EC PROJECT
EVG1-CT-2002-00069

REL. I. E. F.

RELiable Information on Earthquake Faulting

Large Earthquake faulting and Implications for the Seismic Hazard Assessment in Europe: *The Izmit-Düzce earthquake sequence of August-November 1999 (Turkey, Mw 7.4, 7.1)*

FINAL REPORT

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6.1 Background

The knowledge of the characteristics of the seismicity of a region is fundamental to forecast future earthquakes both in terms of location, size and potential damage. Historical and instrumental seismicity, which are traditionally used as the basis to achieve this objective, can be fruitfully integrated with geological information. By providing knowledge about location and slip rates of active faults, location and size of subsequent ruptures, recurrence times, fault segmentation models at different scale, etc., geology represents a useful tool to understand and describe the seismic behaviour of faults in a region for a time window much longer (up to 10 kyr) than that usually covered by the instrumental (ca. 100 yr) and historical (ca. 1-2000 yr) records. This, coupled with a better understanding and modern reappraisal of the historical catalogues and new description of the laws that control the propagation of and the response to the seismic waves, are among the key input to modern hazard assessment.

6.2 Scientific/technological and socio-economic objectives

The main objective of the work that INGV has developed within the RELIEF project was to contribute with new data and new approaches to the knowledge of the seismic behaviour of the Düzce fault segment of the North Anatolian Fault Zone as input to reliable assessment of the seismic hazard. Following the achievement of this objective substantial effort was focused on: (1) understanding the internal complexity of active fault zones and its impact on fault segmentation during major earthquakes; (2) understanding the relations between the structures observed at the surface and the structures at depth (e.g., damage zone, principal slip zone); (3) recognition and dating of paleoearthquakes that ruptured the Düzce and Mudurnu faults; (4) testing of new approaches in paleoseismology (e.g., dendrochronology) and new dating techniques (e.g., 210Pb dating).

Dissemination through GIS database and WEB site was also a major objective for INGV to be achieved during the project.

From a social-economic point of view the achievement of these objectives represents an important contribution to future planning of social and economic activities in the area. This is particularly true for the Düzce area where development is still ongoing and is expected to be boosted further by the completion of the new freeway, connecting Ankara with Istanbul.

6.3 Applied methodology, scientific achievements and main deliverables

Traditional and experimental methodologies have been applied. The main part of the study was based on tectonic geomorphology, structural geology and traditional geological mapping both in the field or by means of aerial photo, DEM and satellite images interpretation. Paleoseismology was carried out mainly through trenching and study of tree cores. Detailed stratigraphic analyses and high quality dating both for ^{14}C and ^{210}Pb were used to support and complete the paleoearthquake history.

All the geological, geomorphological and topographic data have been collected in a GIS database to maximize the potential for data integration, analysis and representation. A key for dissemination was the planning, realization and maintenance of the RELIEF WEB site.

The deliverables to which the work performed by INGV has substantially contributed are:

D5 - High resolution DEM, geomorphology maps
D6 - Geophysical and trench sections
D8 - List of paleoearthquakes (trenching)
D9 - List of paleoearthquakes (tree ring analysis)
D10 - Recognition, dating and size of earthquakes
D15 - Analysis of slip distribution depth/surface
D16 – Re-evaluation of seismic catalogue, maps of damage (subcontracted to SGA)
D18 - Attenuation models and seismic hazard maps
D21 - Map of segmentation and friction models, seismic strain release
D22 - Integrated catalogue of Holocene earthquakes and recurrence intervals
D28 - Publications
D29 – Web site
D30 - Geographic Information System

In the following chapters we present the main scientific achievements of INGV, with the indication of the specific deliverables to which each set of results has contributed.

6.3.1. The Düzce Fault and its evolution (contribution to deliverables 5, 15, 21)

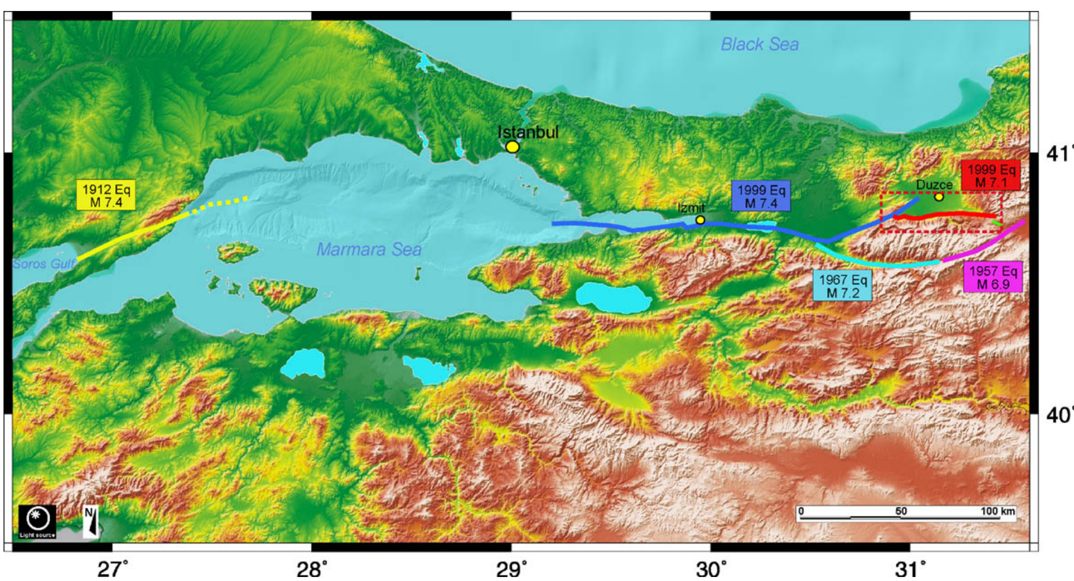


Figure 1. Study area of the RELIEF project; the northern branch of the NAFZ between Bolu and Saros Gulf was the focus of this project. The red dashed rectangle indicates the area of detailed investigations around the Düzce fault (red line). The on-land earthquake segments of the North-Anatolian fault along with the date of their most recent large earthquake are shown.

