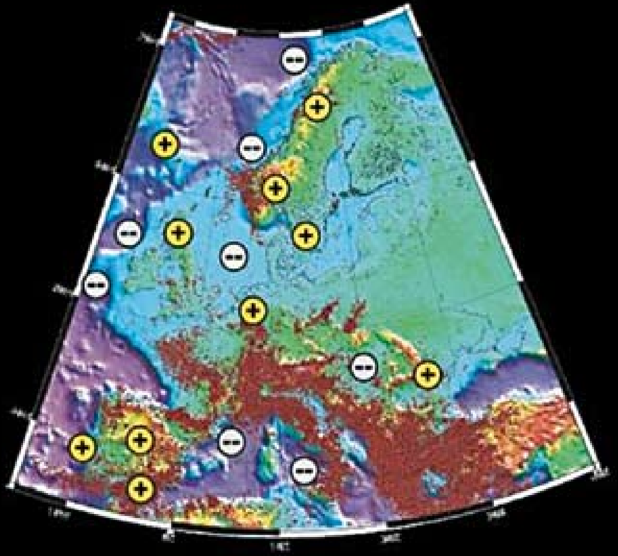

On-going crustal deformation in Europe.
(red dot): earthquake epicentres (source: NEIC).
(+): areas of Neogene uplift.
(−): areas of Neogene subsidence.
Background: elevation image (source USGS ETOPO2)

Déformation de la croûte terrestre en cours en Europe.
(red dot) : épicentres sismiques (source NEIC).
(+) : zones de surrection néogène.
(−) : zones de subsidence néogène.
Fond d'image : carte des altitudes (d'après USGS ETOPO2)

Coupled Deep Earth and Surface Processes Shaping European Topography: The TOPO-EUROPE Project

TOPO-EUROPE is an ILP- and ESF-sponsored multidisciplinary research program that addresses the interaction of processes inherent to the deep Earth (lithosphere, mantle) with surface processes (erosion, climate, sea level) controlling the development of topography. The objective is to assess neotectonic deformation rates and to quantify and predict related geo-risks, including flooding, earthquakes, landslides, rock falls and volcanism.

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The rationale behind TOPO-EUROPE

Continental topography results from combined deep Earth, surface and atmospheric processes. It affects society by slow changes in landscape and by its effects on the environment and geohazards potential. Rising sea-, lake- or groundwater levels and land subsidence increase flooding risks, thus threatening the human habitats. Conversely, declining water levels and land uplift promote erosion and desertification. In the recent past, catastrophic landslides and rock falls in Europe caused heavy damage and fatalities. Mounting population in river basins, coastal lowlands and mountainous regions, combined with global warming and associated increasingly frequent exceptional weather events, exacerbates the risk of flooding and devastating rock failures. Compounding this hazard, earthquakes and volcanic eruptions along active deformation zones cause short-term localized topographic changes, yet these also yield valuable information on stress and strain accumulations, of prime importance in seismic and volcanic hazard assessment. Whilst natural processes and human activity induce geohazards and environmental changes, their relative contribution is still poorly understood. Although topography clearly influences climate, techniques were only recently developed to model its effects in regions where good (paleo)topographic and climatologic data are available.

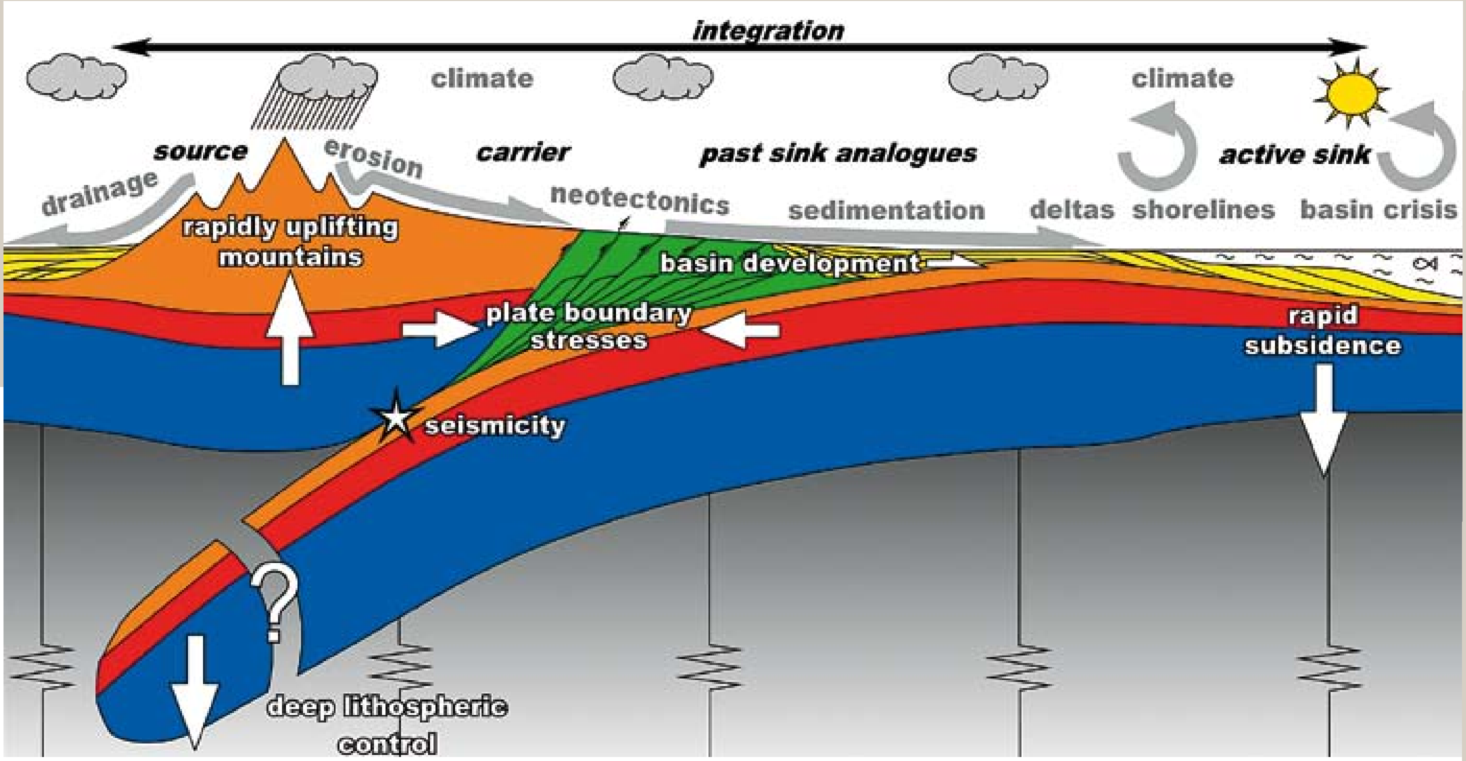


Fig. 1: Schematic Source-to-Sink systematics and coupled orogen-basin evolution driven by continental collision.

