A GEOLOGICAL AND GEOPHYSICAL INFORMATION SYSTEM FOR EURASIA

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The topography and crustal structure variations along 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 nonproliferation, verification and yield estimation. Work in progress has realized useful datasets for Eurasia, including a set of maps of crustal thicknesses and sedimentary basin depths. Our work collecting and organizing available topographical, geological and geophysical datasets for Eurasia is expanding to include China, the Middle East and North Africa. We store the data in an information system with a network-accessible server to which can connect X Window System 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 could also be used to model propagation of crustal phases in three dimensions. The data server at Cornell will allow clients to directly connect to databases that we are generating and improving. This will allow IMS users and other DARPA researchers to utilize data as soon as it is available.

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SUMMARY

The topography and crustal structure variations along 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 nonproliferation, verification and yield estimation. Work in progress has realized useful datasets for Eurasia, including a set of maps of crustal thicknesses and sedimentary basin depths. Our work collecting and organizing available topographical, geological and geophysical datasets for Eurasia is expanding to include China, the Middle East and North Africa. We store the data in an information system with a network-accessible server to which can connect X Window System 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 could also be used to model propagation of crustal phases in three dimensions. The data server at Cornell will allow clients to directly connect to databases that we are generating and improving. This will allow IMS users and other DARPA researchers to utilize data as soon as it is available.

INTRODUCTION

Successful monitoring of comprehensive or threshold nuclear test ban and nonproliferation treaties depends on the integration of many different types of data. Seismic data have been central to the problem, but the trail of seismic research has now reached the point where traditional "layer cake" structures 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. 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 in Eurasia, the Middle East and North Africa.

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 and yield estimation. 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 build upon our experience with computer manipulation of large spatial datasets to develop a GIS that provides effective access to these three-dimensional datasets through the CSS. We are utilizing the Internet (formerly ARPAnet) network to share datasets with 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 have collaborated with DARPA Researcher Bill Menke at Lamont to design a raster addition to the Lamont "view-server" protocol, and our server is compatible with the new protocol. 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 four gigabytes (GB), of high-resolution Digital Terrain Elevation Data (DTED—Level 1) that we received through our first contract for a large area of Central Asia. We are now processing a larger DTED volume for the Middle East and North Africa that we received a few weeks ago, and we hope to soon receive the DTED that we requested for Europe and western Asia (Figure 1). 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, a file of manageable size for manipulation and storage on optical media.

We have developed, adapted, and implemented several visualization techniques to aid in the analysis of digital topography at a variety of scales. A preliminary 1/20 resolution (60 points per degree) mean-value mosaic of the recently received data for a portion of the Middle East was projected into a Lambert Conformal Conic map projection at ~2 km resolution and then converted to a gray scale in Arc/Info to produce Figure 2.

This mosaic is an accurate representation of the topography 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. A shaded-relief image prepared from this mosaic can also be viewed in stereo on a full-color computer screen (such as the International Imaging Systems IVAS displays at Cornell and at CSS) to better visualize the third dimension of the data.

All of our topography, including both the reduced resolution mosaics and the full resolution topography blocks, and other archived datasets, such as the digitized geological and geophysical datasets shown in Figures 3 and 4, are being stored in our recently acquired 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 in the library unit. Our server program is able to load any part of the dataset in a short time.

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 (Figures 5, 6, and 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 L_g and other regional phases.

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 is already in use at the CSS, while some processing has been strengthened by the development of special programs running on our Sun workstations. 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.

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) profiles and other data and published in 1987. 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. An example of a portion of this gridded dataset is shown in Figure 4. The two datasets were combined with our topographic dataset to produce Figure 5 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.

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 basin area. We also have begun digitizing another map of crustal and lithospheric thicknesses published by Trifonov for the former USSR at 1:7,000,000 scale. We will compare the resulting grid with that from the IPE map to get some idea of the uncertainty in the Moho depths contoured. We will continue to search for more accurate data on the crustal structure of the former USSR, especially the original DSS data and other measurements upon which such maps are based.

We have begun to digitize 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 3. 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.

We digitized a geologic map of 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. 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.

NETWORK DATA SERVER

We are utilizing the rapidly accelerating Internet (formerly ARPAnet) network to share datasets with CSS and other DARPA researchers. We have begun development of a "server" system at Cornell to allow "client" modules of the IMS to directly connect to databases that we are generating and improving. This would allow IMS users to utilize data as soon as it is available. The server will be compatible with the Lamont vector view-server protocols (Menke et al., 1991). 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 have collaborated with DARPA Researcher Bill Menke at Lamont to design a raster addition to the "view-server" protocol. Our program is compatible with the new raster view-server protocol and with client programs developed at Lamont. 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, so we have proposed a "second-generation" version of the raster view-server protocol.

