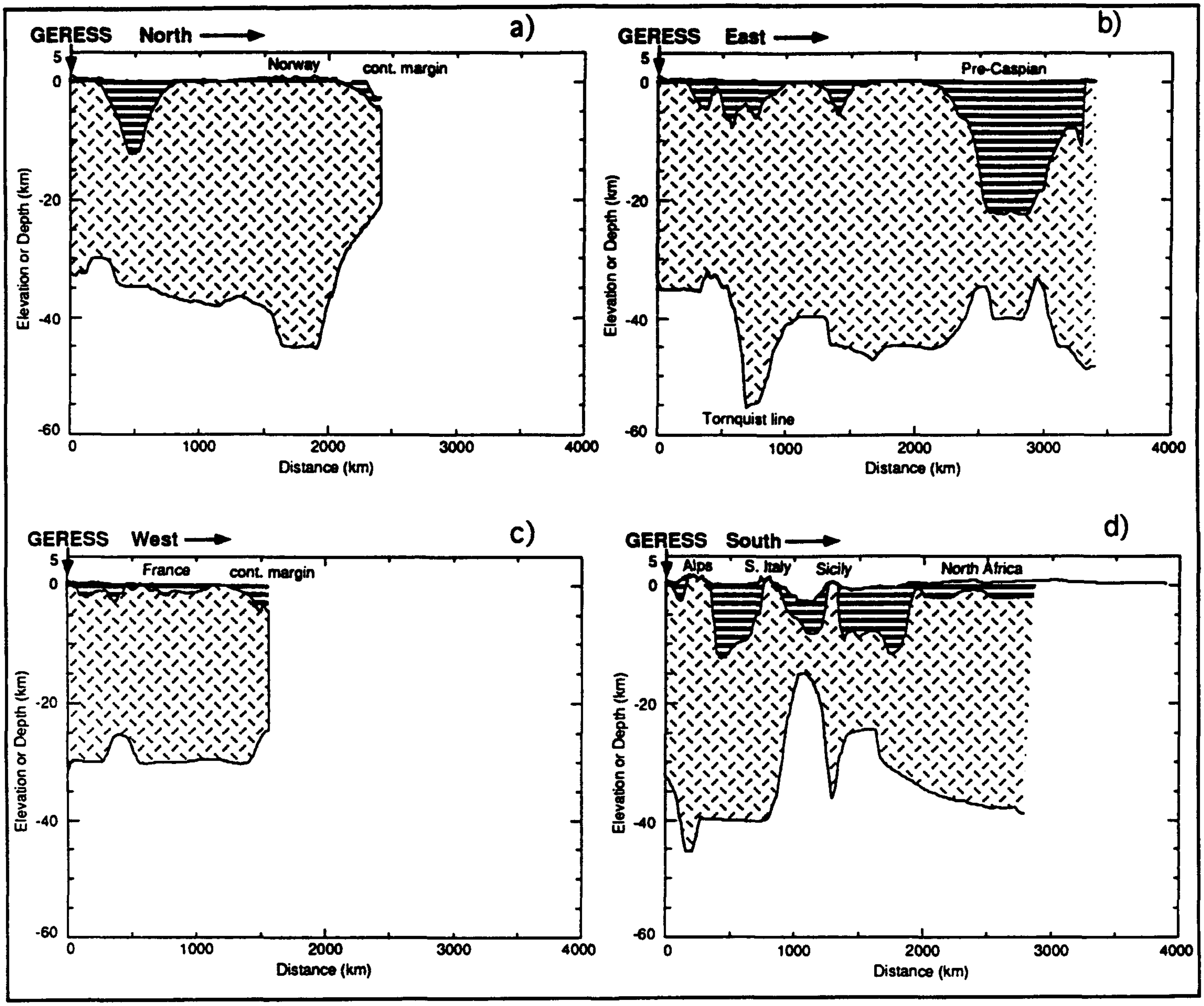


Figure 14. Profiles of topography, basement depth, and Moho databases along great circle paths from GERESS array in Germany in the four cardinal directions (see map in Fig. 15 for locations of profiles). All profiles are plotted at the same scale with a high degree of vertical exaggeration. For clarity in these reduced size figures, the interpreted sedimentary basins between the topographic surface and the "seismic basement" are *filled with a horizontal line pattern*, and the crystalline crust down to the Moho is *filled with a tick pattern*. Note the significant variations in topography, sedimentary basins and crustal thickness that may affect the propagation of crustal phases, such as L_g. a) Profile to the north from GERESS. b) Profile to the east from GERESS. c) Profile to the west from GERESS. d) Profile to the south from GERESS. These profiles are an example of the information that can be extracted from our network-accessible databases.

and West; see Figure 15 for locations). While we are not confident in every detail of these databases in Europe (as described above), the profiles give a provocative initial look at the crustal structure of Europe. Harjes and others (1992a, 1992b) have described a lack of significant L_g energy at the GERESS array from distances greater than 500 km for propagation paths in most directions.

