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Probing Tectonic Topography in the Aftermath of Continental Convergence in Central Europe

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Continental topography is at the interface of processes taking place at depth in the Earth, at its surface, and above it. Topography influences society, not only in terms of slow processes of landscape change and earthquakes, but also in terms of how it affects climate. The Pannonian Basin–Carpathian Orogen System in Central and Eastern Europe represents a key natural laboratory for the development of a new generation of models for ongoing orogeny and its effect on continental topography development (Figure 1). This system comprises some of the best documented sedimentary basins in the world, located within the Alpine orogenic belt, at the transition between the western European lithosphere and the East European Craton. It includes one of the most active seismic zones in Europe, with intermediate depth (50–220 km) mantle earthquakes of significant magnitude occurring in a geographically restricted area in the Vrancea zone of southeastern Romania.

The objective of TECTOP (TECtonic TOPography) is to quantify the links between neotectonics and continental topography in the aftermath of continental convergence. TECTOP was initiated in fall 2001 by the Netherlands Research Centre for Integrated Solid Earth Science (ISES), the University of Bucharest, Romania and the Eötvös University in Budapest, Hungary. This article highlights the generic concept and the first results of TECTOP.

With the establishment of a strong network of collaborating institutes, the international TECTOP program is now in a position to tackle a set of outstanding questions pertaining to lithospheric processes controlling landform evolution and natural hazards during the recent evolution of the Pannonian/Carpathian system. TECTOP involves a dedicated effort through interpretation of existing data, new data acquisition, deployment of analytical facilities, and process-oriented, three-dimensional modeling. The focus of the research is on the interplay among active tectonics, topography evolution, and drainage pattern development. The principal aim is to understand and quantify neotectonic processes controlling landscape formation and natural hazards during the late-stage (late Pliocene – Quaternary, cc. the last 5 Ma) evolution of the Pannonian Basin–Carpathian System.

Geoprediction in this polydeformed and active orogenic system requires multidisciplinary efforts and, therefore, the interaction and collaboration of researchers covering a broad field of expertise [*Cloetingh et al.*, 2002]. A crucial element of the project is the investigation of the mechanics of coupling back-arc deformation in the Pannonian Basin with continental collision and foreland basin evolution along the Carpathian arc. This is addressed through a combination of dynamic and kinematic modeling studies constrained by integrated basin analysis in the Pannonian sector and by thermochronology and structural field studies in the Carpathian belt. TECTOP will directly involve some of the best young researchers from the area, fully utilizing existing links developed over the last few years.

Pannonian/Carpathian Natural Laboratory

The Pannonian Basin evolved from its syn-rift to post-rift phase during Early to Late Miocene times (cc. 20–5 Ma), when back-arc extension was coupled with subduction dynamics in the Carpathian orogenic arc system [*Royden and Horváth*, 1988]. The intrinsic weakness of the Pannonian Basin lithosphere [*Lankreijer et al.*, 1999], as well as its tectonic setting, locked within the Carpathian arc, has made it a particularly sensitive recorder of changes in lithospheric stress induced by near-field and far-field plate boundary processes [*Bada et al.*, 2001]. High quality constraints exist on the present-day and paleostress fields in the lithosphere as a result of earthquake focal mechanism studies, analyses of borehole break-outs, and studies of paleostress field indicator data. A close relationship has been demonstrated between the timing and nature of stress changes in the extensional basin and structural episodes in the surrounding thrust belts, pointing to an intrinsic mechanical coupling between orogen and basin [e.g., *Fodor et al.*, 1999].

The Pannonian Basin, the hottest in continental Europe, is thought to have gone through a rapid temporal transition from passive to active rifting during Late Miocene to Pliocene (11–5 Ma) times, simultaneously with the climax of compression in the Carpathian arc [*Huismans et al.*, 2001]. Previous research [*Horváth and Cloetingh*, 1996] established the importance of Late Pliocene through Quaternary compression in the Pannonian Basin, explaining its anomalous uplift and subsidence as well as intraplate seismicity, thus establishing a novel conceptual model for structural re-activation in back-arc basins in orogenic settings. The basin system has reached an advanced stage of evolution with respect to other Mediterranean back-arc basins, and its structural inversion has been taking place for the last few millions of years. Basin inversion is related to changes in the regional stress field, from one of tension that controlled basin formation and subsidence, to one of compression resulting in contraction and flexure of the lithosphere associated with differential vertical movements.

