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**A GEOLOGICAL AND GEOPHYSICAL INFORMATION SYSTEM
FOR EURASIA**

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SUMMARY

Topography and crustal structure variations have significant effects on the propagation of regional seismic phases. Geological and geophysical data are also useful for other aspects of the problems of nonproliferation, verification and yield estimation. We are collecting datasets for Eurasia, China, the Middle East and North Africa. Available now are digital databases of topography, crustal thicknesses, and sedimentary basin depths. Work continues on collecting and organizing available topographical, geological and geophysical datasets. We store the data in an information system with a network-accessible server to which can connect client modules of future versions of the Intelligent Monitoring System (IMS) running at the Center for Seismic Studies and other DARPA researchers. We have created regularly spaced grids of the crustal and sediment thickness values from preliminary 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. The gridded data can also be used to model propagation of crustal phases in three dimensions. The data server at Cornell allows clients to directly connect to databases that we are generating and improving. This allows IMS users and other DARPA researchers to utilize data as soon as it is available. We encourage researchers to contact us about access to these databases and with suggestions for improvements. The e-mail address is "fielding@seismo.css.gov".

INTRODUCTION

Successful monitoring of nonproliferation treaties depends on the integration of many different types of data. Seismic data have been key to threshold treaty monitoring, but the recent geopolitical changes require the application of data to new areas where traditional "layer cake" structures for crustal phase propagation are no longer adequate and need to be replaced by models with more geologically realistic heterogeneous structure and topography. For example, it is likely that surface topography, sedimentary basins, changes in crustal thickness and structure, as well as the nature of the source itself, strongly control the excitation, propagation and reception of the L_g phase at regional and continental scale distances. Yield estimation is critically dependent upon these geological complexities when yields

are estimated for new sites with little or no statistical data that can be used for empirical calibrations. The important controlling features are specific to the particular locations of the sources, stations and propagation paths. They can be determined only by amalgamation of diverse datasets on topography, potential fields, seismicity, tectonics, crustal structure and geology. Increasing sophistication in analysis of seismic waves must be matched by advances in the ability to capture and apply available geophysical, geological, and topographical data relevant to the propagation of high-frequency seismic waves along specific regional or continental scale paths throughout a much larger part of the world than has been previously studied.

We are collecting and organizing available topographical, geological and geophysical datasets for Eurasia, including China, the Middle East and North Africa into a network-accessible information system. The information system is organized to extract and usefully display the information most relevant to verification, yield estimation, and non-proliferation monitoring. 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. We are developing a Geographic Information System (GIS) that provides effective access to these three-dimensional datasets through the CSS and the Internet to CSS and other DARPA researchers. We have completed a preliminary version of a network "raster server" program that allows "client" programs to access our topography datasets over the Internet. We encourage DARPA researchers to contact us about gaining access to our databases at these computer mail addresses: "eric@geology.cornell.edu" -or- "fielding@seismo.css.gov".

DATASETS ACQUIRED

Digital topography

We have processed and analyzed a large volume, more than ten gigabytes, of high-resolution Digital Terrain Elevation Data (DTED—Level 1) that we have received so far from the Defense Mapping Agency (DMA). The area covered (Figure 1) includes Central Asia, the Middle East, and North Africa. We still hope to receive the DTED that we requested for Europe and western Asia (Figure 1) to complete our coverage of the propagation paths of seismograms recorded at stations and

arrays in Europe. The basic processing of the raw DTED into an accessible format included the creation of mosaics of the full resolution data for each 5° by 5° block (with some smaller blocks in the areas of sparse coverage in North Africa), files of manageable size (72 MB or less) for manipulation and storage on optical media. We hope that some of the holes in the DTED will be filled in as the DMA continues their process of generating data.

All topography files have now been converted into a simple, standard "image" format with ASCII text files that specify the file contents, including the size, spacing, spatial limits and projection information. These text files allow the data to be displayed immediately in the Arc/Info GIS and the ER Mapper image processing system. We have cooperated with DARPA researcher Francis Wu and Alan Jones at SUNY Binghamton to create a program to convert our image format the commonly used GMT System file format (Wessel and Smith, 1991). This program is available via anonymous FTP from Cornell.