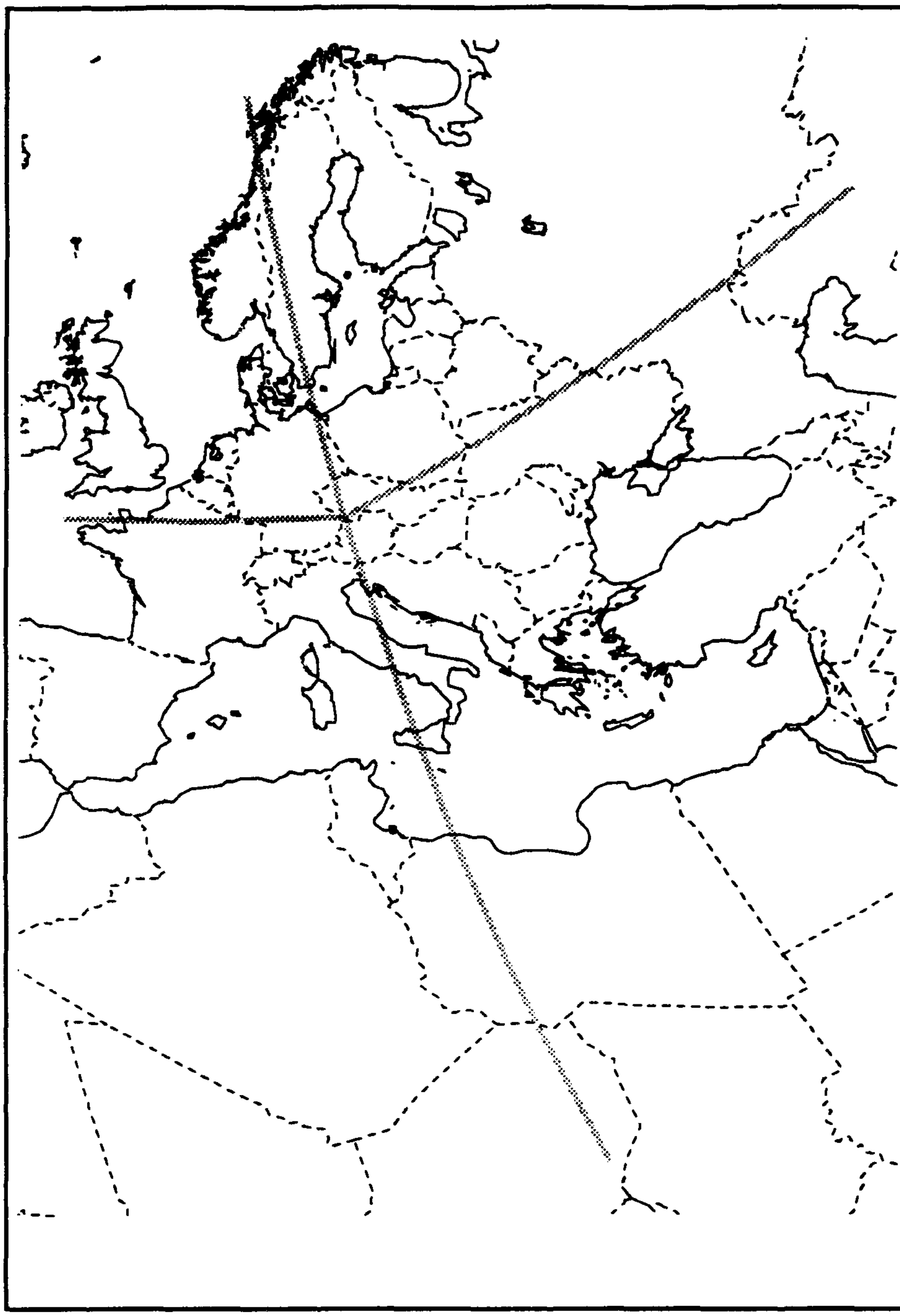


Figure 15. Map of Europe showing locations of profiles shown in Figure 14. Great circle paths of profiles are *gray lines*. Coastlines of oceans, seas, and major lakes are *solid lines* and country borders are *dashed lines*. Map is in the same azimuthal equidistant projection as Figure 1.