The Düzce fault was the eastern and second of the NAFZ segments that ruptured in 1999 (Figures 1 and 2). The Düzce fault has been mapped in detail both from a geomorphic and structural point of view. A 1:20.000 scale map of the ca. 40

km-long 1999 surface rupture, including ca. 350 measurements of the coseismic and cumulative offsets, and a photo gallery was completed.

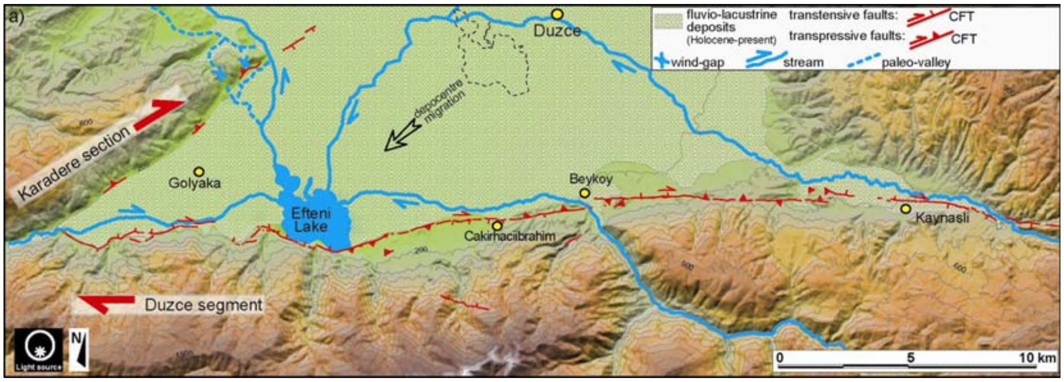


Figure 2. Trace of the 1999 earthquake surface ruptures (CFT, red line) and main features of the drainage system.

The coseismic surface ruptures (CFT) *[CFT=coseismic fault trace]* are organized in over-lapping *en échelon* systems. The main characteristics of the system are left-stepping synthetic Riedel shears (R-shears) and a right-stepping array of compressional fold axes (Figure 3).

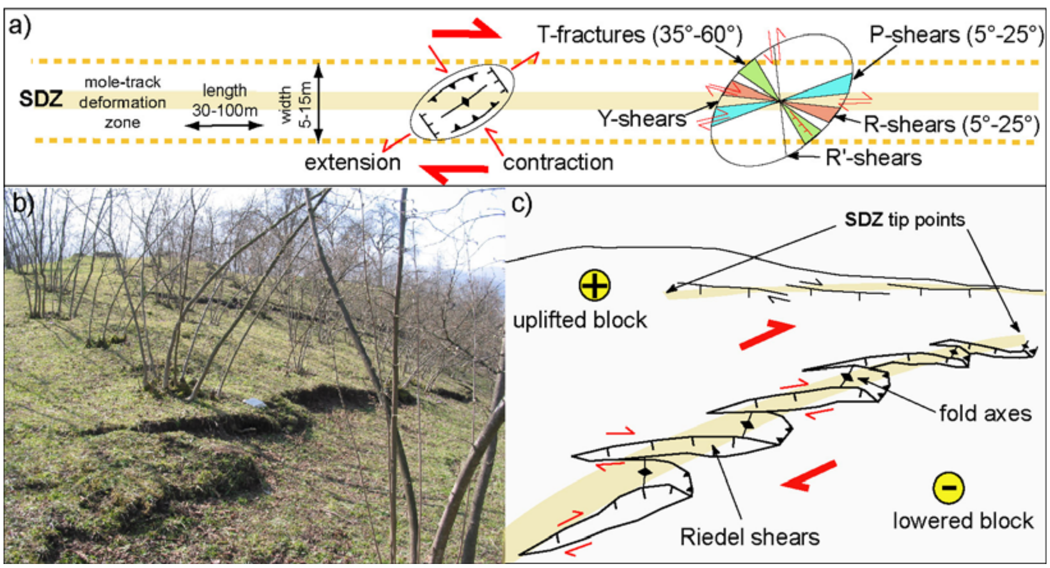


Figure 3. a) Sketch of typical dextral single displacement zone (SDZ) and its approximate size. Outcrop scale structural elements are drawn along with the relative angle of deviation from the SDZ. b) and c) oblique photo and sketch of a single displacement zone (SDZ) in the study area.