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 use of "widgets" or functional elements that communicate with the user and with the databases is an effective way to create an interface that is easy to use and easy to modify. Many modifications can be made via "resource" files that specify parts of the interface and properties of the widgets without recompiling the programs. This allows the user to customize much of the "look and feel" of the interface. The prototype client program can connect to the database servers at Cornell and elsewhere and display raster data obtained from the server.

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 (ARPAnet) 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) makes communication between Cornell and the Internet especially rapid. As described above, we will make the processed topography data available to the CSS and others, beginning with the reduced resolution mosaics that will be most useful to other DARPA researchers

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, for example, have noted or modeled the effects of three-dimensional heterogeneities within the crust along the propagation paths of regional seismic phases, especially L_g (e.g., Kennett and Bostock, 1989; Baumgardt, 1990; Bennett and others, 1991; Cormier, 1991; Kennett, 1991; Kennett and others, 1990; Lynnes and others, 1990). Qualitative studies have noted the lack of propagation of high-frequency L_g waves across major mountain ranges, such as the Central Andes (Chinn, Isacks, and Barazangi, 1980), Himalaya–Pamirs (Ni and Barazangi, 1983; Francis Wu, pers. comm. 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 Caspian Sea–Caucasus mountains (Kadinsky-Cade et al., 1981; Given, 1991) and the Barents Sea between Novaya Zemlya and Norway (see Figure 7; Baumgardt, 1990). Extreme surface roughness caused by fluvial and glacial erosion and sharp changes in sedimentary basin and Moho depths (e.g. Figures 4–7) 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.

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 (Figure 5). Our three-dimensional database of crustal structure for Eurasia will be empirically compared to measured propagation anomalies and will be made available through the CSS for those researchers modeling the effects of propagation paths on received seismic signals.