To enhance access to the voluminous database, we have written a subroutine library to easily read and write files in the image format with their accompanying text description 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. We have already used this program to supply areas of topographic data to DARPA researchers at the USGS, Lamont, University of Wisconsin, and SUNY Binghamton. Enhancements to this extraction program under development include the ability to use averaging to reduce the resolution of a patch as it is extracted. Again, any DARPA researchers are welcome to request patches of topographic data for their research from us.

All of our topography, including both reduced resolution mosaics and the full resolution topography blocks, and other archived datasets are being stored in the Cornell Epoch mass-storage device. 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 in the library unit. Our server program is able to load any part of the dataset in a short time.

As an example of our newly processed DTED, we prepared some figures made from the volcanic complexes of North Africa (Figures 2 and 3). 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 2). The explosions were apparently emplaced in a granite mountain that 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 3). Both of these complexes of Tertiary volcanism in the middle of a Precambrian shield have been attributed to a hot spot in the mantle.

We have recently begun merging the much lower resolution ETOPO5 dataset with our 1/10 full resolution DTED mosaic to produce a ~1 km resolution mosaic without holes for central Asia (Figure 4). 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. Since there are many holes in the DTED available for the Himalayas and nearby areas of Central Asia, we have used the ETOPO5 to "fill in" the DTED holes to produce a merged dataset. This required interpolation of the ETOPO5 dataset from 12 to 120 points per degree to match the grid spacing of the ~1 km DTED mosaic. The resulting mosaic shows some join lines where the elevations of the two datasets don't match exactly, but it provides a "best available now" approximation of the topography at this resolution. Figure 4 shows a shaded relief rendering of the merged dataset.

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 an advanced commercial geographic information system 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.

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

We started with a set of crustal seismic structure maps of Eurasia, at a scale of approximately 1:15,000,000. These include maps of crustal thicknesses (depth to Moho) and sedimentary basin depths (depth to seismic basement), both prepared by Professor Kunin's group at the Institute for Physics of the Earth in Moscow from a large amount of Deep Seismic Sounding (DSS) and seismic reflection profiles and other data (Kunin, 1987). These maps also cover Europe, the Middle East and northernmost Africa, although we are not so confident in these areas at the edges of the map.

Using the attributes capability of Arc/Info, we recorded which contours are dashed (inferred or interpolated) and which are solid. Arc/Info was used to edit the resulting databases and project the unusual projection data into latitude-longitude coordinates. We then created regularly spaced grids of the crustal and sediment thickness values from these preliminary maps. We are making these preliminary grids available to DARPA researchers via both our raster server and via anonymous FTP, while we continue to improve the datasets. An important application of the datasets is the extraction of profiles along great circles that show the crustal structure along the propagation path of lithospheric phases, such as L_g , to better understand and predict the path effects on phase amplitudes, a key to estimating magnitudes and yields. We have already supplied the raster data or profiles made from them to researchers at the Phillips Lab, CSS, Teledyne Geotech, SAIC San Diego, Univ. of Connecticut, and ENSCO.

We have begun the evaluation of the accuracy of the databases derived from the IPE maps. We are investigating ways of updating the databases with new information while maintaining a database of what data comes from what source. We

have consulted with DARPA 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 have 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 version of Arc/Info. We are also searching for digitizable versions of the data published by Meissner (1987), to improve the database for Europe.

The two datasets were combined with our topographic dataset to produce Figure 5 which shows the crustal structure along great circle paths from the GERESS array of Germany in the four cardinal directions (North, East, South and West). 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. It can be seen in Figure 5 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 is 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 5b). The deep Moho root of the Alps (Figure 5d) 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).