At places, where the width of the deformation zone increases, Riedel systems develop a second array of right-stepping synthetic shears (P-shears or Thrust-shears), that locally join or end up to the R-shears [e.g., Tchalenko, Geol. Soc. Am. Bull., 1970; Wilcox et al., A.A.P.G. Bull., 1973; Naylor et al., JSG, 1986]. At a few sites, the zone of deformation consists also of P-shears together with compressional fold axes. Here, P-shears have grown and linked to R-shears, forming shear lenses, and afterwards Y-shears have also developed, in a typical anastomosing pattern of a through-going wrench fault, parallel to the SDZ [e.g., Woodcock and Schubert, P.L. Hancock Eds., 1994; Naylor et al., JSG, 1986] (Figure 4).

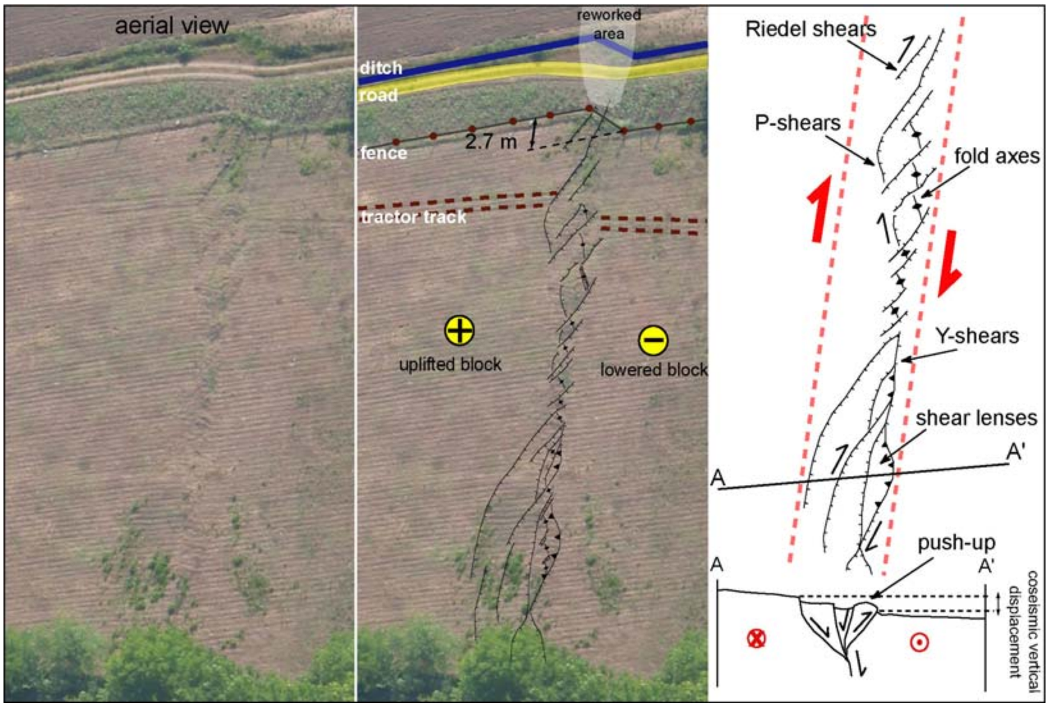


Figure 4. a) and b) Aerial view of typical anastomosing pattern of a single displacement zone (SDZ) and c) simplified sketch map coupled with not-in-scale topographic profile.

This arrangement can be recognized at different scales: (1) at the outcrop scale, where 1-10 m-long *en échelon* structures define single displacement zones (SDZ); (2) at the hundreds-of-meters scale, with 30-100 m-long *en échelon* SDZ, forming 300-800 m-long principal displacement zones (PDZ) (Figure 5); (3) at the kilometer-scale, where also 1999 fault trace subsections, both transpressional and transtensional, define an *en échelon* pattern.

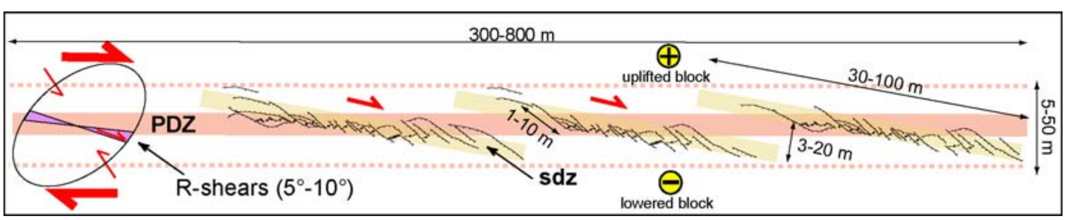


Figure 5. Sketch of the en-échelon arrays formed by single displacement zones (SDZ), whose envelope represents a principal displacement zone (PDZ).

On the basis of cumulative tectonic landforms we traced the long-term fault expression at the surface along the 1999 rupture zone (e.g. Figure 6). This long-term fault expression brings out that the bulk of the ongoing dextral displacement is localized mostly along the coseismic ruptures and, in addition, illustrates the existence of fault splays and a broad band of subsidiary deformation, both brittle or plastic, which are part of the PDZ. The cumulative tectonic landforms along the 1999 rupture zone indicate also a fault pattern consistent with the coseismic one.