Fig. 1 : Schéma du système source-puits et de l'évolution couplée orogène-bassin engendrés par la collision continentale.

Processes on a variety of time scales control the present state and behaviour of the Shallow Earth System. These include the long-term effects of tectonic uplift, subsidence and the development of river systems, residual effects of the ice ages on crustal movement, natural climate and environmental changes, and the powerful anthropogenic impact of the last century. If we are to understand this complex system so as to predict its future and to engineer our use of it, more must be learned. The challenge to Geosciences is to assess its current state, monitor changes, forecast its evolution and, in a collaborative effort, evaluate how human society may best use it sustainably.

Topography and natural hazards

To better understand how topography, geohazards and the environment interrelate, the evolution of topography during the recent past but also during the last 10-20 million years must be assessed. Yet paleo-topography analyses face fundamental problems. Apart from dealing with topography that no longer exists, its dimensions, the timing of events and underlying dynamic processes that controlled its development and life cycle pose major challenges, and to solve these, a spectrum of disciplines is needed.

TOPO-EUROPE's geographic scope calls for co-operation on a European scale. Mountain ranges (increasing surface topography) and adjacent sedimentary basins (decreasing surface topography) record signals and proxies that tell the story of the topographic life cycle, in which the source-to-sink relationship (*figure 1*) is of key importance. Yet, these signals and proxies are still poorly understood, and we have only just begun to decipher the few we know. It is essential to extract all information from the system and interpret it in terms of controlling processes. Innovative analytical techniques, improved methodologies, and data interactive forward-backward modelling are required.

A key issue in topography-related geohazard research is developing and verifying physical models of hazardous Earth systems, integrating all relevant data, describing hazards versus time, and construing that they stem from the evolution of a non-linear system, where processes acting on various temporal and spatial scales can cause major disasters. Resulting from the interaction of shallow and deep Earth processes, topography plays a prominent role and, combined with other parameters, yields information on the stress field and its changes through time.

> *"The challenge is to monitor changes of the Shallow Earth System, forecast its evolution and evaluate how human society may best use it sustainably."*

► The TOPO-EUROPE network

The TOPO-EUROPE network was launched in October 2005 during a symposium held in Heidelberg and was recognized by the International Lithosphere Program (ILP) as one of its Regional Coordinating Committees. The project focuses on the interplay between active tectonics, topography evolution and related changes in sea-level and drainage patterns. Geoprediction in polyphase deformed and tectonically active systems requires implementation of an integrated observation and analysis strategy and the interaction and collaboration of researchers covering a wide spectrum of geosciences. TOPO-EUROPE addresses scientific issues of key relevance including (I) 4D topography development, (II) source-to-sink relationships to quantify sediment budgets, (III) quantification of land subsidence in basins and deltas, (IV) quantification of land uplift in orogenic and intraplate domains, (V) quantification of tectonically controlled river evolution and (VI) effects of climate changes.

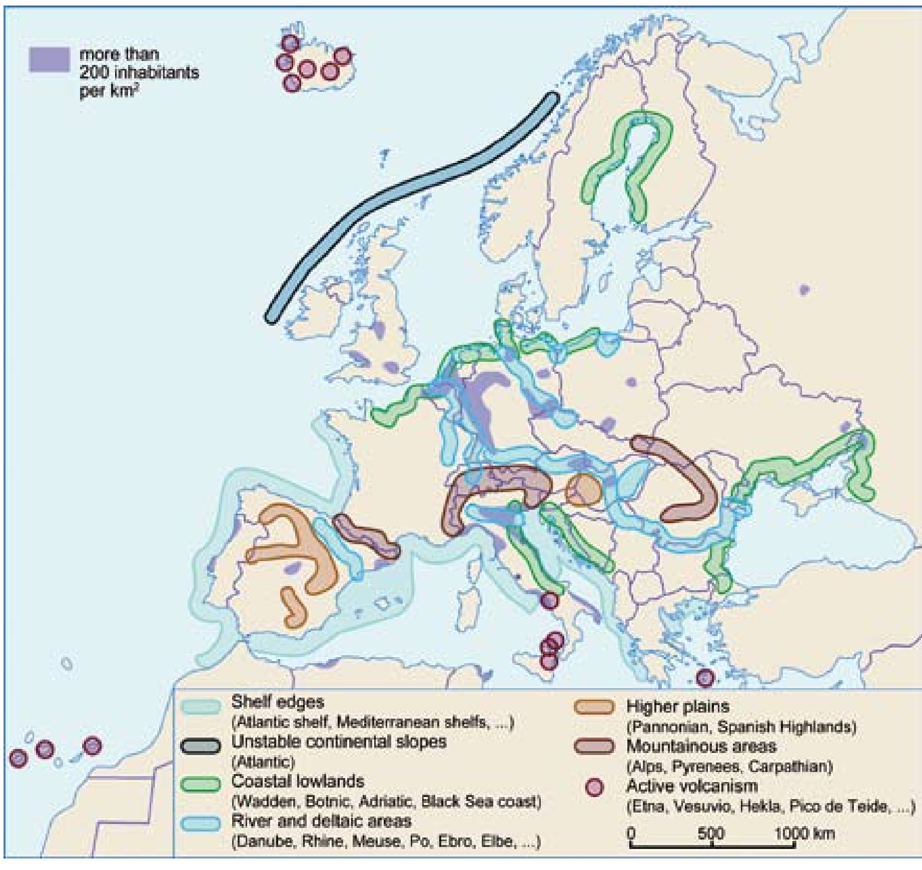
Progress in quantitative geopredictions is mainly expected in interactive forward-backward modelling of data. The network aims at acquiring high-resolution multidisciplinary data sets and closing the loop between observation, reconstruction and process-oriented modelling. Research targets four interrelated components: 1) Geodetic monitoring of the Earth System, 2) Geophysical imaging and high-performance computing of the deep Earth and lithosphere, 3) Geological dynamic topography reconstruction and 4) Process modelling and validation [Cloetingh *et al.* (2007)]. This requires iterative runs of the sequence "observation, modelling, process quantification, optimisation and prediction". Concerted efforts on common data sets provide the frame for intense cross-fertilization between disciplines and optimal result dissemination.