NETWORK DATA SERVER

We are continuing to use the Internet (formerly ARPAnet) network to share datasets with CSS and other DARPA researchers. We pursue the enhancement of our "server" system at Cornell to allow "client" modules of the IMS to directly connect to databases that we are generating and improving. We have completed a preliminary raster server that distributes our crustal structure datasets over the

Internet. This allows IMS users and other researchers to utilize data as soon as it is available. The server is compatible with the raster view-server protocol that we developed in collaboration with Lamont, and with client programs developed at Lamont. 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 "pyrope.geo.cornell.edu". Several seismic researchers have already obtained copies of our crustal structure databases (as described above), and several new requests for data have been received recently.

A concern has been raised about unlimited access to topographic data and other proprietary or copyrighted data, so we are studying 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. We will propose a "second-generation" version of the raster view-server protocol, with the user validation and other modifications, when the needs are clarified.

We continue to work closely with CSS researchers and programmers on a prototype of an interface to display information from our databases over network connections. The client display program is 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 database 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. Another feature that is being developed for the raster client is the extraction of profiles through the databases along a great circle path to create crustal profiles (similar to Figure 5) that could be used for interpretation or synthetic modeling programs, such

as the Xgb and GBseis programs under development for CSS (Davis and Henson, 1992).

CONCLUSIONS AND RECOMMENDATIONS

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 between NORESS and the Kazakhstan test sites, with paths to events in other locations that have not been studied in great detail to enhance the monitoring of nonproliferation treaties.

We will continue to work closely with CSS personnel to develop an interface that is best for cooperation with systems in use at CSS. We will continue to make our databases available via Internet connections to CSS and other DARPA researchers. We will continue close contact with the DARPA researchers at Lamont to avoid duplication of effort and make our network database system compatible with their view-server system. We have proposed some modifications to the protocol of their system to make some data types more accessible, especially high-resolution "raster" or gridded data. The fast connection of Cornell to the NSFnet (T3 backbone) and the current installation of a FDDI (fiber-optic) backbone at Cornell makes communication between Cornell and the Internet especially rapid.

The data of our digital geological and geophysical information system when incorporated into future versions of the IMS at the CSS will be extremely useful for the interpretations of the seismic data. 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-Pamirs (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 5b; Kadinsky-Cade et al., 1981; Given, 1991) and the Barents Sea between Novaya Zemlya and Norway (Baumgardt, 1991). 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 structure (Figure 5). Extreme surface roughness caused by fluvial and glacial erosion and sharp changes in sedimentary basin and Moho depths (e.g., Figure 5) 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, and basement and Moho relief images can similarly be used to map significant relief on those crustal boundaries.