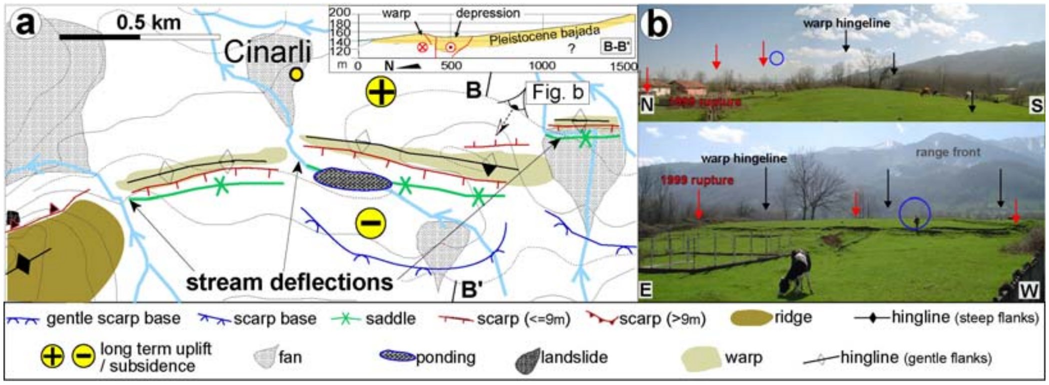


Figure 6. Cumulative tectonic landforms along the Cinarli subsection. a) Main tectonic and geomorphological features of the Cinarli subsection. Contour interval 10 m. The inset shows a simplified cross-section of the long-term escarpment on the Pleistocene bajada deposits that was affected by the 1999 ruptures. b) Photos of tectonic warp (man in circle for scale*).*

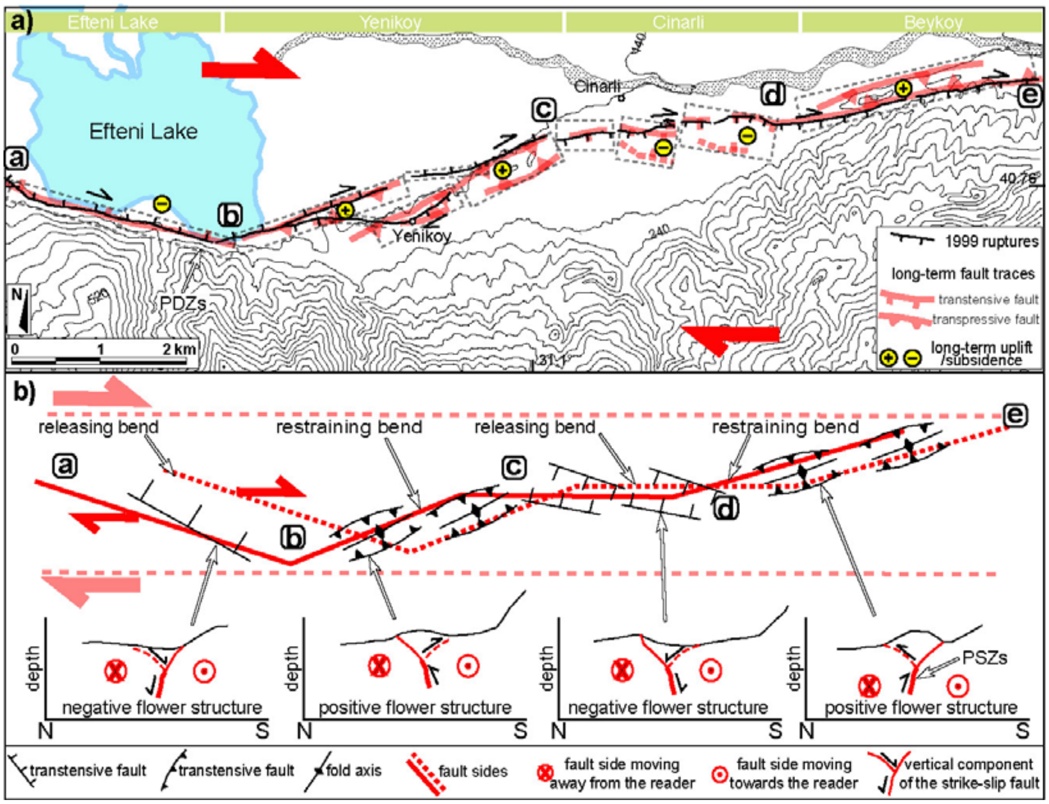


Figure 7. a) Comparison of the 1999 coseismic ruptures and the fault trace inferred from near-fault cumulative tectonic landforms. Contour interval 20 m. b) Sketch showing the coherence between restraining and releasing bends of the 1999 coseismic ruptures (a-b, b-c, c-d and d-e subsections) and the location of typical cumulative tectonic landforms. Simplified cross sections for each fault subsections are also shown. Big red arrows show the shear couple of the Duzce fault. Small red arrows show relative movement, both coseismic and long-term, of the two fault sides (dashed and continuous red lines).

Furthermore, these landforms suggest different local kinematics which can be largely explained by the different orientation of the PDZ portions with respect to the average strike of the Düzce fault (e.g., Figure 7). The transtensional and transpressional structures produce local vertical deformations that are related to shallow, near-surface features and do not represent the dip-slip component described by geodetic data or the almost pure strike-slip motion at seismogenic depth.

Cumulative tectonic landforms in the *far field* zone of deformation suggest that the Düzce Fault System (DFS) is more complex. In fact, this fault system is formed by: the WNW-ESE and SW-NE trending Plio-Quaternary range front fault system (PQFS) (e.g. Figure 8a), and the WSW-ENE to E-W striking PDZ. Overall, the DFS represents the fault damage zone embedding also the principal slip zone (*sensu* Sibson [BSSA, 2003]) whose surface expression is the PDZ.