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FIGURES

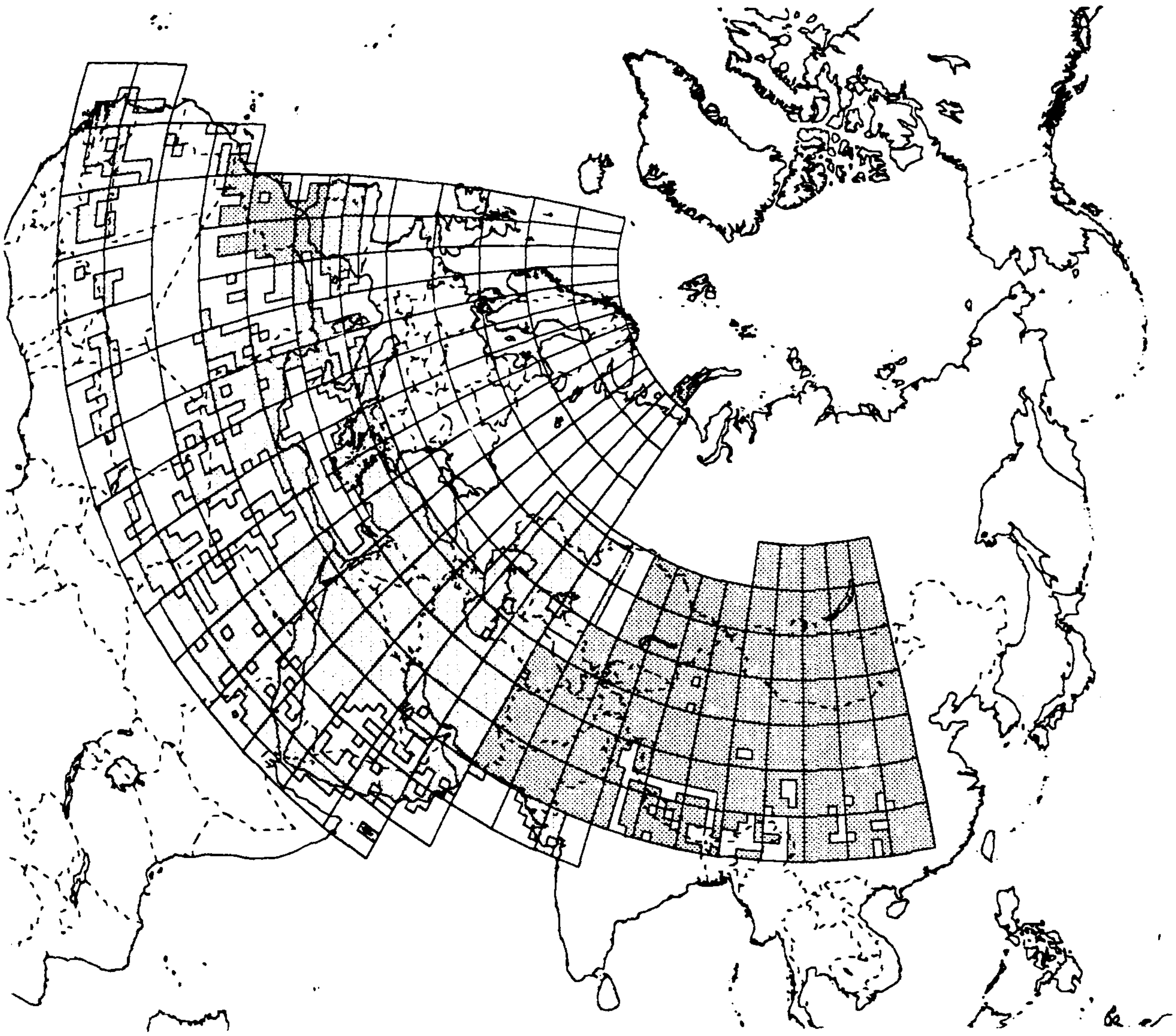

Figure 1: Map of Eurasia, the Middle East and North Africa showing area covered by our present databases of digital topography. Coastlines of oceans, seas, and major lakes are *solid lines* and country borders are *dashed lines*. Acquired and processed DTED cells are *filled light gray* and outlined 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.