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FIGURES

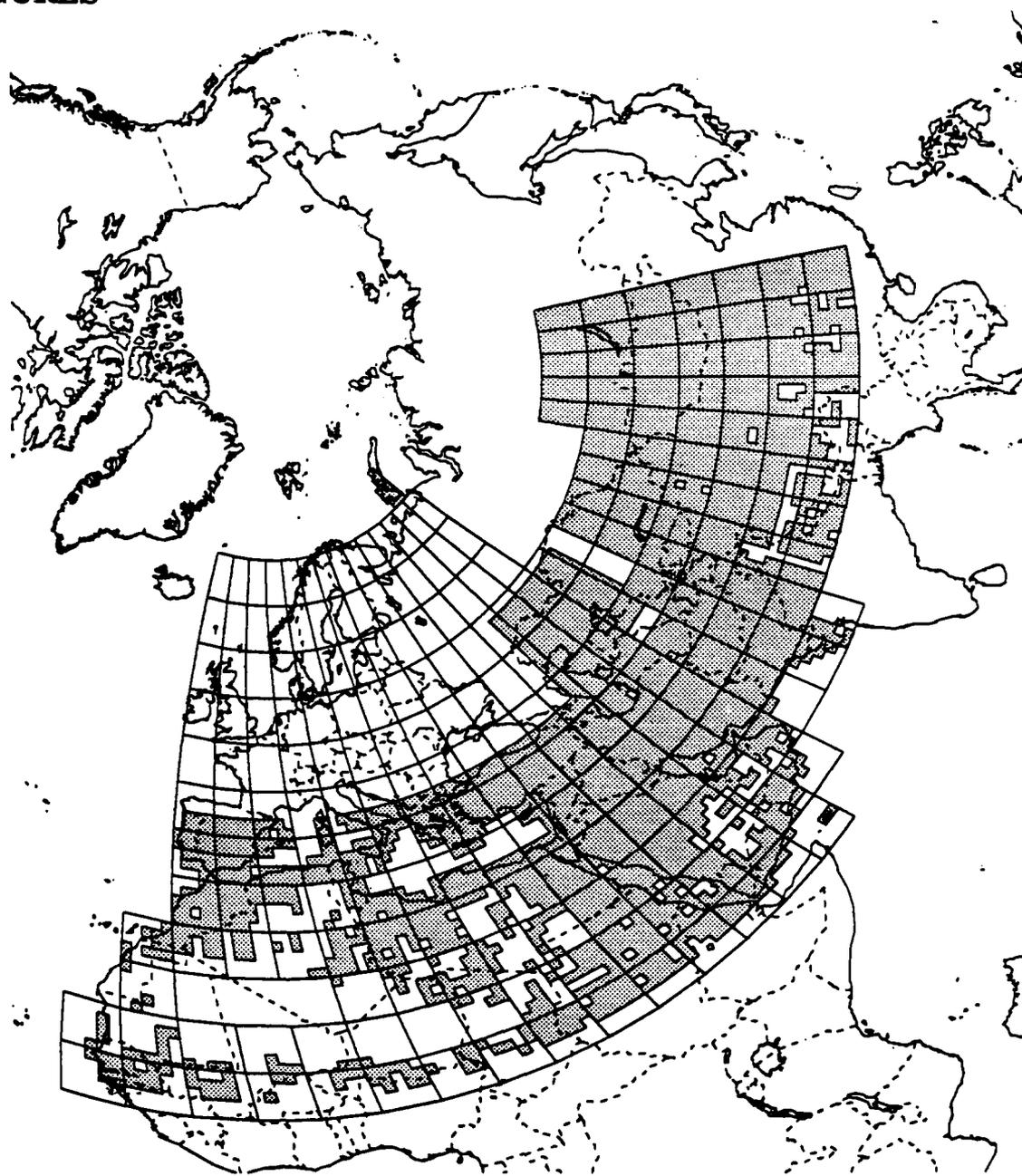


Figure 1: Map of Eurasia, the Middle East and North Africa showing area covered by our present databases of digital topography. Coastlines of oceans, seas, and major lakes are *solid lines* and country borders are *dashed lines*. Acquired and processed DTED cells are *filled light gray* and outlined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