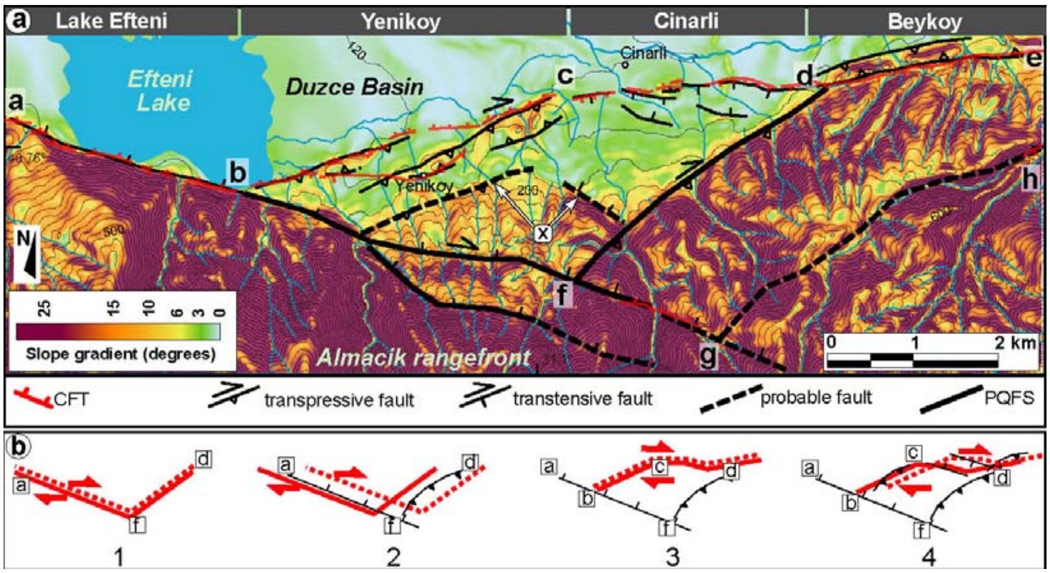


Figure 8. a) Slope gradient map from DEM and long-term fault system of a key area. Contour interval 20 m. b) Schematic evolution of the Düzce fault system in the study area. Grey arrows show relative movement of the two fault sides (dashed and continuous grey lines). 1- The range front faults (a-g and f-d) start to be active (Middle/Late Miocene or Late Pliocene); 2- The geometry of the range front faults produce extensional (a-f) and compressional (f-d) local stress fields (up to Early/Middle Pleistocene ?); 3- The northern strand (b-c-d) starts to be active (Late Pleistocene?); 4- The geometry of the Yenikoy (b-c) and Cinarli (c-d) subsection produce compressional and extensional local stress fields respectively.

The consistency of geometry, location and style of the 1999 ruptures with the *near fault* long-term tectonic landforms is a strong indication that the characteristics and complexities of the 1999 rupture in the study area have been persistent during several seismic cycles or more (e.g. Figure 6). The *far field* landforms suggest that, during the Late Pleistocene, the Düzce fault developed structures with the tendency to simplify the complex geometry of the PQFS into a more straight fault trace (e.g. Figure 8b) and we expect this fault system to continue to straighten out in the future, until it become a smooth and narrow fault zone.

Cumulative deformations for estimating slip rates of the Düzce fault for different intervals of time were mapped and measured. We reconstructed right-hand stream deflections of about 100 m, and offset of the remnant of an old be-headed alluvial fan of about 900 m and 300 m. Radiocarbon and OSL dating was performed to provide chronological constraints (Figure 9). Obtained slip rates are in the range 12-17 mm/yr (Figure 10).

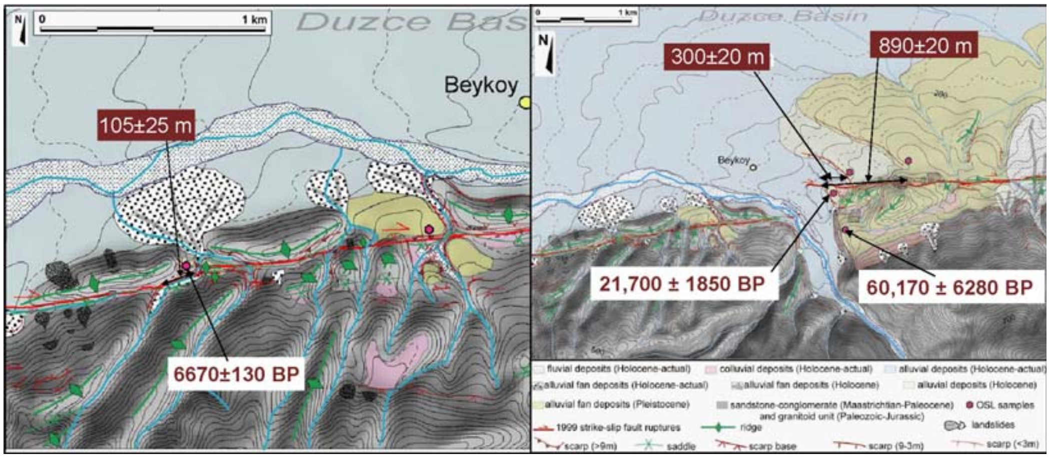


Figure 9. Offsets and dating of geomorphic markers for slip rate calculations at different timescales during the past 60,000 years.