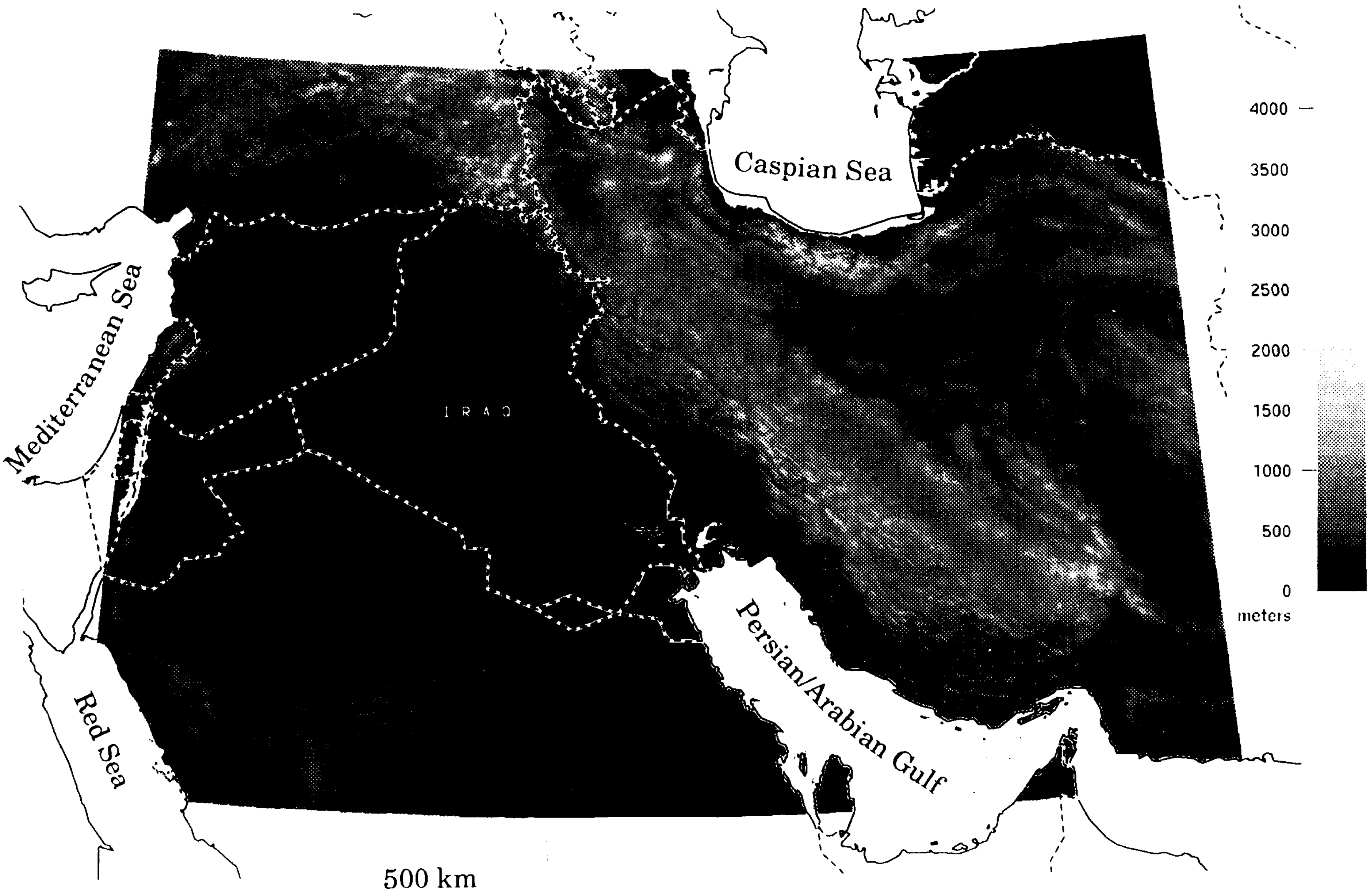

Figure 2: Grayscale (color not feasible in this report) rendering of Lambert projection ~2 km resolution mosaic for northern Middle East. *White areas* are areas below sea level or outside this preliminary mosaic. *Solid lines* mark coastlines of seas and major lakes. *Dashed lines* mark boundaries of countries (and former USSR republics).