It can be seen in Figure 14 that there are significant changes in sedimentary basin depths and/or Moho depths at distances of about 500 km to the north, east, and south from GERESS. There a smaller contrast in crustal structure to the west where Gestermann in Harjes and others (1992a) reports more efficient L_g. The blockage of L_g is especially strong to the east and northeast due to the sharp change in Moho depth along the Teisseyre-Tornquist line (Gestermann and others, 1991; Harjes and others, 1992a) where Meissner and others (1987) report Moho depths reaching 60 km (see also Figure 15b). The deep Moho root of the Alps (Figure 15d) may also explain an azimuthal bias or secondary arrivals and other anomalies of events in the eastern Mediterranean received at GERESS (Jenkins and others, 1992; Harjes and others, 1992a).

A comparison between the first-order IPE and the higher resolution, more accurate EGT databases can be made between Figure 14 and Figure 12, which shows the depth to Moho profile from the GERESS array towards the south. This type of profile of crustal structure can be compared by an analyst or an automatic program with the crustal seismic phases received along the propagation path to better understand and predict the path effects. The Xgbm (v. 1.1) program can connect to our raster database server over the network, extract the depths of the Moho and seismic basement along a great circle, and then use this type of profile as the basis for ray tracing of seismic phases and gaussian beam approximation of the seismic waveforms (Davis and Henson, 1992; 1993).

NETWORK DATA SERVER

We are utilizing the rapidly accelerating Internet (formerly ARPAnet) network to share datasets with CSS and other ARPA researchers. We developed a "server" system at Cornell to allow "client" modules of the IMS to directly connect to databases that we are generating and improving. This allows IMS users to utilize data as soon as it is available. Our network "raster server" program that allows "client" programs, such as the "Xgbm" program (Davis and Henson, 1992; 1993) to access our crustal structure datasets over the Internet, extracting a profile along a great circle path and then using the structure for seismic propagation modeling. In addition to the raster-server access, we are also making our databases available via the simple, but standard, anonymous FTP server on our machine "hugo.geo.cornell.edu". Several seismic researchers have obtained copies of our crustal structure databases (as described above), and several new requests for data have been received recently. We encourage researchers to contact us about gaining access to our databases at the computer mail addresses listed in the beginning of this report. Due to data access restrictions imposed by the DMA, we are not able to provide network access to our digital topography databases, but we encourage ARPA and Air Force researchers to contact us about access to processed versions of the topography for use in their seismic research. Our crustal structure databases are without restriction.

Our raster server is compatible with the Lamont vector view-server protocols (Menke et al., 1991). We collaborated with ARPA Researcher Bill Menke at Lamont to design a raster addition to the "view-server" protocol to create the "raster view-server protocol". Our program is compatible with the raster view-server protocol and with client programs developed at Lamont.

A concern was raised about unlimited access to topographic data and other proprietary or copyrighted data, so we studied a modification to the raster-server protocol that would require a user validation procedure (username and password) for access to such databases. This would not restrict access to other databases, such as our crustal structure databases and the public domain ETOPO5 topography, which would continue under the existing protocol. In addition, while implementing our server, we have found that some modifications of the protocol would greatly increase the efficiency of access to high-resolution raster data, such as the ability to request data for an area smaller than a square degree. Another apparently popular function that could be made part of the server protocol is the extraction of the lithospheric structure along a great circle path from the our raster datasets. We proposed a "second-generation" version of the raster view-server protocol, with the user validation and other modifications, but this version has not yet been implemented.

We worked closely with CSS researchers and programmers on the interfaces to display and utilize information from our databases over network connections. The client display programs are built upon "widgets" from the Motif toolkit and the X Window System to create a user interface that is compatible with existing programs at CSS. The interface is intended to be easy to use and easy to modify, similar to the "Geotool" program developed at CSS by Ivan Henson and John Coyne. The prototype client program can connect to the raster view-servers at Cornell and elsewhere and display raster data obtained from the server. We have written and tested a subroutine for the client program to allow the user to "save" a dataset or portion of a dataset to their local machine in a choice of formats, and this routine should be incorporated in the next major revision of the client program.