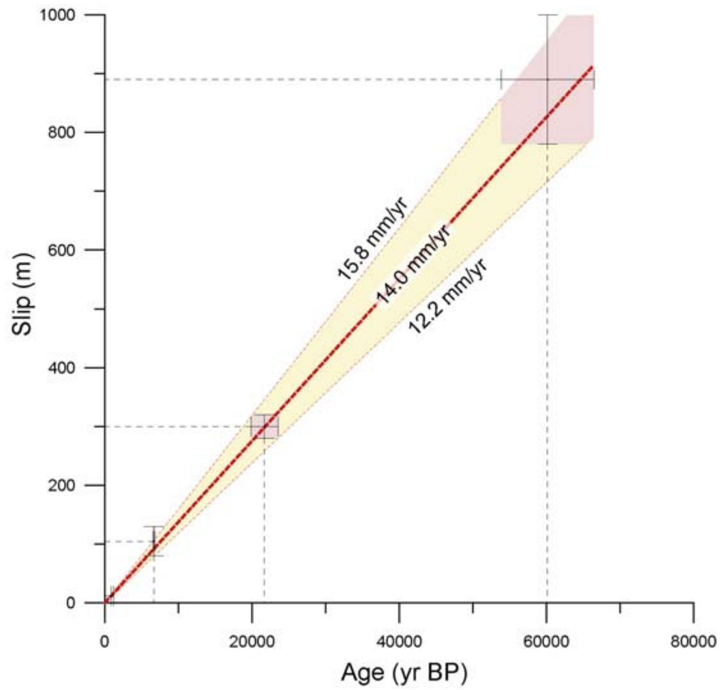


Figure 10. Slip rates calculated on the base of geomorphic marker offsets during the past 60,000 years.

As already mentioned, the comparison between the PDZ (CFT and its long-term expression) and the PQFS was used as a basis for depicting the evolution of the internal complexity of the fault through time. In particular, on the basis of the characteristics of the fault at the surface we were able to subdivide the Düzce fault into two sections (Figure 11). The western one, where the PDZ follows mainly the saw-tooth trajectory of the PQFS, and the eastern section, where the PDZ cross-cuts the en-échelon pattern of the PQFS and is formed by mature E-W trending Y-shears. The eastern and western fault sections represent different stages of the evolution of the PQFS toward the present PDZ.

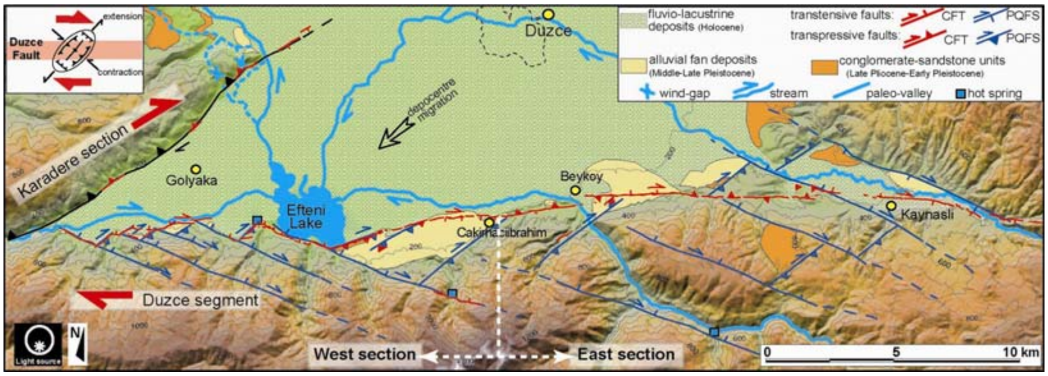


Figure 11. Trace of the 1999 earthquake surface ruptures (CFT, red line) and simplified reconstruction of the range front system (PQFS, blue faults).

The difference between the two Düzce sections appears to originate from the releasing junction between the Düzce and Karadere faults. In fact, the mechanical interaction of these faults produces a zone of low normal stress across the western part of the Düzce fault. Interestingly, the difference between the two Düzce sections is a permanent feature at the surface that coincides with a change in the 1999 earthquake slip distribution at depth (Figure 12). In this hypothesis, the low normal stress across the western Düzce fault becomes a permanent characteristic of that part of the fault and results in an unfavorable setting for hosting important asperities in this part of the fault also in the future.