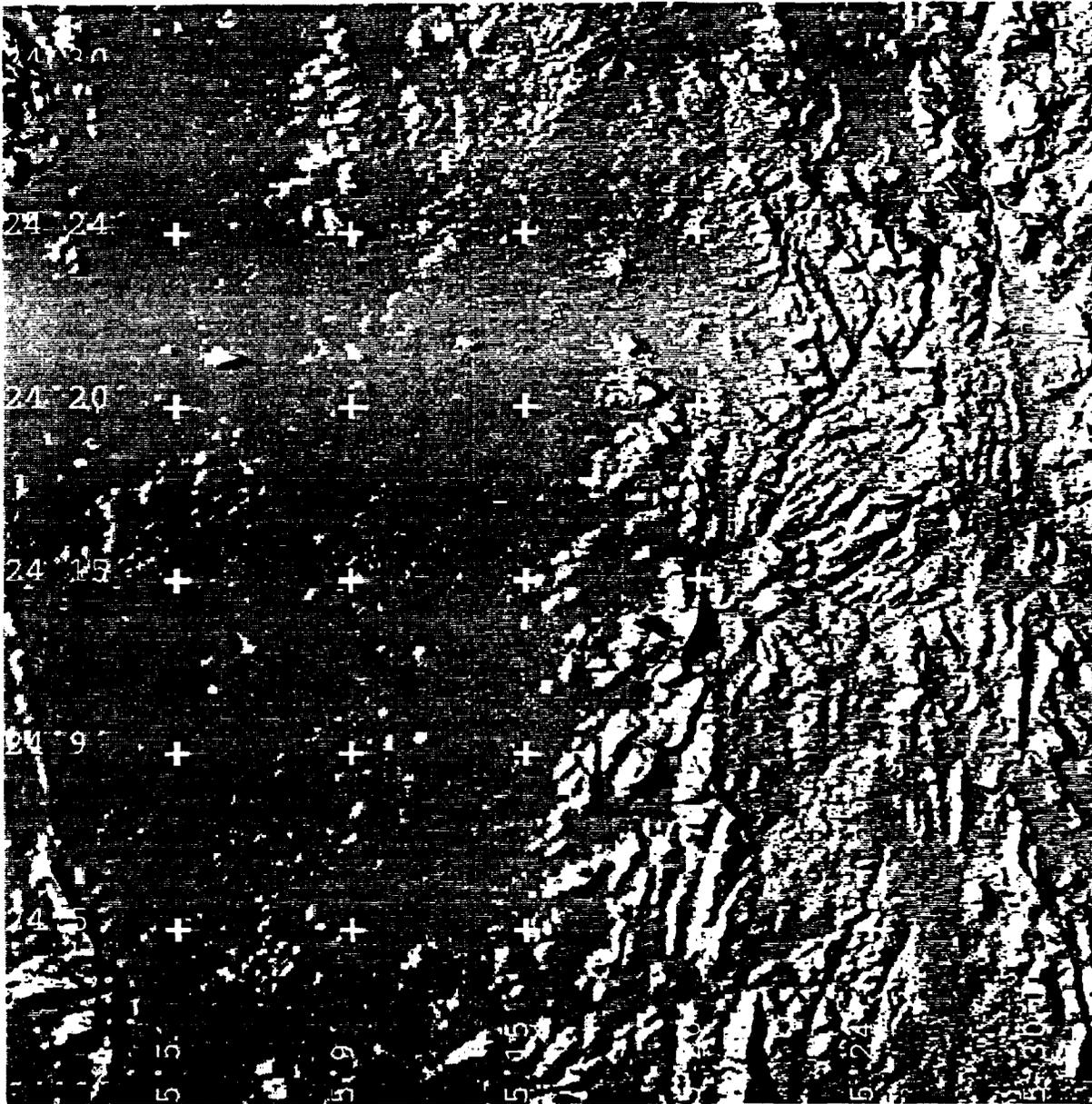


Figure 2: Grayscale shaded rendering (as color is not feasible in this report) of full resolution topography for the Hoggar site of French underground nuclear test in Algeria. Shading is with a "light" from the upper left of the page. *Small white circles* mark locations of tests extracted from the CSS "explosion" database, and *white crosses* mark 5 arc-minute latitude (N) and longitude (E) tics. The mountain where the tests were emplaced has a maximum elevation of ~1950 m.