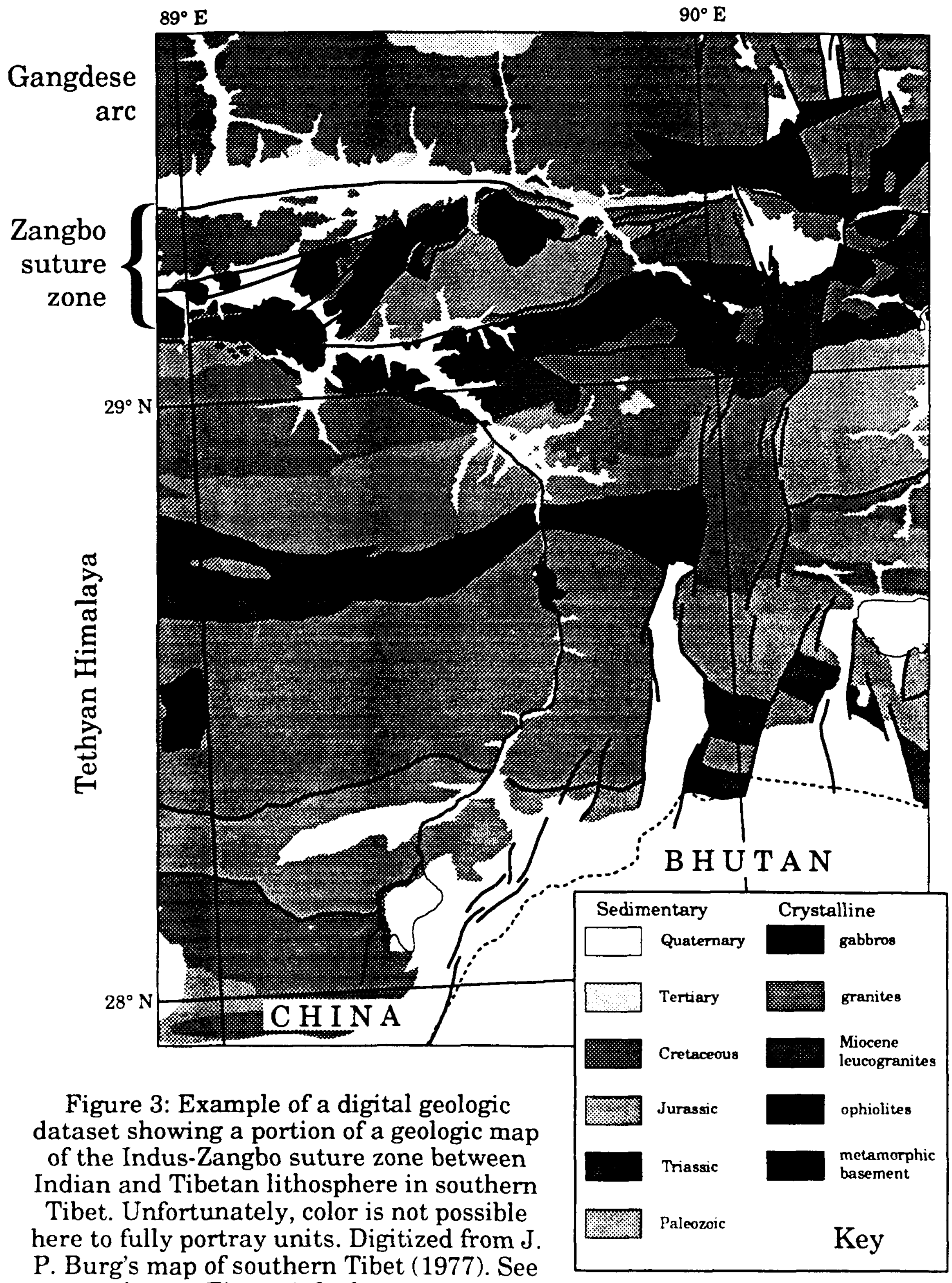

Figure 3: Example of a digital geologic dataset showing a portion of a geologic map of the Indus-Zangbo suture zone between Indian and Tibetan lithosphere in southern Tibet. Unfortunately, color is not possible here to fully portray units. Digitized from J. P. Burg's map of southern Tibet (1977). See box on Figure 5 for location.

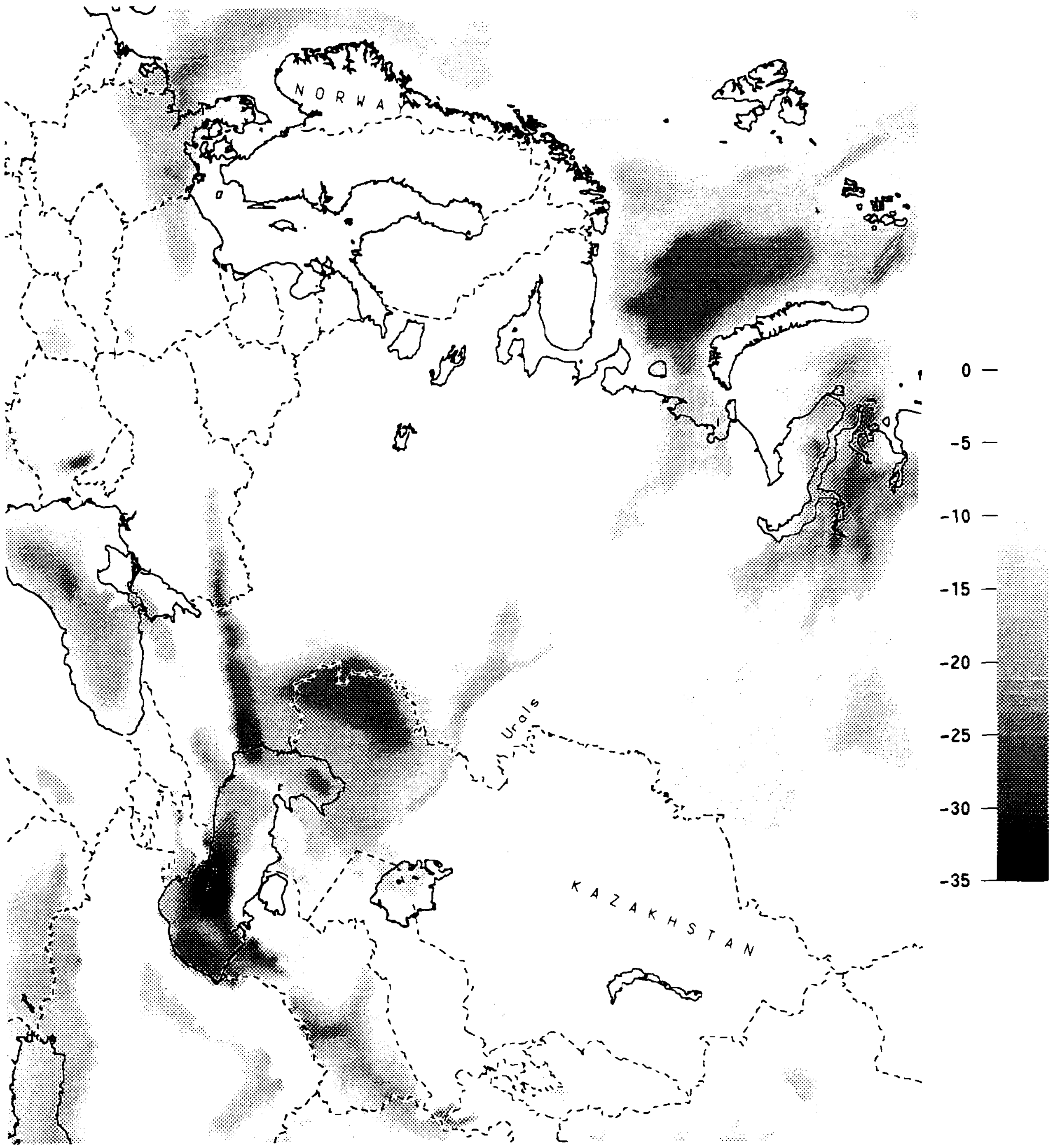

Figure 4: Map of a portion of the gridded database of depth to "seismic basement" showing eastern Europe, northern Middle East and west central Asia. Dataset was digitized for all of Eurasia, the Middle East and North Africa from a map by IPE, Moscow. *White areas* are areas of basement at the surface 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 modelling 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.