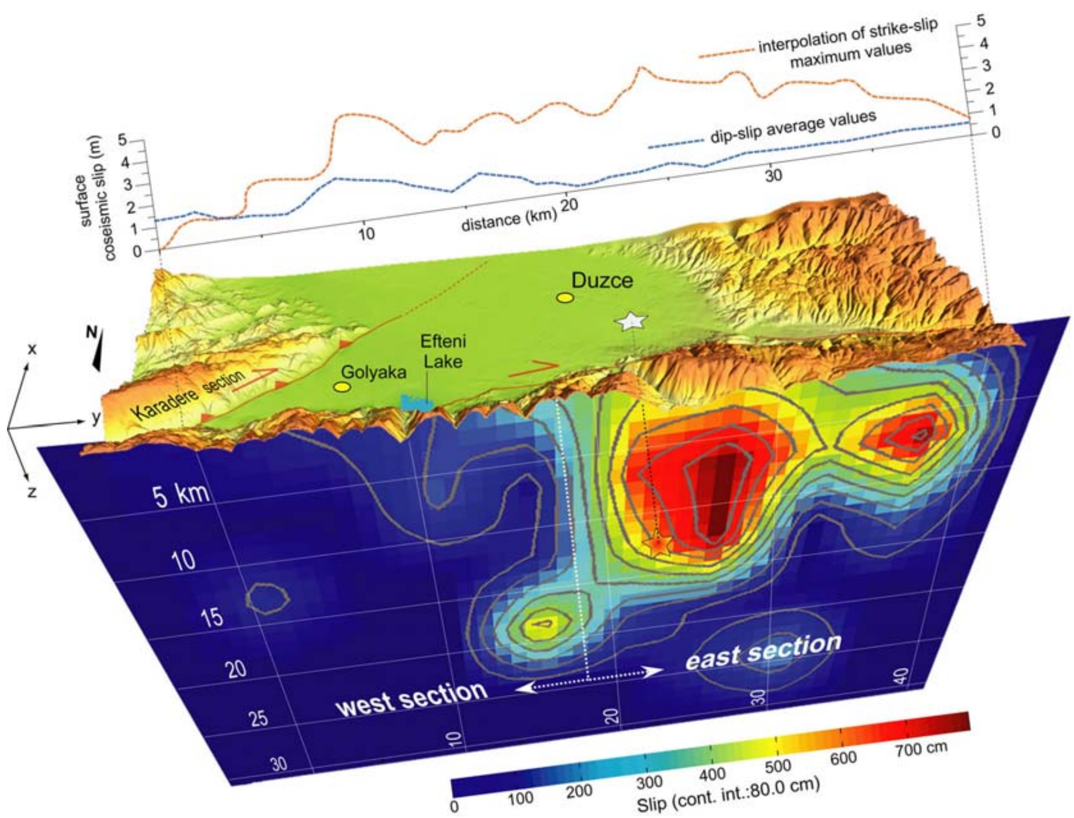


Figure 12 Block diagram showing the coseismic strike-slip distribution at depth of the 1999 Düzce rupture (in scale after Delouis et al. http://www.seismo.ethz.ch/srcmod) for a comparison with the structures, morphology and coseismic strike and dip-slip distribution at the surface. Dashed white line

indicates the boundary between the two Düzce fault sections. Hypocentre and epicentre of the mainshock are also drawn (after Delouis et al. http://www.seismo.ethz.ch/srcmod).

6.3.2. Paleoseismology of the Düzce fault (contribution to deliverables 6, 8, 10, 22)

In 2003 and 2004 we excavated five sites along the Düzce fault at locations where the 1999 ruptures were still visible (Figure 13).

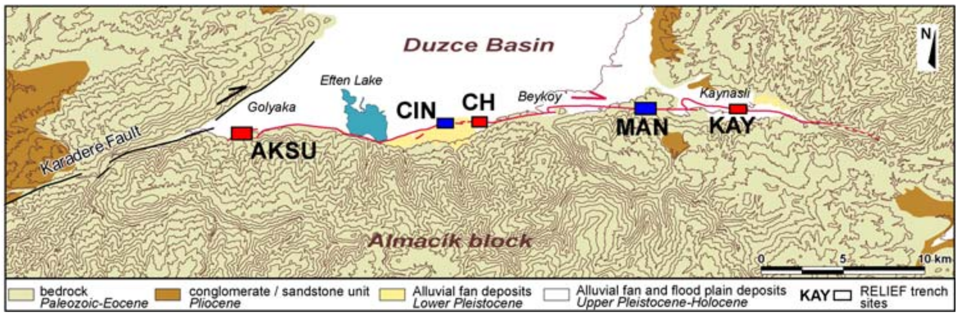


Figure 13. Location of the RELIEF paleoseismological trench sites along the Düzce fault. Blue boxes are the 2003 trench sites, red boxes are the 2004 trench sites.

We excavated a total of 10 trenches, 7 across the fault, and 3 fault-parallel ones. Because of the type of sediments and sedimentary structures crossed, no piercing points to measure horizontal offset were found, thus the fault parallel trenches were not studied in detail.

On the basis of sedimentary and structural relations we found in all the trenches evidence for 2 to 3 surface faulting paleoearthquakes pre-dating the 1999 event. A few examples are shown in figure 14.

Dating of paleoearthquakes was based both on radiocarbon and ^{210}Pb analyses. Although dating was rather problematic and age ranges of occurrence of paleoearthquakes are quite broad, by merging the results obtained from all the trenches it is possible to reconstruct the seismic history of the Düzce fault for the past 800 yr. We correlate events between different trenches on the basis of their stratigraphic position and their age under the assumption that, similarly to the 1999 event, paleoearthquakes on the Düzce fault ruptured the whole fault. Unfortunately, no insights can be derived from the historical records, in fact even though historical evidence for damaging earthquakes exists in Turkey for the past 2000 yr, no clear evidence for potential historical earthquakes produced by the Düzce fault in specific during the past centuries has been found. The only historical earthquakes that are known to have produced damage near the Düzce fault are the AD1719 earthquake, which possibly occurred along the Karadere fault, and AD1878 earthquake, which possibly occurred along the Hendek fault. Interestingly, local people living near the Mengencik (MAN) site recall their grandparents telling them about an earthquake at the end of the 19th century, producing ground ruptures exactly where these occurred in 1999. Unfortunately, no independent evidence for this has been found yet, but because this information fits well with the results from trenching, we take this information as a possible reference.