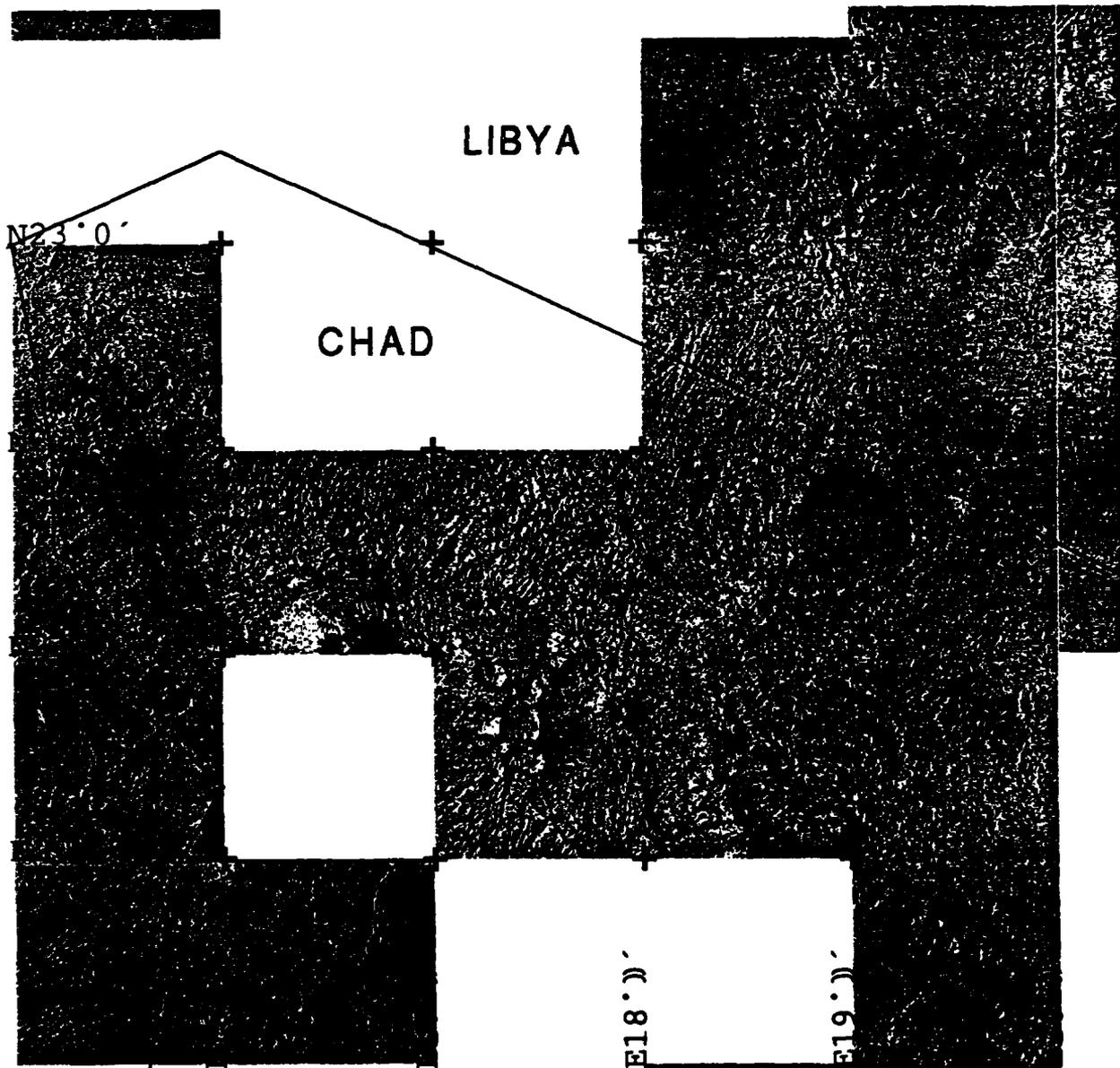


Figure 3: Grayscale shaded rendering of DTED for the Tibesti volcanic complex in Libya and Chad, which is similar to the Hoggar complex in Algeria. *White areas* are areas missing from the available DTED coverage. *Black lines* mark country boundaries, and *black crosses ticks* mark latitude and longitude degrees. The Tibesti complex has a maximum elevation over 3100 m.



Figure 4: Shaded relief rendering of merged topography datasets for Tibet and surrounding areas (in gray tones as color is not possible here). We have used the low-resolution, world-wide ETOPO5 database of topography to fill in the holes where high-resolution DTED is not yet available. The resulting merged dataset has an approximate resolution of ~1 km (120 x 120 points per degree).