TECTOP will connect these findings with results of seismic tomography that images the development of hot mantle under the Pannonian Basin [*Wortel and Spakman*, 2000] and the presence of late-stage detachment of the lithosphere in the Vrancea area of the Romanian Carpathians [*Hauser et al.*, 2002]. Major research efforts will be made to analyze the present-day three-dimensional deformation pattern and related landscape evolution in the actively inverting Pannonian Basin. Data indicate a strong spatial as well as temporal variation of both the stress and strain fields during late-stage basin evolution. Accordingly, the related structural styles of basin inversion vary both in time and space, resulting in a complex pattern of ongoing tectonic activity. TECTOP focuses on the recent stress field history and active fault behavior and the quantification of vertical crustal movements and its control on continental topography. For this purpose, data acquisition has taken place at various localities, both in the actively subsiding Great Hungarian Plain and in the uplifting areas of Transdanubia, in the eastern and western part of Pannonian Basin respectively. These data appear to be vital for the quantification of the

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Quaternary vertical movements in the Pannonian Basin.

Dating Topography

TECTOP aims for a better understanding of landscape, topography, and drainage pattern development in the light of neotectonic and surface processes. A major TECTOP effort is, therefore, on low temperature geochronology for determining amplitude and rates of uplift-denudation-erosion processes, in order to address the linkage and interaction among tectonics, erosion, and climate. A key factor is the quantification of feedback between deep crustal/lithospheric processes and the observed Pliocene-Quaternary to recent surface deformation patterns.

The ages of several ancient landforms are being determined by means of various isotopic age techniques that quantify vertical motions. By measuring cosmogenic isotopes (He, Ne), the cosmic ray-exposure history of the surface sediments is also analyzed. The main target of our field campaign is the axial zone of the uplifting Transdanubia region (TR in Figure 1), where the Danube River incises a Middle Miocene andesitic series. Data were collected along selected geomorphic profiles for systematic exposure-age determination of river terraces. Additional locations were sampled to achieve better areal coverage and to get a deeper insight into the various landforming processes. In this context, upper Miocene sandstone series showing traces of wind erosion (ventifacts) were probed for exposure-age dating.

Several Mio-Pliocene volcanic horizons, preserving ancient landforms and morphotectonic features, were sampled for Ar/Ar geochronology. Subvolcanic andesite dykes of middle Miocene age, now exposed as elongated geomorphologic features east of Budapest, were analyzed to quantify erosional rates in that area. Our objective is to reconstruct the three-dimensional uplift and erosion history of the main parts of the TR. As part of these efforts, cave crystal samples were collected for He-U dating from karstic areas near Budapest. Through the joint utilization of sub-aerial and cave surveys, we aim for increased accuracy in the timing of uplift rates. Landform studies are complemented with morphotectonic studies utilizing high-resolution topographic maps and models (DEM) to quantify cumulative tectonic displacements by means of geomorphic markers such as drainage networks, river profiles, piedmont-mountain front junction profiles, and active fault scarps.

Multi-scale Seismic Imaging

Structural field studies in the Pannonian/Carpathian System concentrate on outstanding questions such as how long faults have been active and how much deformation they have accommodated at or near the surface. TECTOP concentrates on the mapping of young structures, the internal geometry of larger-scale shear zones, and the displacement of geomorphic marker horizons. The reconstruction of the temporal and spatial evolution of the late Pliocene-Quaternary stress field points to a strong variation of the stress field in time, as well as in space, both horizontally and vertically. Constraints on active fault kinematics and re-activation, and on stress and strain fields, are being obtained by means of various field techniques.

High-resolution shallow seismics, recently demonstrated to be a particularly effective tool to image fine-scale Quaternary stratigraphy and neotectonic deformation in the Pannonian Basin [e.g. *Bada et al.*, 2001], will be extended to the full scale of the Pannonian/Carpathian System in TECTOP (Figure 1). These data sets will serve as the basis of numerical and analogue modeling of fault dynamics, strain partitioning, and the distribution of brittle deformation (seismic slip) versus creep processes (aseismic slip), all of which are important factors controlling the fine structure of collisional coupling of the Carpathian arc and the Pannonian back-arc system.