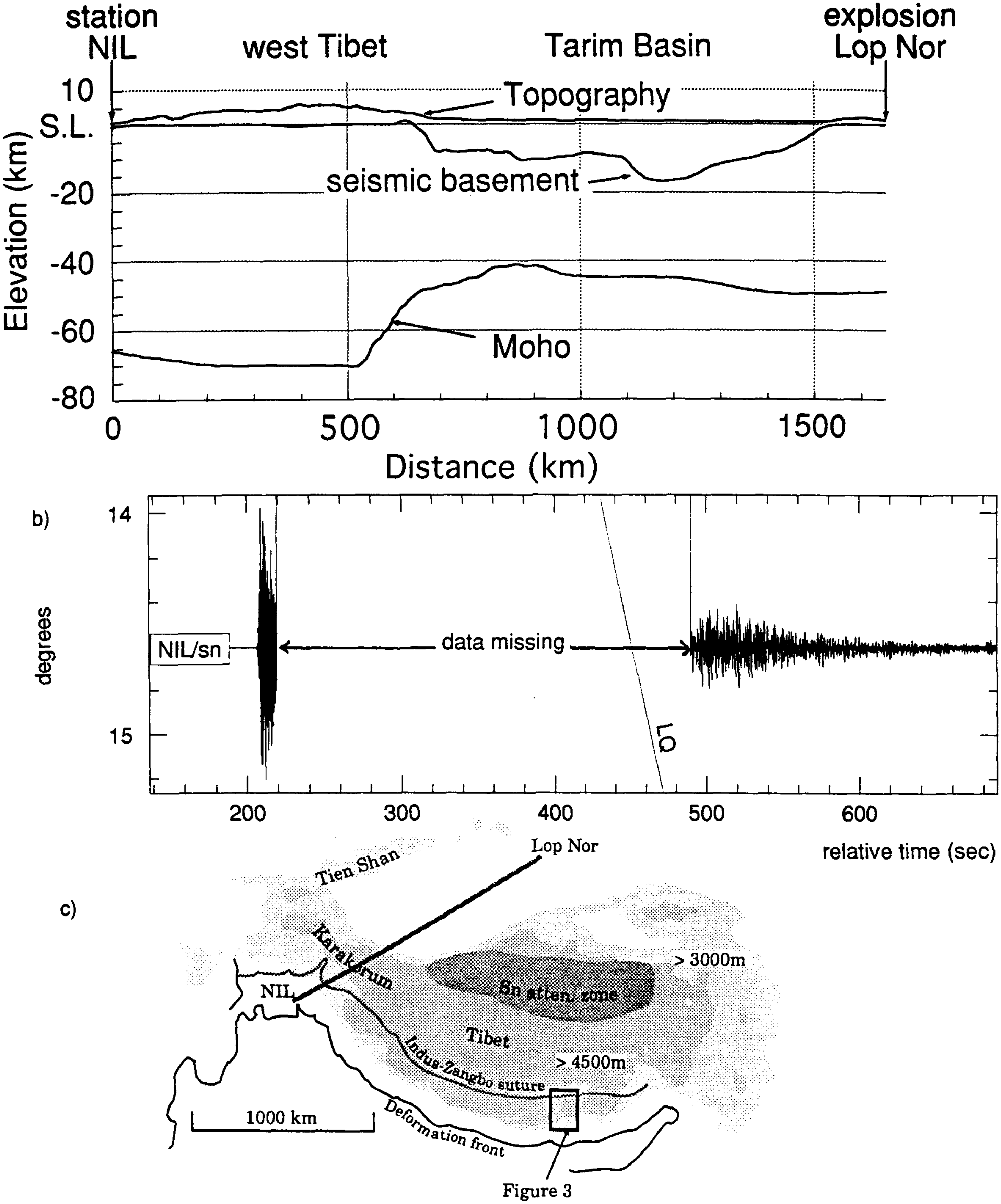

Figure 5: Examples of datasets for recent large Chinese nuclear explosion on May 21, 1992. a) Profiles of topography, basement depth, and Moho databases along great circle path from station NIL in Pakistan to the Chinese nuclear test site at Lop Nor. Note the extreme variations in topography and crustal thickness that will affect the propagation of crustal phases, such as L_g . b) Seismic recording stored at CSS 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 dark gray curve)* and location of geologic map of Figure 3 *(black box)* with major geographic and tectonic features.