The network is a structure fostering (I) understanding of processes controlling topography development and related geohazards, (II) European leadership in continental topography research, (III) work opportunities for high-level researchers and (IV) "brain-drain" prevention.

TOPO-EUROPE has been launched by ESF as a EUROCORES in October 2008 (http://www.esf.org/activities/eurocores/programmes/topo-europe.html).

Fig. 2: Areas of Western and Central Europe exposed to increased geohazards owing to on-going vertical crustal movements, illustrating societal relevance of neotectonics (after Cloetingh *et al.*, 2006).

Fig. 2 : Zones de l'Europe occidentale et centrale exposées à des aléas géologiques accrus du fait des mouvements verticaux de la croûte, illustrant ainsi l'importance de la néotectonique pour la société (d'après Cloetingh et al.*, 2006).*



Geohazards and topography are closely related (*figure 2*). Topography is a major factor controlling slope instabilities triggering landslides, both on – and offshore, seen in areas of recent uplift such as Fennoscandia and the Romanian Vrancea zone. A second important parameter in catastrophic earth movements is the internal friction of soil, which in turn depends largely on hydrological conditions and precipitation intensity. Thus, climate changes involving decay of permafrost and/or increased precipitation also promote slope instability, landslide and rock-fall activity.

Earthquakes, reflecting brittle deformation of the crust and mantle, occur in various parts of Europe (*heading illustration*). Whilst frequent large-magnitude earthquakes are mainly associated with the Alpine-Mediterranean orogens, significant seismicity characterizes also some parts of the European intraplate domain. In intensely urbanized and industrialized areas like the Rhine Graben, moderate hazards can escalate into major risks. The current "3rd generation method" of probabilistic seismotectonic hazard analysis uses not only instrumental earthquake data but also draws on information from historical seismicity and paleo-earthquakes to determine an annual probability of exceeding a given ground-motion parameter. Now, the challenge to Solid-Earth science is to develop

► La base de données des séismes « SisFrance »

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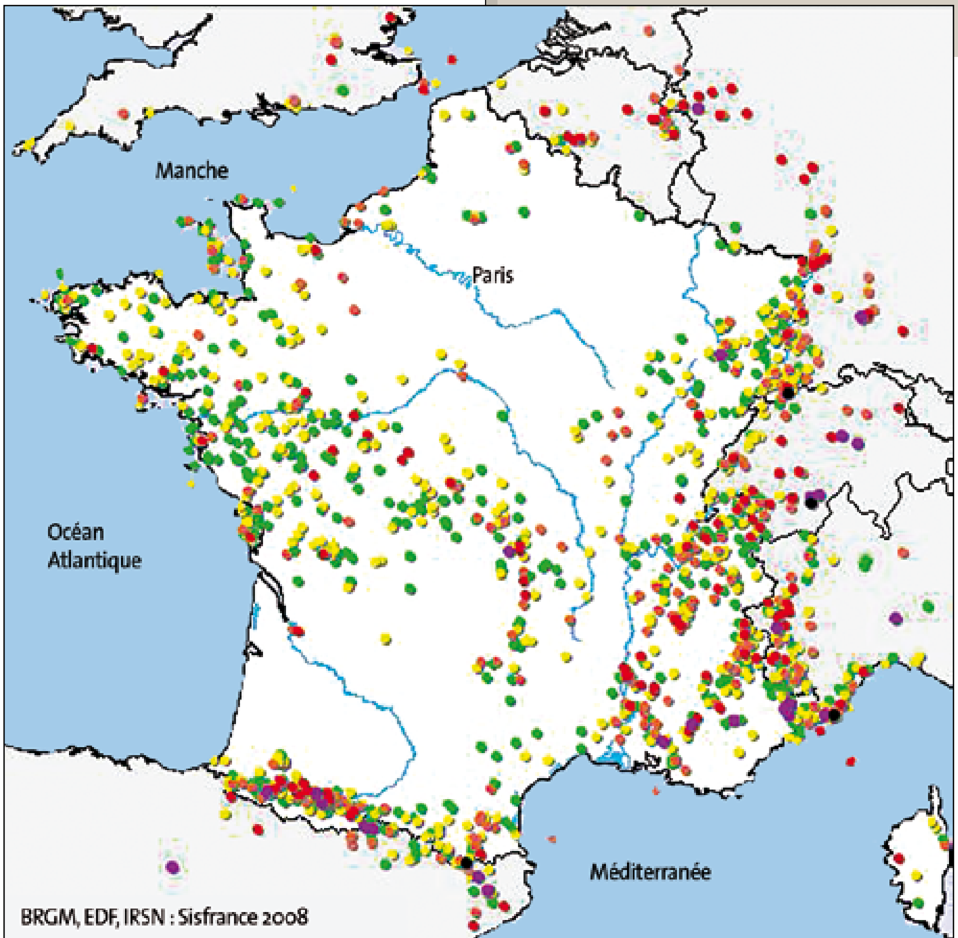
Jugée modérée à l'échelle européenne, la sismicité de la France métropolitaine est typique des régions intracontinentales à faible taux de déformation, impliquant une période de retour longue des événements sismiques majeurs. Ainsi, sur mille ans d'histoire, on relève par siècle, en moyenne, un séisme fortement destructeur et quatre séismes responsables de dommages sévères.
Mais, la poussée démographique et le développement économique augmentent le degré d'exposition des populations et des biens aux agressions naturelles, notamment sismiques, qui ne peuvent être prédites à court terme. Ces constatations ont conduit les pouvoirs publics à porter une attention particulière à l'analyse du risque sismique lors du lancement du programme électronucléaire.