ONGOING RESEARCH

We are expanding the scope of our information system to include more data on the Middle East and North Africa. Under the auspices of several other ongoing projects at Cornell we have collected a very large literature collection, satellite imagery and some detailed datasets, especially in Syria and Morocco. In Syria, data include DSS and industry seismic reflection profiles, drill hole analyses, magnetic and gravity measurements, and possibly the data from a 20 station digital seismograph network to be installed soon with the help of Cornell scientists. For Morocco, data include seismic reflection profiles with drill hole tie points, gravity measurements, and many digital records from a network of about 30 seismograph stations that we helped to establish. For both Syria and Morocco, we have complete coverage of digital Landsat Multispectral Scanner scenes, complete sets of geologic maps, and all available DTED. In the near future, we will be making new databases from the Middle East and North Africa available via the Internet.

CONCLUSIONS AND RECOMMENDATIONS

We are happy to report that numerous CSS, ARPA and Air Force researchers are already using our databases in their ongoing studies. We have supplied datasets and maps made from our datasets to CSS, SAIC, ENSCO, Phillips Lab, SUNY Binghamton, Univ. of Conn., Univ. of Wisconsin, Australian National Univ., UC Santa Cruz, Univ. of New Mexico, Harvard, Univ. of Toronto and ARPA scientists in the course of the contract.

Geophysical and geological datasets can provide important ancillary information on the propagation of seismic phases through the continental lithosphere. In turn, this bears on the detection, discrimination, and yield estimation of nuclear explosions. The rapidly changing geopolitical situations in Eurasia, North Africa, and the Middle East make it imperative that databases are extended to areas outside the former Soviet test sites. The types of datasets that we are compiling can be used to compare well studied propagation paths, such as within Europe, with paths to events in other locations that have not been studied in great detail to enhance the monitoring of nonproliferation treaties.

The data of our digital geological and geophysical information system will be extremely useful for the interpretations of the seismic data in non-proliferation monitoring. Several workers are studying the effects of three-dimensional heterogeneities within the crust along the propagation paths of regional seismic phases, especially L_g (e.g., Baumgardt, 1990, 1991; Chun and Zhu, 1992; Clouser and Langston, 1992; Cormier, 1991, 1992; Israelsson, 1992; Jih and Lynnes, 1992; Lay and others, 1992; Schwartz and Mandel, 1992; Schwartz and others, 1992; Wallace, 1992). Qualitative studies have noted the lack of propagation of high-frequency L_g waves across major mountain ranges, such as the Alps (Harjes and others, 1992a), Himalaya–Tibet–Pamirs (Figure 13; Ni and Barazangi, 1983; Francis Wu, personal communication 1992), Turkish and Iranian Plateaus (Kadinsky-Cade, Barazangi, Oliver, and Isacks, 1981), and other ranges in Central Asia (Ruzaikan and others, 1977). Other features also seem to at least partially block L_g such as the Pre-Caspian depression–Caspian Sea–Caucasus mountains (see Figure 9; Kadinsky-Cade et al., 1981; Given, 1991) and the Barents Sea between Novaya Zemlya and Norway (Baumgardt, 1991; see Figure 16).

The crust of parts of central Europe around the GERESS array seems to be inefficient in L_g propagation especially to the east and south (Harjes and others, 1992a, b), as described above, possibly due to changes in crustal structure (Figures 12 and 14). Extreme surface roughness caused by fluvial and glacial erosion and sharp changes in sedimentary basin and Moho depths (e.g., the Karakoram of Figure 13) may significantly contribute to explaining the lack of L_g propagation across high mountain ranges. Use of L_g amplitudes along such paths for discrimination or yield estimation could be invalid or require correction factors. Surface roughness images can be used to map out areas of significant topographic relief. Basement and Moho depth images can similarly be used to map significant relief on those crustal boundaries.