Over the last few years, much attention has focused on the spatial and temporal variations in thrusting along the Carpathian arc, and its relationship to unusual foredeep geometry and lateral variations in flexural behavior [*Matenco et al.*, 1997]. The Alpine tectonic evolution of the Carpathians is normally subdivided into Triassic to Early Cretaceous extension, followed

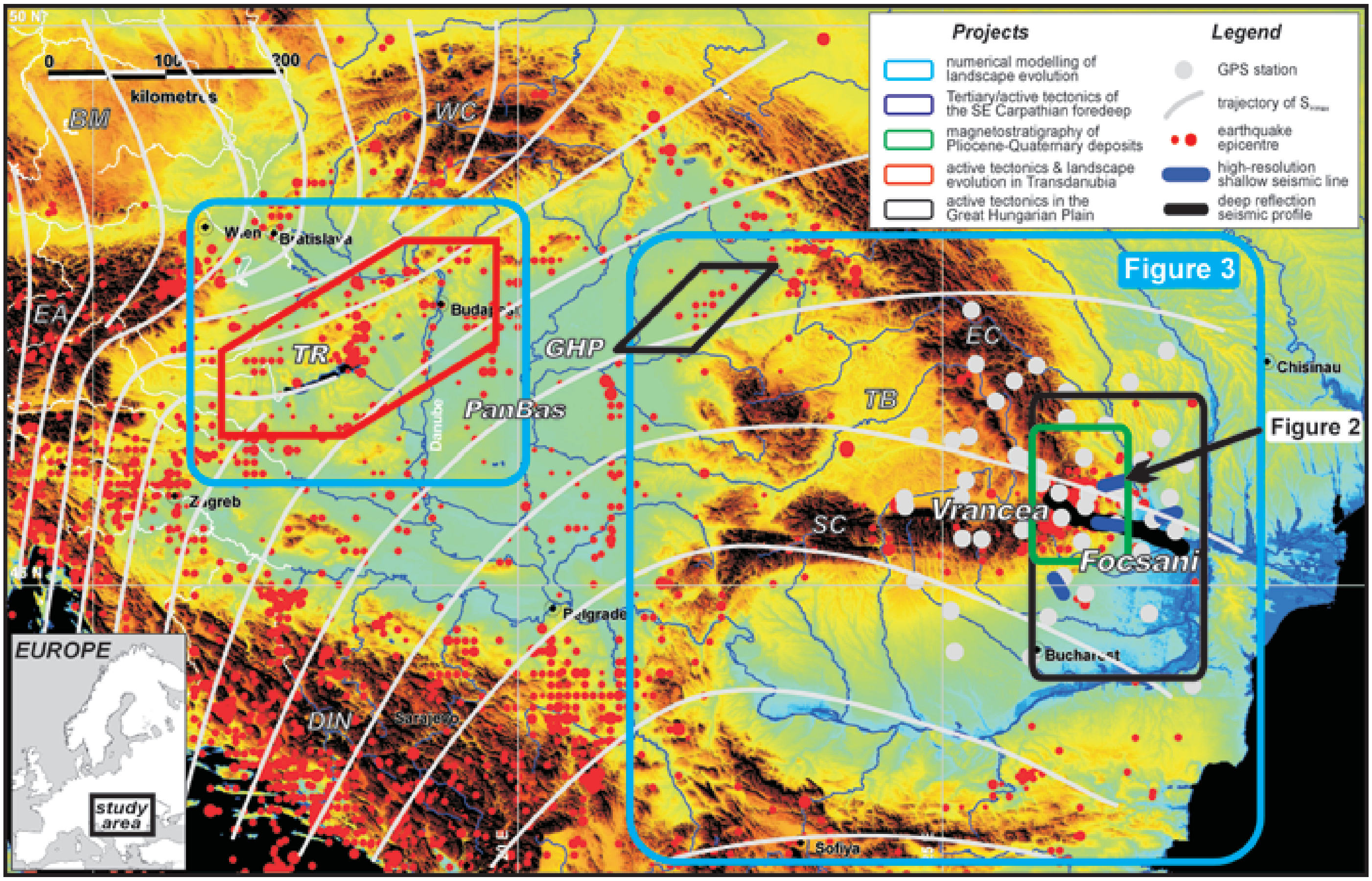

Fig. 1. Topography of the study area: the Pannonian Basin-Carpathian System in Central and Eastern Europe. Seismicity of the region (red circles - size proportional to magnitude), present-day maximum horizontal stress trajectories (S_{Hmax} - grey lines), and the location of the array of research activities/projects initiated by TECTOP are also shown. BM: Bohemian Massif; DIN: Dinarides; EA: Eastern Alps; EC: Eastern Carpathians; GHP: Great Hungarian Plain; PanBas: Pannonian Basin; SC: Southern Carpathians; TB: Transylvanian Basin; TR: Transdanubia; WC: Western Carpathians.

by Middle Cretaceous to Miocene shortening, with the main collisional event taking place during the Middle Miocene (i.e., 11 Ma). The reconstruction of uplift and erosion history in and around the Carpathians and subsidence modeling in its foreland have elucidated for the first time the complex interplay of flexural downloading during collision, followed by unroofing by unflexure and isostatic rebound [*Sanders et al.*, 1999]. Fission track analysis demonstrates up to 5 km of erosion with systematic non-cylindricity of the chain, from the northwestern part of the Romanian Carpathians, uplifted since 12 Ma, toward the bend area where uplift and erosion was initiated from 4 Ma onwards [*Sanders et al.*, 1999]. Magnetostratigraphy studies are also carried out to provide high-resolution constraints on the timing of these vertical motions.

Late Miocene to Quaternary basin evolution studies demonstrate large-scale subsidence in front of the SE Carpathians, culminating in significant differential vertical motions along and across the arc during the later stages. Consequently, as much as 1 km of Quaternary sediments were accumulated in the foredeep (Figure 2), while a similar amount of uplift is recorded toward the