La connaissance de notre passé sismique, combinée aux autres disciplines des sciences de la Terre, permet de mieux appréhender l'ampleur et les effets des séismes susceptibles de se (re)produire sur le territoire. Pour cela, le BRGM, EDF et l'Institut de Radioprotection et de Sûreté Nucléaire ont mis en chantier dès 1975 un vaste programme de caractérisation de la sismicité historique de notre pays par la recherche et l'analyse des témoignages sur les tremblements de terre conservés dans notre patrimoine littéraire. Ces témoignages constituent la base de la macrosismicité « SisFrance », qui bénéficie d'une actualisation permanente de manière à garantir un état des connaissances toujours plus satisfaisant. Sous l'impulsion du MEEDDAT, SisFrance est accessible sur Internet depuis 2002 et recense pour la métropole et son voisinage plus de 6 000 séismes, décrits par 100 000 observations et 10 000 références documentaires.



Intensités des épicentres de séismes (années 1300 à 2008) – Échelles MSK 64 et EMS 98
- Secousse modérée (4 à 4.5)
- Secousse forte (5 à 5.5)
- Dommages légers (6 à 6.5)
- Dommages prononcés (7 à 7.5)
- Destructions importantes (8 à 8.5)
- Destructions massives (9 et sup.)

À l'initiative du BRGM et du MEEDDAT, des bases de données semblables recensent aussi l'histoire sismique des territoires et départements d'outre-mer : Guadeloupe, Martinique, Guyane, Réunion, Mayotte, Nouvelle-Calédonie. Par ailleurs, le BRGM vient de créer un site sur les tsunamis historiques observés sur les côtes de France (métropole et outre-mer). Tous ces sites bénéficient d'une actualisation annuelle.

www.sisfrance.net
www.tsunamis.fr

« In intensely urbanized and industrialized areas like the Rhine Graben, moderate hazards can escalate into major risks. »

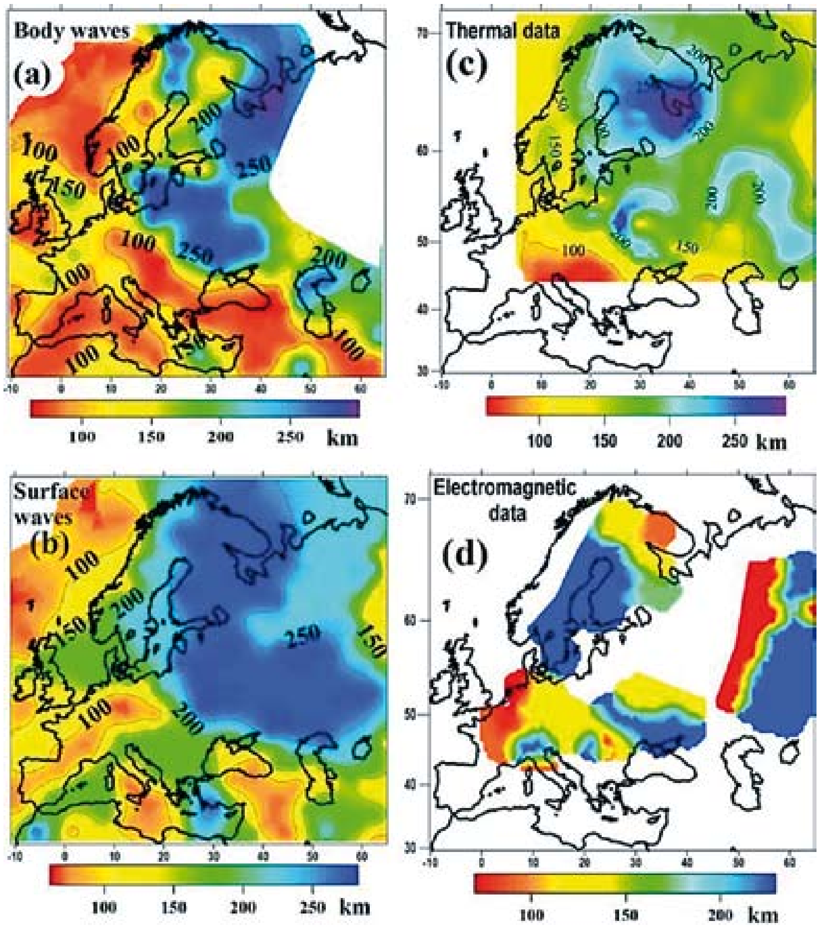


Fig. 3: Thickness of the European lithosphere as determined by: (a) seismic tomography; (b) surface wave tomography; (c) geothermics and (d) magnetotellurics (after Artemieva *et al.*, 2006).

Fig. 3 : Épaisseur de la lithosphère en Europe déterminée à partir de : (a) la tomographie sismique ; (b) la tomographie des ondes de surface ; (c) la géothermie et (d) la magnétotellurique (d'après Artemieva et al.*, 2006).*

4th generation methods that also factor in dynamic parameters of earthquake-inducing processes, and notably stress. Stress fields are strongly influenced by surface topography and the configuration of the crust-mantle and lithosphere-asthenosphere boundaries (*figures 3 and 4*). Highly sophisticated time-dependent hazard assessment models can be developed by linking several processes, such as mantle dynamics, structure and rheology of the crust and mantle (*figures 5 and 6*), changes in surface topography, erosional mass re-distribution and sedimentation, and post-seismic relaxation. Verified by recent deformation data (GPS, geomorphology) and tectonic stress, such models can provide insight into the stress and strain evolution of key European seismogenic areas. This type of