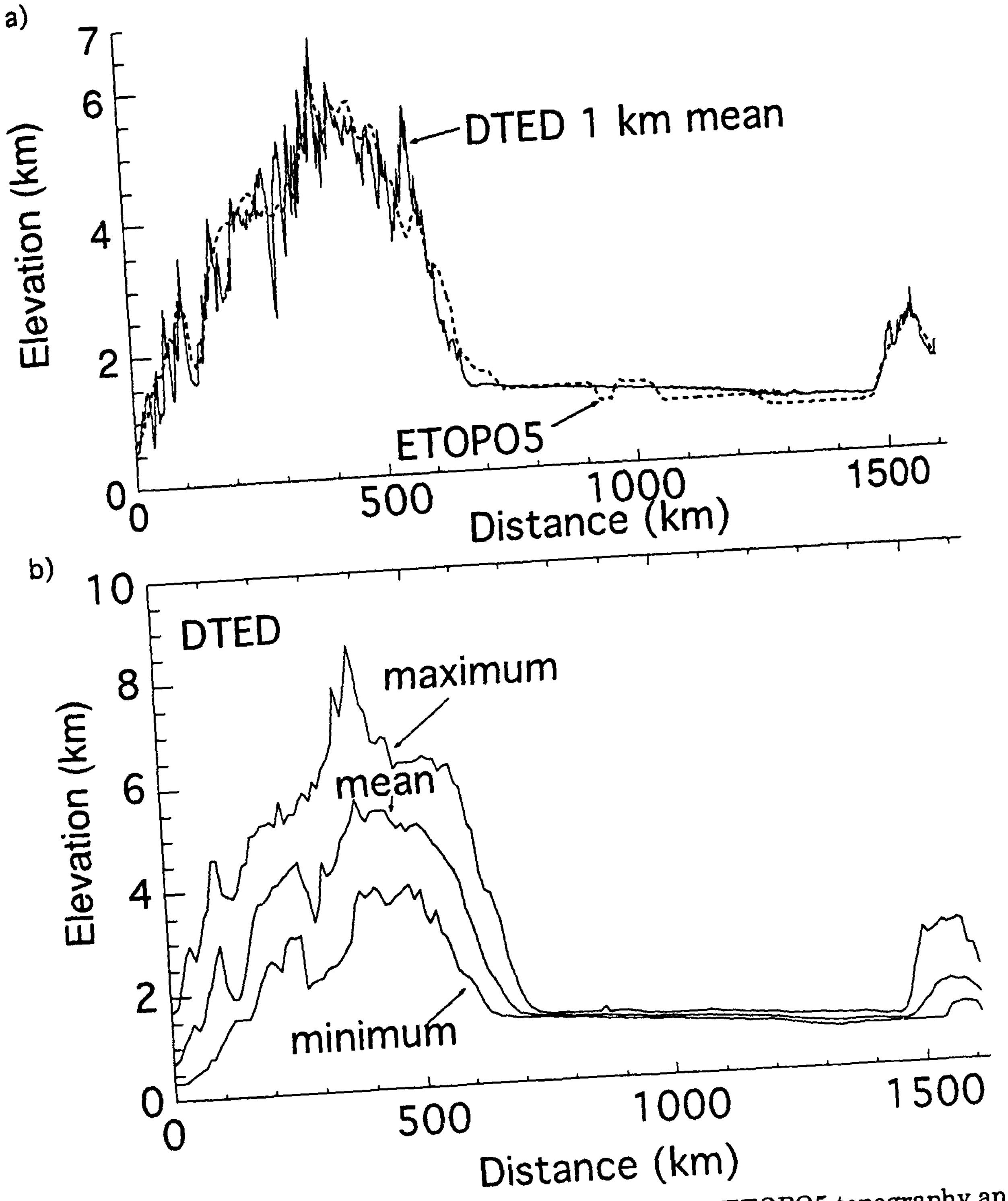

Figure 6: Comparison between low-resolution ETOPO5 topography and medium-resolution (~1 km) mosaic from DTED along the same great circle path between station NIL in Pakistan and the Chinese test site at Lop Nor that is shown in Figure 5. a) single profile lines of 1 km DTED and ETOPO5. b) Maximum, minimum, and mean elevations from DTED within windows 100 km wide and 10 km long in a swath centered on the great circle path showing local variation in topography portrayed by 1 km resolution mosaic.