neighboring nappe pile, with no apparent role played by typical orogenic thrusting mechanisms. The entire internal zone is tilted, indicating that differential movements are not controlled by single faults but are related to large-scale tilting with a wavelength of tens of kilometers. Active topography development appears to be the consequence of both neotectonics and significant climatic changes during the Quaternary, resulting in variations of erosion rates and sediment supply.

TECTOP has acquired a deep multi-channel seismic reflection profile through the southeastern Romanian Carpathians to image crustal and upper lithosphere architecture of this key segment of Pannonian/Carpathian System and its foreland (Focsani Basin). The deep seismic reflection component of the research comprises a 140-km, near-vertical profile across the Vrancea Zone and Focsani Basin. Data acquisition took place in August-September 2001, as part of the integrated refraction/reflection seismic field program Vrancea-2001 [see also *Hauser et al.*, 2002]. Station spacing was every 100 m with shot points every 1 km. The data are integrated with industry seismics and basin analysis studies. So far, the detailed three-dimensional geometry of the Miocene to Pliocene sediments has been quantified, in order to provide further constraints for the numerical modeling of the Neogene evolution of Focsani Basin.

In 2002, about 100 km of medium- to high-resolution seismic reflection profiles were collected at 5-m station spacing in the Focsani Basin to image the uppermost 500 m of the sedimentary architecture (Figure 2). This allowed mapping of the internal geometry of the Quaternary deposits and inferences to be made about neotectonic activity, a prerequisite for understanding and quantifying the control of near-surface faulting on tectonic geomorphology. First results (Figure 2) show large-scale tilting and successive internal deformations of the Quaternary deposits, in combination with large rates of sediment supply, leading to shifts in depocenters. The shallow seismic study has been combined with a study of the three-dimensional effects in reflection seismics, carried out along one of the high-resolution seismic profiles.