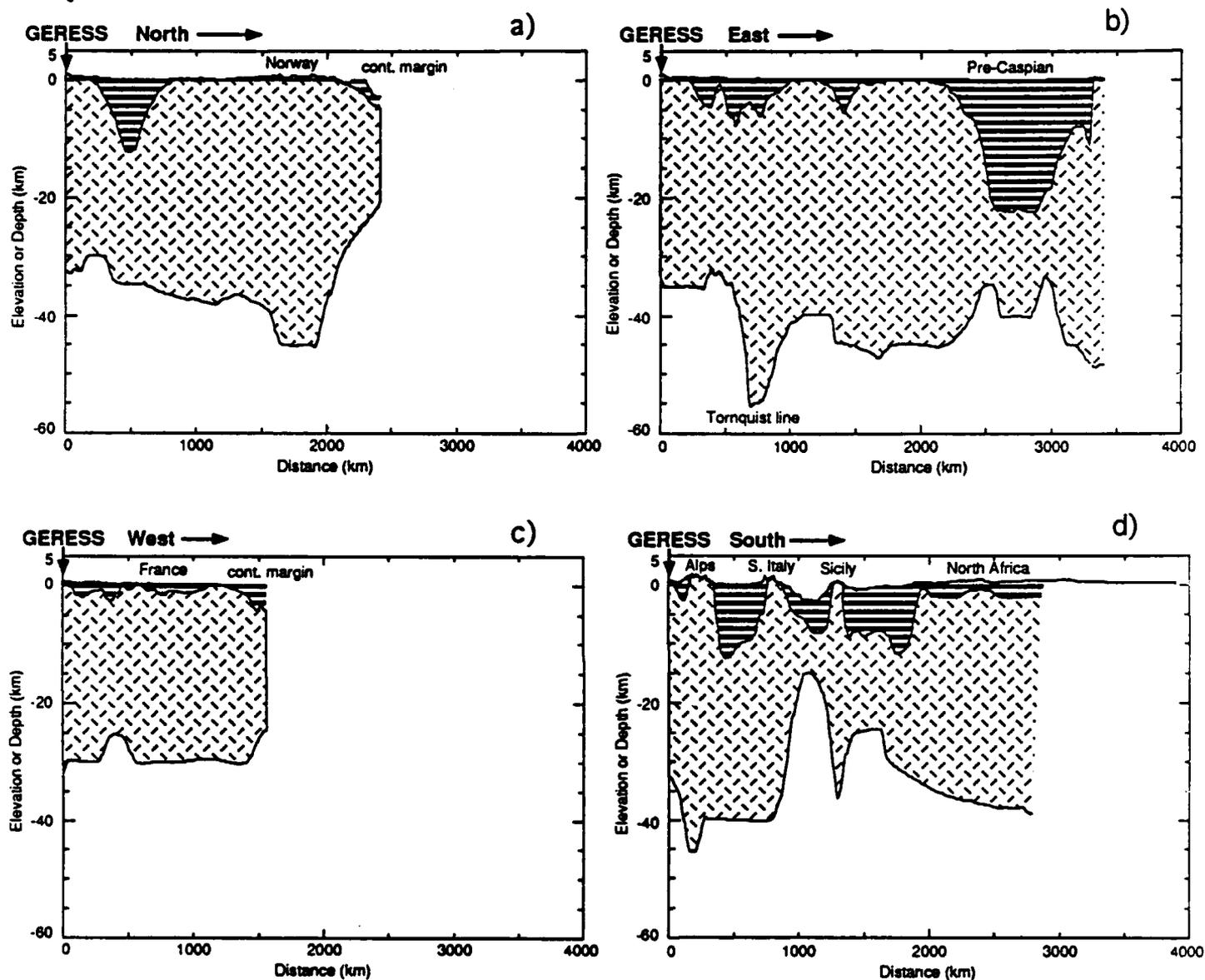


Figure 5: Profiles of topography, basement depth, and Moho databases along great circle paths from GERESS array in Germany in the four cardinal directions (see map in Figure 6 for locations of profiles). All profiles are plotted at the same scale with a high degree of vertical exaggeration. For clarity 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.