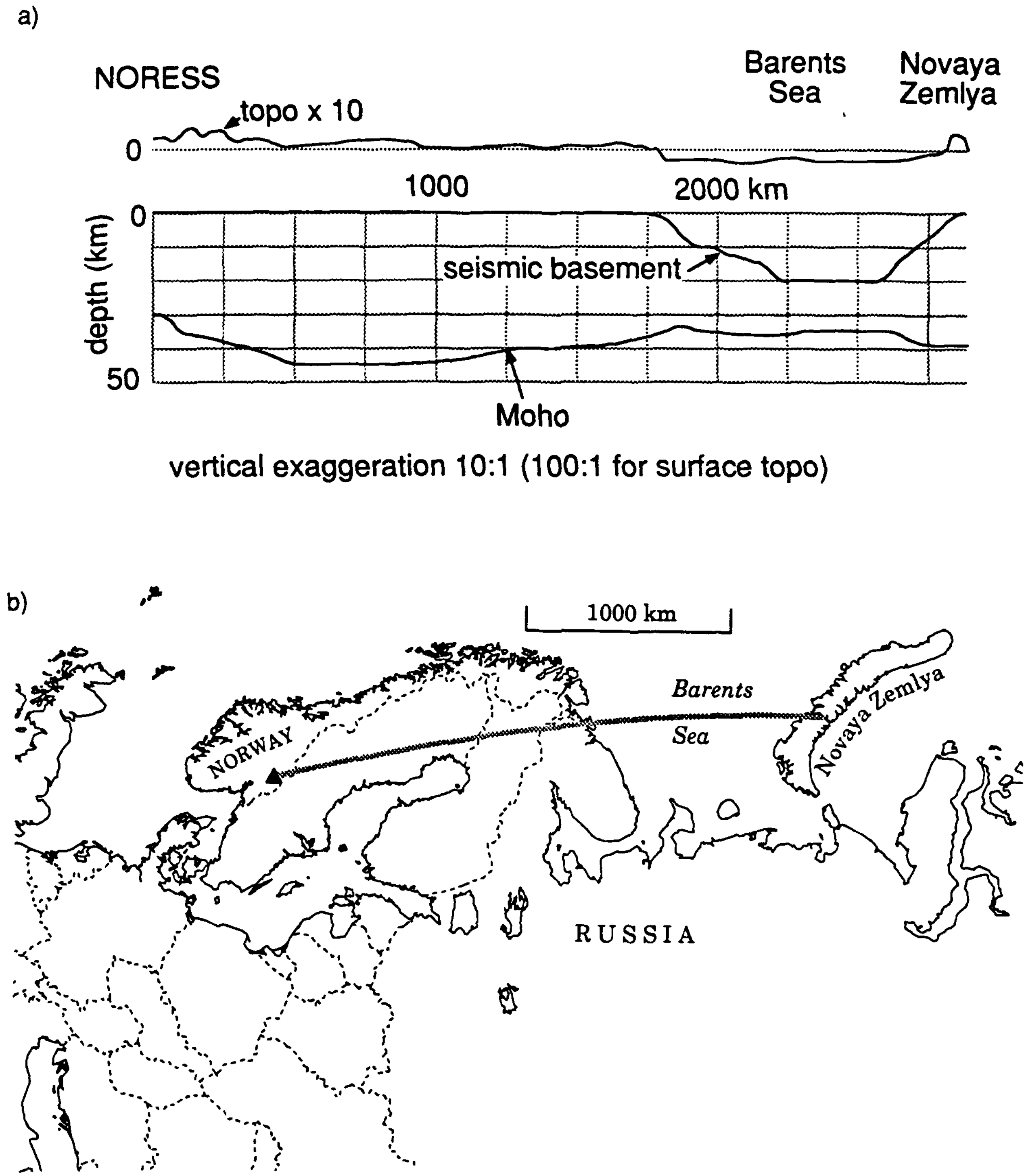

Figure 7: Crustal profile generated along great circle path between NORESS array and the Novaya Zemlya test site, similar to Figure 5. a) profiles of topography, depth to seismic basement, and depth to Moho. b) Map of the area is in an azimuthal equidistant projection and with symbols same as Figure 1. Researchers have found a significant blockage of Lg along this path, probably caused by the crustal thinning under the Barents Sea, which is not reflected in the low-relief topography along this profile.