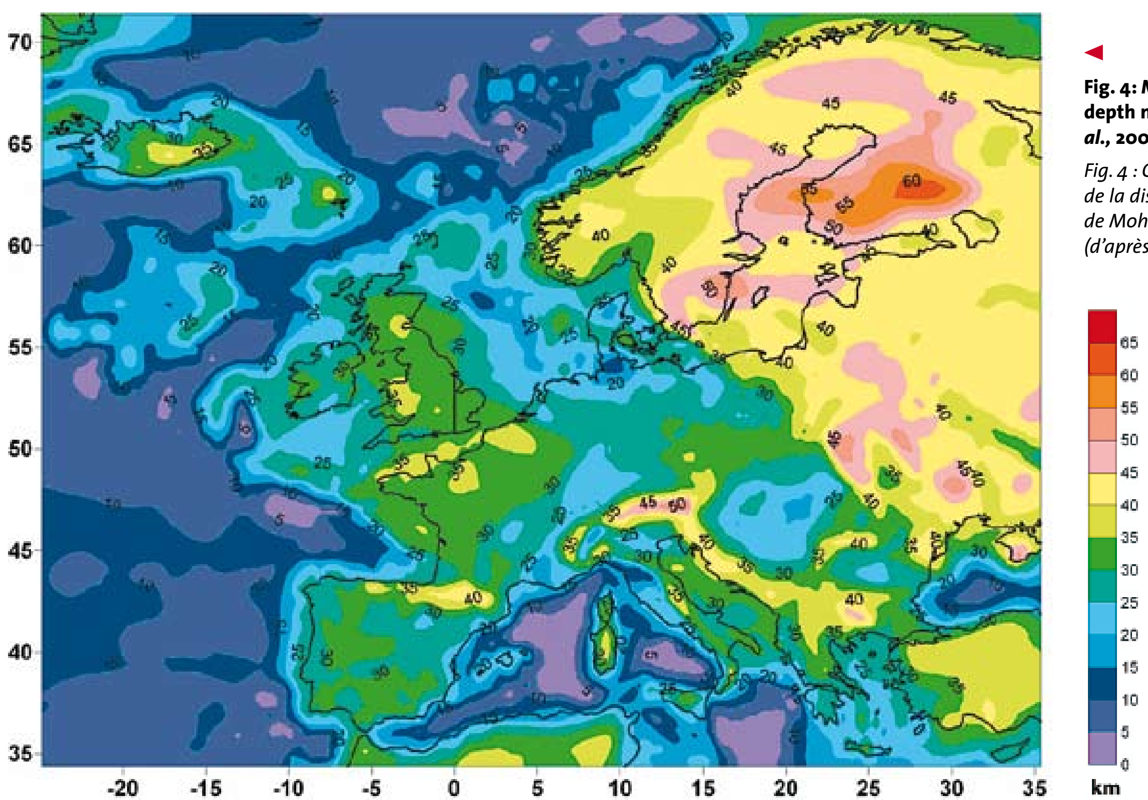


Fig. 4: Mohorovicic discontinuity depth map (km) (after Tesauro *et al.*, 2008).

Fig. 4 : Carte des profondeurs (km) de la discontinuité de Mohorovicic (d'après Tesauro et al.*, 2008).*

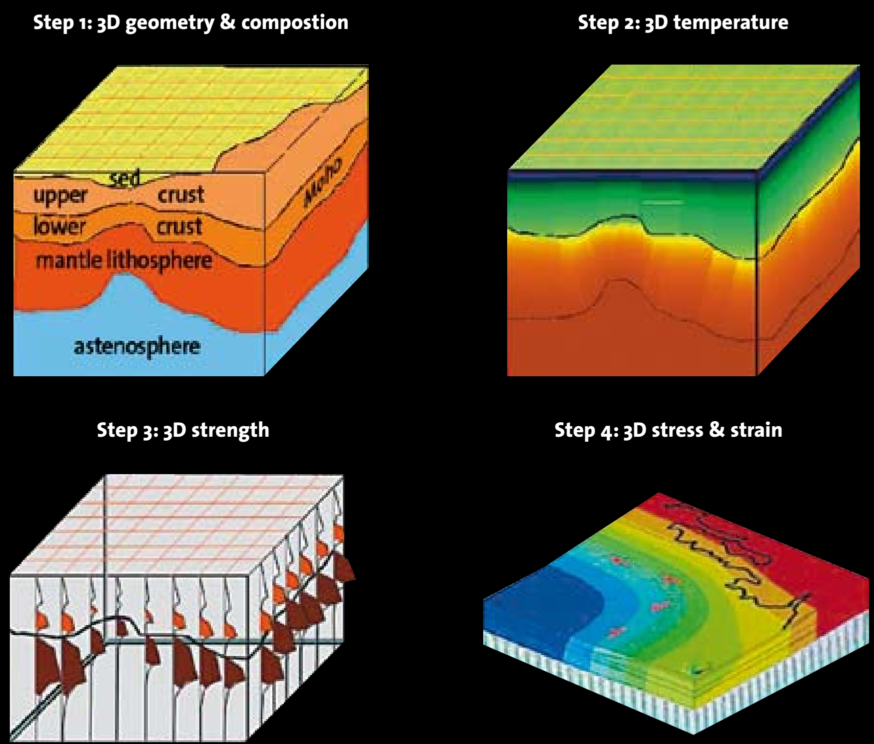


Fig. 5:
From crustal thickness (top left) and thermal structure (top right) to lithospheric strength (bottom left): conceptual thermal structure and composition of the lithosphere, adopted for the calculation of 3D strength models.

Fig. 5 :
De l'épaisseur crustale (en haut à gauche) et la structure thermique (en haut à droite) à la résistance de la lithosphère (en bas à gauche) : structure thermale conceptualisée et composition de la lithosphère retenues pour le calcul de modèles 3D de la résistance de la croûte.

modelling may evolve into a viable approach to constrain extreme events with high societal impact.

Intraplate seismicity (*figure 6*) is still poorly understood and tends to follow episodic intermittency patterns rather than the quasi-periodic earthquake activity of plate boundaries. TOPO-EUROPE will establish a database to systematically combine lithospheric data (e.g. Moho and LAB geometry, temperature, stress, structure) and recent movements, including topography changes, for all levels of seismicity: highly active plate boundaries, moderate intraplate activity and seismic quiescence.