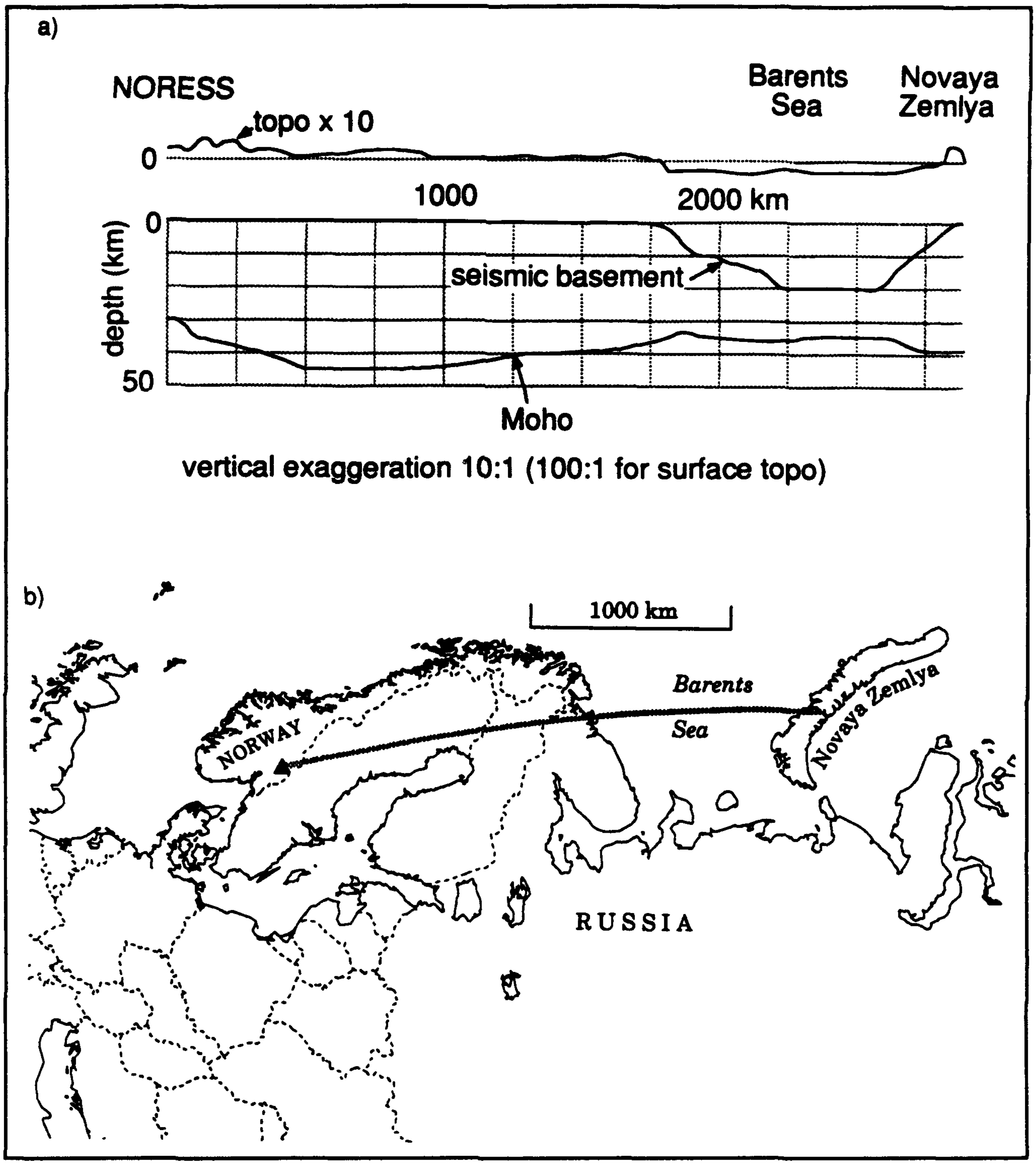


Figure 16. Crustal profile generated along great circle path between NORESS array and the Novaya Zemlya test site, similar to Figure 13. a) profiles of topography, depth to seismic basement, and depth to Moho. b) Map of the area in an azimuthal equidistant projection with symbols similar to Figure 1. Researchers have found a significant blockage of L_g along this path, probably caused by the crustal thinning under the Barents Sea.

Profiles of topography, sedimentary basins, and Moho depth in a swath along the propagation path of L_g from a given event show the amount of topographic relief at the surface, top of basement, and Moho that could contribute to scattering high-frequency energy (Figures 12–16). Our three-dimensional database of crustal structure for Eurasia can be empirically compared to measured propagation anomalies and is available via our network database servers for those researchers modeling the effects of propagation paths on received seismic signals.

These datasets of digital geological and geophysical information can now be incorporated into modules of the IMS at the CSS and other seismic monitoring systems and will be extremely useful for the interpretations of seismic data. We will continue to make our databases available via the Internet to ARPA and AFOSR researchers. We proposed some modifications to the protocol of the raster server to make some data types more accessible, especially high-resolution satellite imagery and lithospheric structure along great circle paths. The direct connection of Cornell to the NSFnet (T3 backbone) makes communication between Cornell and the Internet especially rapid. As described above, we are making the processed topography data available, beginning with the reduced resolution mosaics that will be most useful for seismic researchers.

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