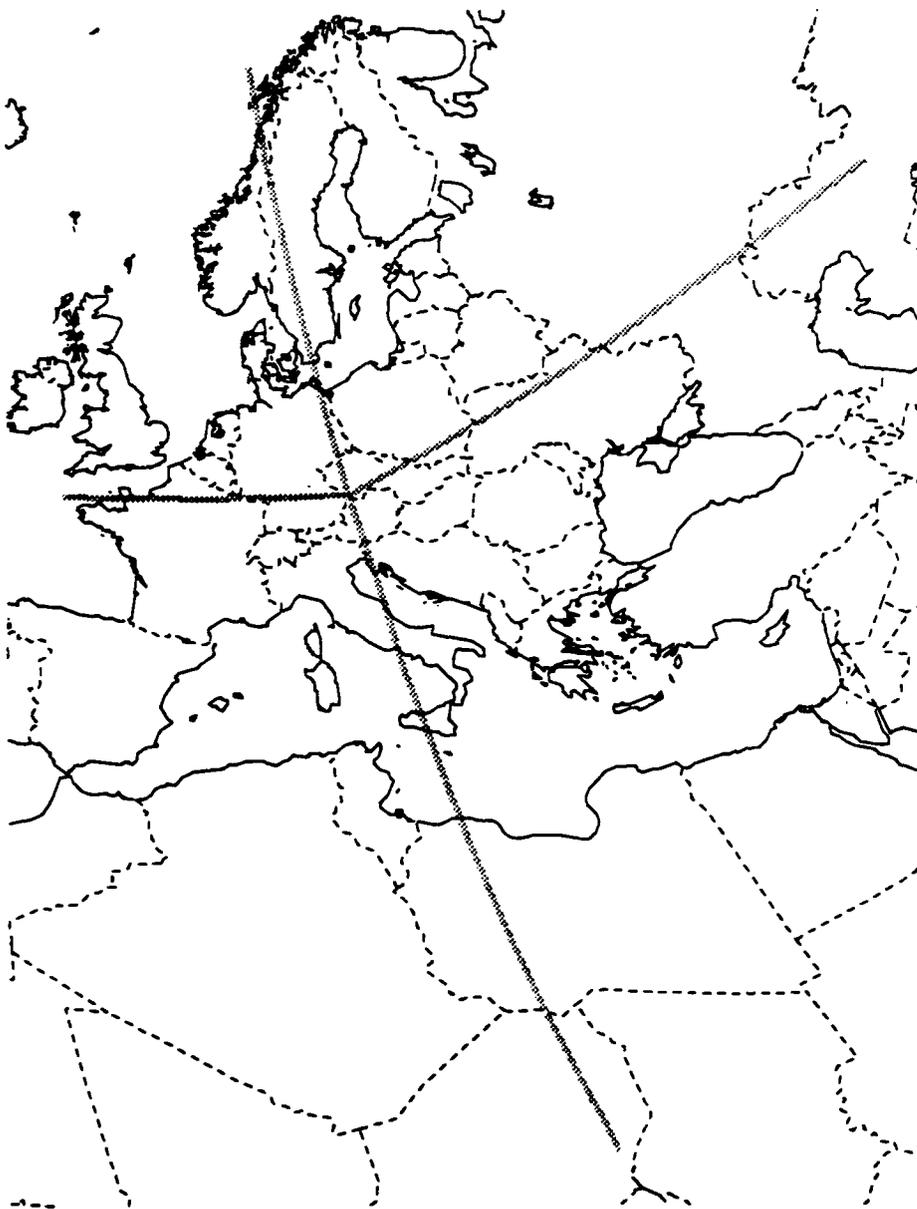


Figure 6: Map of Europe showing locations of profiles shown in Figure 5. Great circle paths of profiles are shown as *thick gray lines*. Coastlines of oceans, seas, and major lakes are *solid lines* and country borders are *dashed lines*. Map is in the same azimuthal equidistant projection as Figure 1.