Europe's coasts and river basins are subject to recurrent flooding, a major hazard to population and industrial agglomerations. The damage potential of floods is linked to even minor topographic changes that control the depth of inundation. TOPO-EUROPE will combine regional climate predictions with changes in sea and river level, and Holocene subsidence and uplift data in an effort to quantify Europe's flooding hazards.

The main risk factor for human society is the growing exposure and vulnerability of its assets (buildings, infrastructure, social systems). Over the past 150 years anthropogenic modification of the planetary environ-

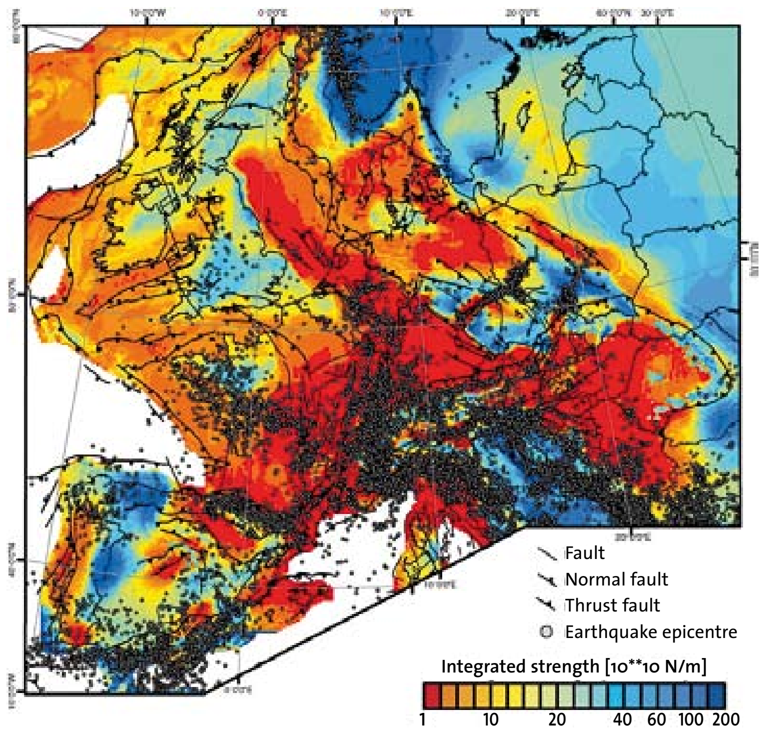


Fig. 6: Spatial comparison of crustal seismicity and integrated crustal strength (Cloetingh *et al.*, 2005). Earthquake epicentres after NEIC, 2004 queried for magnitude > 2 and focal depths < 35 km).

Fig. 6 : Comparaison spatiale entre la sismicité crustale et la résistance intégrée de la croûte terrestre (Cloetingh et al.*, 2005). Épicentres sismiques (déterminés par NEIC) correspondant à des événements de magnitude > 2 et de profondeur de foyer h < 35 km.*

ment has increased hazard potentials. For instance, groundwater extraction under and near cities affects surface elevation, the flooding potential. impacts on soil stability, and thus on ground motion during earthquakes (liquefaction potential, landslides).

"Provide new numerical modelling concepts and their validation by datasets from selected, well-documented regions."

Natural laboratories and analogues

The TOPO-EUROPE network provides a forum for multidisciplinary research, operating in a feedback mode between the advancement of new numerical modelling concepts and their validation by datasets from selected, well-documented regions covering a wide range of geodynamic settings – the so-called natural laboratories. Each of these, in a specific geodynamic setting, is optimally suited to address coupling between tectonic (endogenic) and surface (exogenic) processes and their effects on topography and geohazards.

TOPO-EUROPE natural laboratories (*summarized in table 1*) comprise some of the best-documented orogens, sedimentary basins and continental margins worldwide. As such, they are key areas for developing new-generation models for on-going lithospheric deformation and its effects on continental topography development at regional and local scales.

Integration and efficient handling of data sets are vital to the observation, modelling, process quantification, optimization and prediction chain. This can be achieved by (1) creating think-tanks to develop and implement new conceptual approaches; (2) creating Earth System teams to focus on unexplored interfaces between existing research activities and (3) building information technology cells to optimize data handling, software integration and modelling.

Table 1: TOPO-EUROPE natural laboratories.

Tab. 1 : Laboratoires naturels répertoriés dans TOPO-EUROPE.

AREA	WHY	HOW
The Alps/Carpathians-Pannonian Basin System	Mountain building and the development of deep continental basins have created Europe's weakest crust, prone to major earthquakes, land slides and flooding.	Coupling surface to deep processes for innovative reconstruction and for modelling landform evolution.
The Western-Central European Platform	In this region the continent is breaking apart, land is subsiding below sea level and much of Europ's population and infrastructure are concentrated.	Multi-scale seismic imaging, monitoring and modeling of environmental (neo-)tectonics.
The Aegean-Anatolian and Apennines-Tyrrhenian regions	Seismicity, volcanism and mountain building in the region result from the ongoing collision of the European and African-Arabian plates during the final closing stages of an ocean.	From deep structure to the surface for large-scale process understanding.
The Iberian Peninsula	Discrimination is needed between deformations induced by plate bondary forces and by deep-seated thermal anomalies.	Detailed imaging of the upper mantle (PICASSO-project) and coupling to surface processes.
The Scandinavian Continental Margin	Continental rupturing resulted in opening of an oceanic basin and the development of ocean-continent boundary zones rich in hydrocarbons.	Constraining and modeling differential vertical motions and continental break-up mechanisms at ocean-continent boundaries.
The East-European Platform	Ancient tectonic analogues of modern geodynamic processes and on-going subsidence of the southern margins.	Imaging the detailed structure of the upper mantle to evaluate the effect of deep mantle processes on reworking of lithosphere.
The Caucasus and the Levant	Interaction between continental colision and continental extension.	Source-to-Sink reconstructions of uplift, erosion, sedimentation and differential topography development.
Analogues, such as the Andes, the western USA and the Middle East	Regions where processes analogue to those in Europe result in constrating topographic expressions.	Effects of tectonics/climate interaction on topographic expression.