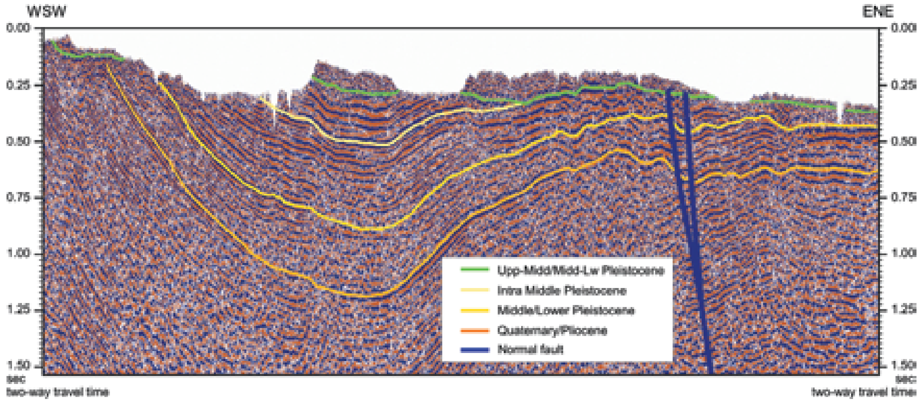

Fig. 2. Preliminary processing and interpretation of the high-resolution, two-way travel time (in seconds) shallow seismic line, acquired by SC Prospectiuni S.A. along Putna valley, SE Carpathians foredeep (see location in Figure 1). Note the large thickness of the Quaternary strata in the center of the Focsani Basin, and the great dip of the reflectors on the western flank, demonstrating uplift of the neighboring area. Note also the slight tilt of the Upper Pleistocene sediments showing active deformation and topography development in the SE Carpathian foreland.

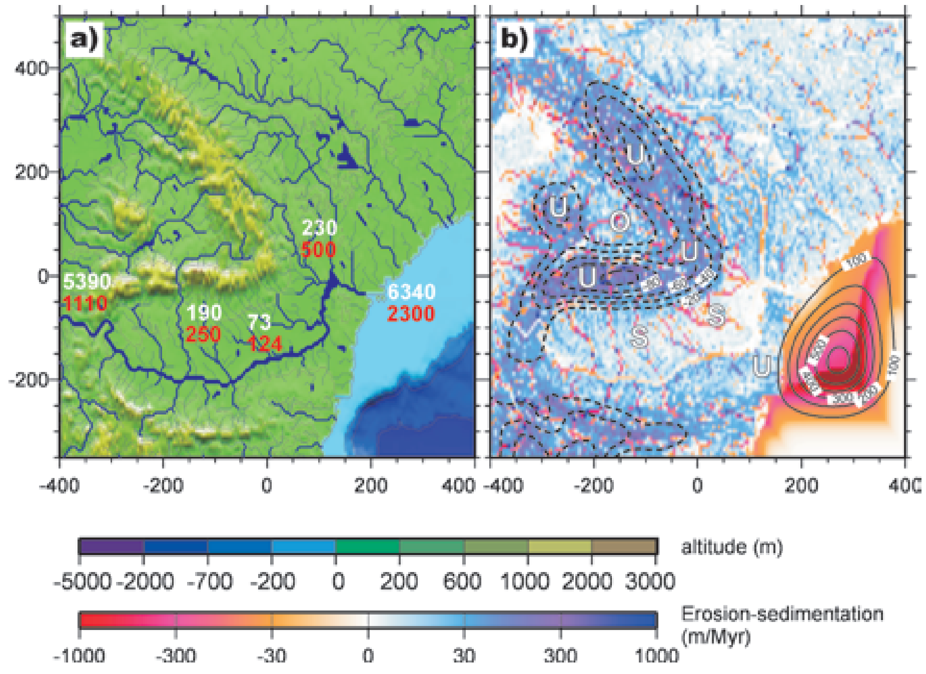

Fig. 3. Numerical model of surface transport in the Romanian Carpathians. (a) Present-day observed topography and predicted drainage network using the historical mean runoff distribution. Numbers indicate water discharge (white, in m^3/s) and sediment load (red, in kg/s) at selected locations of the Danube River and its tributaries. River width is plotted proportional to the predicted water discharge. (b) Predicted erosion/deposition (shade) and isostatic vertical velocity of the crust related to the surface mass transport (isolines labeled in mm/yr; dashed lines correspond to uplift). U, S, and O indicate present-day uplift, subsidence, and stable topography, respectively, as inferred from geodetic leveling measurements.

Active Landscape Evolution

Dedicated efforts have been made to deploy a GPS network to quantify recent strain rates along the Romanian Carpathians and the neighboring Transylvanian Basin (Figure 1). The main focus of this campaign is the seismically active Vrancea area and the associated Focsani Basin. This will also allow us to quantify the role of the far-field stresses along the orogenic chain and associated intra-montane basins. For the first time, data from permanent GPS stations are combined with the results of a dense network of temporary GPS campaigns to measure changes in the middle- to-long-term dynamic relief induced by deep lithospheric processes.