Earth Science analogues provide keys to reconstruct the past and predict the future. Natural laboratories yield information at different temporal and spatial scales. Comparison and quantitative analysis of high-resolution 4-D data cubes generated by the integrated TOPO-EUROPE components Monitoring, Imaging, Reconstruction and Process Modelling will improve the understanding of the Solid-Earth system. This process is iterative, with initial models building on existing data and concepts. New data from the natural laboratories will be used to test and refine these models.

The research program centres on critical regional and continental-scale Earth Science problems in natural laboratories. Together these cover the whole range of plate interaction processes expressed in current active tectonics to be explored, with the highest possible resolution, to discriminate between endogenic and exogenic processes and quantify their coupling. This is exemplified in the TOPO-WECEP Project, a follow-up to the EUCOR-URGENT network for the Neotectonics and Evolution of the Upper Rhine Graben.

The TOPO-WECEP natural laboratory

The Western-Central European Platform (WECEP) is a natural laboratory to assess the response of an intraplate domain to collision-related and ridge-push forces and thermal instabilities in the sub-lithospheric mantle. The WECEP underwent a polyphase Cenozoic evolution involving the development of the Cenozoic Rift System (ECRIS), inversion of Mesozoic tensional basins and upthrusting of basement blocks, lithospheric folding controlling uplift of the Vosges-Black Forest Arch and Armorican Massif, subsidence of the North Sea Basin, and thermal doming of the Rhenish Massif and the Massif Central [Dèzes *et al.* (2004); Ziegler and Dèzes (2007)].

In the context of TOPO-WECEP [1], new databases for the present-day stress field and ongoing vertical crustal motions will be developed, and close links will be established between stress field, neotectonic intraplate deformation, seismicity distribution and topography. State-of-the-art means of investigation will be applied to reconstruct the complex history of the WECEP and to identify the spectrum of dynamic forces driving its evolution. Notably, the present-day stress field reflects a combination of Alpine collisional coupling and Atlantic ridge-push forces. Thermo-mechanical forces are a crucial factor, accounting for lithospheric weakening in the Massif Central and Rhenish Massif.

(1) http://www.topo-wecep.eu/.

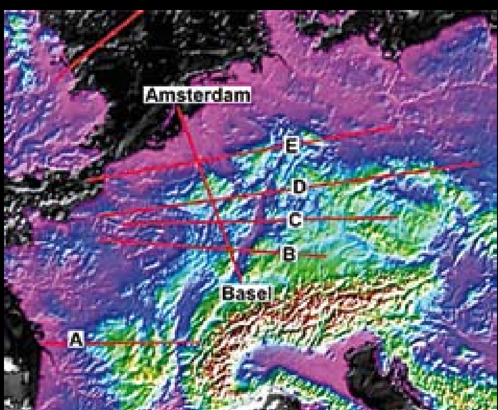
ECRIS evolution and uplift of the Massif Central, Vosges Black Forest Arch and Rhenish and Bohemian Massifs during the last 20 My had severe repercussions on the WECEP drainage system [Ziegler and Dèzes (2007)]. This development has hazard implications, insofar as parts of this system are prone to repeated catastrophic flooding (e.g. Northern Germany and Poland), and are highly susceptible to neotectonic deformation (*figure 7*).

Ensuring TOPO-EUROPE's future: material and intellectual means and funding

As to the means mobilized, future success will be largely conditioned by increasing overall capacity, but even more importantly by achieving true interoperability amongst TOPO-EUROPE's databases and modelling tools. Today's discipline-oriented approaches must be fully integrated to permit expansion into the "next generation" 4D applications. This requires major investments in Information Technology to adapt computer hardware and software facilities accordingly. Thus, added value could accrue by developing a Centre devoted to integrated interpretation, validation and modelling of coupled Deep Earth and Surface Processes, which is equipped with state-of-the art hardware and software, and which is dedicated to streamlined and consistent analysis of large data sets as a base for multidisciplinary research. A further and very vital aspect of TOPO-EUROPE is its investment into the future research capacity of European Earth Sciences by training young scientists in an environment, preparing them for employment.

> *"Future success will be largely conditioned by achieving true interoperability."*

Regarding funding, core activities of the TOPO-EUROPE project have been generously financed to date



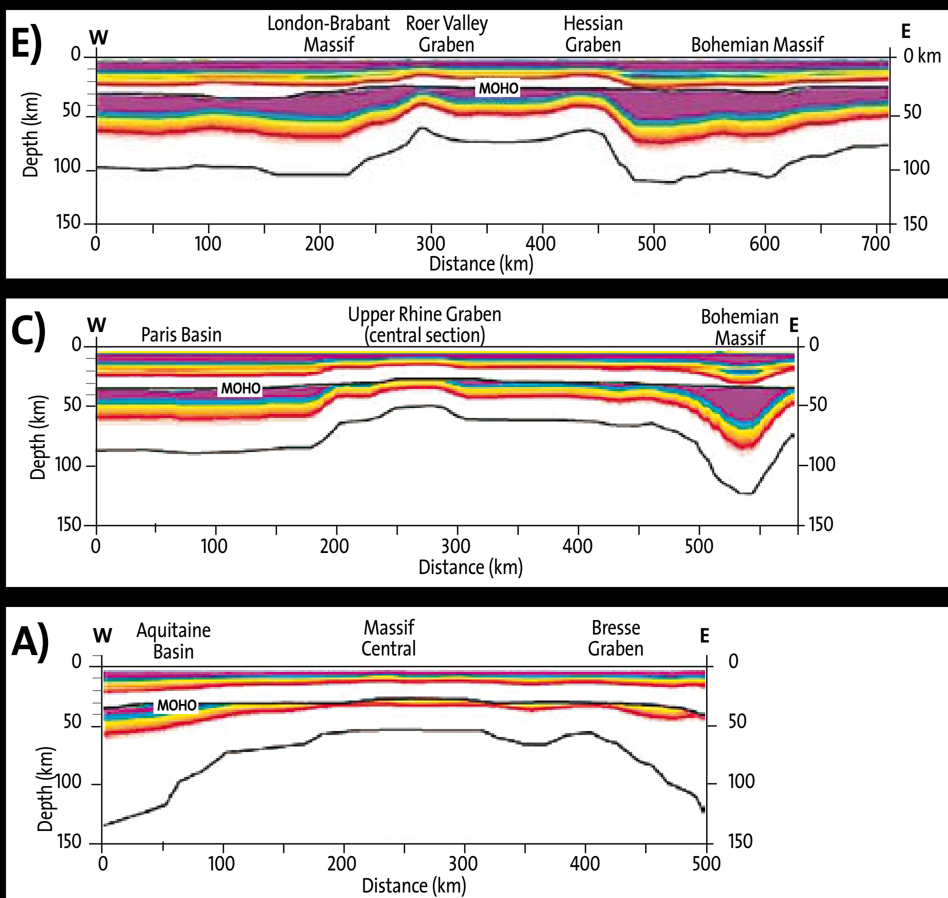


Fig. 7: Rheological cross-sections across the ECRIS:
E) Roer Valley and Hessian Grabens;
C) central part of the Upper Rhine Graben and A) Bresse Graben.

Fig. 7 : Coupes rhéologiques traversant l'ECRIS :
E) fossés de la vallée de la Roer et de la Hesse ;
C) partie centrale du fossé rhénan supérieur et A) le fossé de la Bresse.

► NéoPal, la base de données des indices d'activité néotectonique et des paléoséismes

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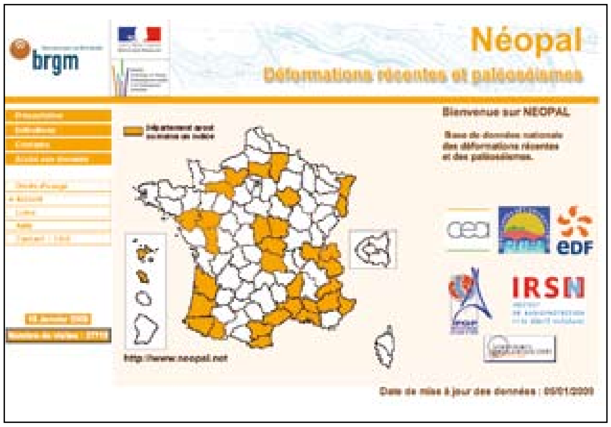
Située en contexte intracontinental, la France métropolitaine est une région où la sismicité est faible à modérée même si plusieurs séismes destructeurs ont été décrits au cours du dernier millénaire. Par ailleurs, des études récentes démontrent l'occurrence de séismes majeurs dont le temps de retour est bien supérieur à la période couverte par la sismicité historique (plusieurs milliers à dizaines de milliers d'années). Bien que ces séismes soient rares, ils pourraient néanmoins se montrer destructeurs. Leur prise en compte est indispensable pour l'évaluation de l'aléa sismique, en particulier pour le dimensionnement et/ou le confortement parasismique des installations industrielles à « risque spécial ». Pourtant, les failles susceptibles de générer de grands séismes en France ne sont pas encore correctement identifiées, en raison de leurs faibles taux de déplacement.



À la fin 2001, le ministère de l'Ecologie et du Développement durable a ouvert au public une base de données nationale gérée par le BRGM pour enregistrer des indices de déformations néotectoniques et les paléoséismes en France. Ces indices sont décrits en détail avec les interprétations des auteurs (origine, âge...) pondérées par l'avis d'un comité d'experts (qui implique également EDF, l'IRSN, le CEA, l'université Paris VI, le CEREGE, l'EOST et l'IPGP). Cet avis repose sur une analyse détaillée et critique de la source bibliographique. La base NéoPal incorpore aussi des failles dont l'activité récente a été discutée dans la littérature et sur lesquelles le comité d'experts émet un avis.

La base de données NéoPal est consultable gratuitement sur internet : **http://www.neopal.net/**

through European Science Foundation (ESF) EUROCORES programme, amounting to 13.5 M€, generating 60 new positions for young researchers (http://www.esf.org/activities/eurocores/ programmes/topo-europe.html). This support is expected to carry forward into the future. However, other research domains must rely on funds and research personnel made available by a range of institutions, public or private, including National Science Foundations and Academies, Research Councils or Ministries, Universities and Geological Surveys.

Couplage profondeur–surface déterminant la topographie européenne : le projet TOPO-EUROPE

La topographie continentale résulte de processus mobilisés dans les profondeurs de la Terre, à sa surface et dans l'atmosphère, ce qui se traduit par des modifications lentes du paysage et des effets sur l'environnement et les risques naturels. Si les eaux (des mers, des lacs ou des nappes) s'élèvent et/ou que les terres s'affaissent, ce sont des inondations qui menacent. Si, au contraire, le niveau des eaux s'abaisse et/ou que les terres se soulèvent, alors cela entraîne des conséquences néfastes en matière d'érosion et de désertification. L'Europe a subi au cours d'un passé récent des pertes humaines et des dommages importants par suite de glissements de terrains massifs. L'accroissement des populations vivant dans des bassins fluviaux et des zones côtières comme dans des régions montagneuses fait redouter de véritables catastrophes, d'autant plus que le réchauffement de la planète déclenche des événements météorologiques extrêmes de plus en plus nombreux. En plus de ces risques, les séismes et les éruptions volcaniques, survenant le long de zones actives, sont à l'origine de modifications topographiques localisées et éphémères, mais, en même temps, ils livrent des informations précieuses et utiles à la prévision des aléas sur les contraintes et les déformations accumulées. Les différents processus du Système Terre impliquent des échelles de temps très contrastées : effets tectoniques à très long terme, effets résiduels des glaciations, changements climatiques et environnementaux, fort impact anthropique du siècle écoulé. L'enjeu des Géosciences est de comprendre ce système complexe, son état actuel et ses évolutions prévisibles, pour mieux l'apprivoiser. Des projets tels que TOPO-EUROPE sont conçus sur mesure pour contribuer à cette entreprise.

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