These processes will be further analyzed through seismic tomography studies that highlight mantle/crustal anomalies and constrain the present-day plate tectonic framework of the Carpathians. In order to quantify the climatic changes and to provide a detailed chronological framework for the Pliocene-Quaternary evolution of the SE Carpathian foreland and the Transylvanian Basin, magnetostratigraphic studies were started during 2002 along a series of profiles on the western flank of Focsani Basin. Fieldwork has concentrated on the continuous Pliocene-Quaternary outcropping sequences and will be correlated with the results of shallow seismic data and basin analysis studies.

In order to link the multi-scale observations described above quantitatively, a major objective of TECTOP is to develop and apply numerical techniques for landscape evolution modeling [*Garcia-Castellanos*, 2002]. The first step in this direction requires parameterization of a surface transport model based on present-day sediment load measurements in the major rivers of the Carpathians and its vicinity (Figure 3a). This parameterization predicts the areal distribution of present-day erosion and deposition, and allows us to estimate the isostatic response of the underlying lithosphere to surface mass redistribution (Figure 3b). The calculated vertical movements shown in Figure 3b are the result of flexural compensation of the induced erosion and deposition in the region, assuming lateral variations of lithospheric elastic thickness [*Matenco et al.*, 1997]. The areal pattern of these results is in good agreement with the vertical movements obtained by repeated geodetic leveling data. However, the absolute values inferred from leveling are one order of magnitude larger than our first predictions. At present, we do not know whether this discrepancy is the result of measuring vertical motions on different time scales or the incomplete understanding of the processes controlling topography in the aftermath of continental convergence.

TECTOP aims to shed light on this, as well as many other fundamental problems in the interplay of deep lithospheric and surface processes, through a major research effort involving a massive amount of new multidisciplinary data. The first results of TECTOP will be presented at the forthcoming St. Mueller topical conference of the European Geosciences Union in Cheile Butii, Romania, 31 May – 5 June 2003. For more information please visit the Web site of the conference at http://www.gg.unibuc.ro/mueller2003.

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National Earthquake Hazards Program at a Crossroads

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The U.S. National Earthquake Hazards Reduction Program, which turns 25 years old on 1 October 2003, is passing through two major transitions, which experts said either could weaken or strengthen the program.

On 1 March, a federal government reorganization placed NEHRP's lead agency, the Federal Emergency Management Agency (FEMA), within the new Department of Homeland Security (DHS). A number of earthquake scientists and engineers expressed concern that NEHRP, which already faces budgetary and organizational challenges, and lacks visibility, could end up being marginalized in the bureaucratic shuffle. Some experts, though, as well as agency officials, said they hope DHS will recognize synergies between dealing with earthquakes and terrorist attacks.

NEHRP's second transition is congressional re-authorization, due this year. This first re-authorization since 1999 could set NEHRP on a path to build on its earthquake research and mitigation successes and enable the program to further help society deal with natural hazards.

NEHRP already has registered a number of successes. Major developments supported by NEHRP include significant progress in understanding and monitoring earthquakes; and the production of national hazard maps, shake maps, seismic design guidelines for building codes, and loss estimation methodologies.

Will Agency Get Lost in the Shuffle?

A 20 February symposium at the U.S. National Academy of Sciences in Washington, D.C. examined NEHRP—an inter-agency program involving the National Science Foundation, National Institute of Standards and Technology, USGS, and FEMA—in light of these events.

Federal officials dismissed concerns raised by a number of scientists at the symposium that NEHRP would have a lower profile within the DHS. Anthony Lowe, who oversees NEHRP as FEMA's administrator for Federal Insurance and Mitigation Administration, said DHS is an "all-hazards agency where the earthquake program will fit right in." Lowe said, "NEHRP's experience is crucial to the nation's emphasis on protecting against all hazards, including the threat of terrorism."

Several participants, including Susan Tubbesing, executive director of the Earthquake Engineering Research Institute (EERI) in California, said they hope the greater resources of DHS and the concern about making the country more secure will benefit NEHRP. However, Tubbesing said, "We don't know what priority FEMA will have within [DHS] and what priority FEMA will give to earthquakes. Everybody is waiting to see what is happening at FEMA."