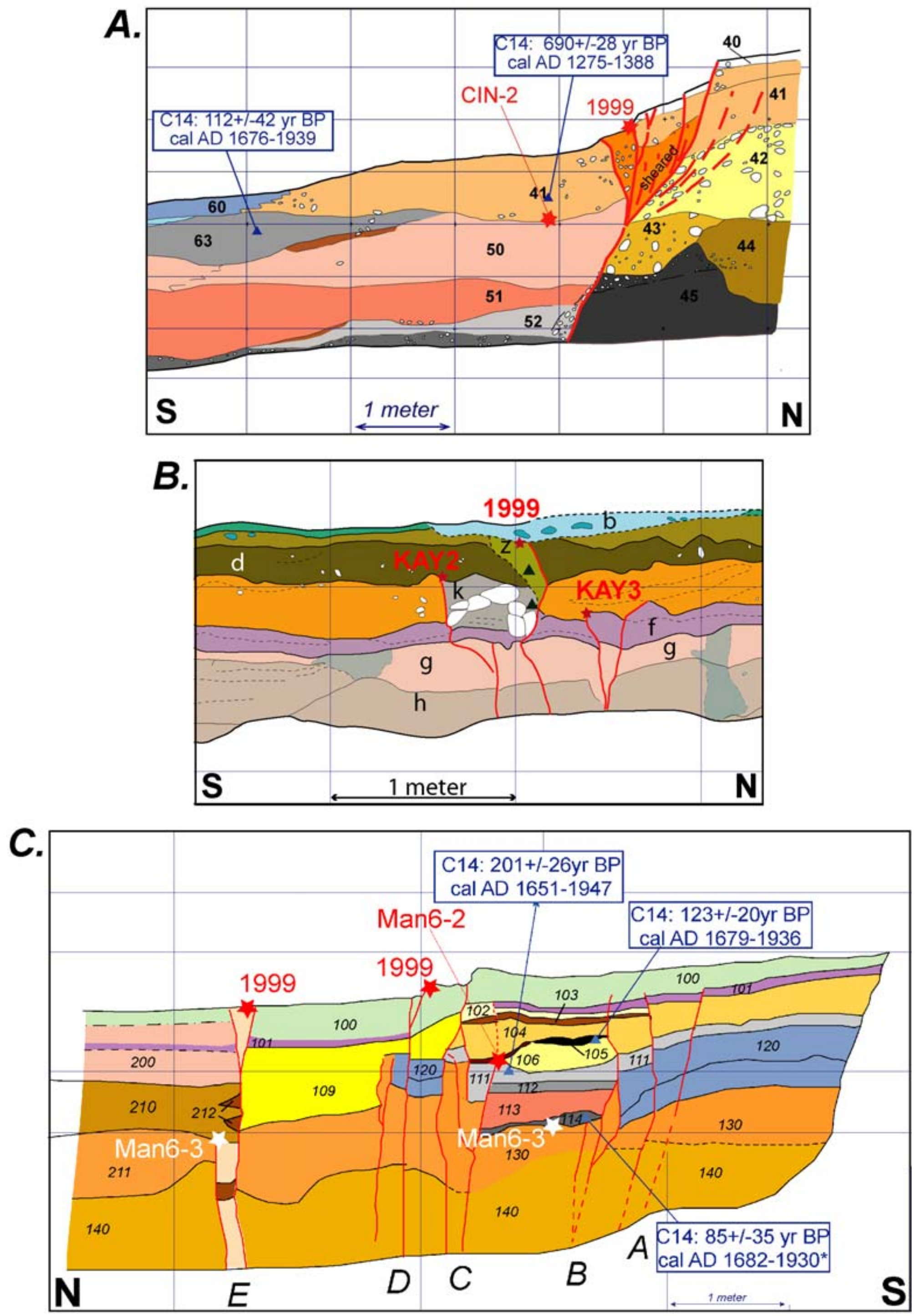


Figure 14. Examples of earthquake recognition in the Düzce paleoseismological trenches. **A.** Upward fault terminations in trench MEN6, **B.** Upward fault terminations in trench KAY, **C.** Colluvial wedge in trench CIN.

Trench KAY 40.776095, 31.313858 (WGS84)	*Earthquake Correlation*	*Age interval*	*Confidence*
Most recent (KAY-1)	DUZ-1	AD 1999	100%
penultimate (KAY-2)	DUZ-2/3	after AD 1475	high

event KAY-3	DUZ-4	AD 1035-1640	medium-high
event KAY-4	DUZ-5	AD 685-1220	medium
Trench MAN1 40.774660, 31.246047 (WGS84)			
Most recent (MAN1-1)	DUZ-1	AD 1999	100%
penultimate (MAN1-2)	DUZ-2	AD 1445-1950 *[possibly close to AD1880*]*	medium-high
event MAN1-3	DUZ-3	AD 1445-1950	medium
Trench MAN5 40.774660, 31.246047 (WGS84)			
Most recent (MAN5-1)	DUZ-1	AD 1999	100%
penultimate (MAN5-2)	DUZ-3	AD1495-1950	medium
event MAN5-3	DUZ-4	AD1185-1655	medium
Trench MAN6 40.774718, 31.248849 (WGS84)			
Most recent (MAN6-1)	DUZ-1	AD 1999	100%
penultimate (MAN6-2)	DUZ-2	AD 1685-1930	high
event MAN6-3	DUZ-3	before AD 1685-1930	medium-high
Trench CH 40.766222, 31.131424 (WGS84)			
Most recent (CH-1)	DUZ-1	AD 1999	100%
penultimate (CH-2)	DUZ-2	AD 1680-1950 *[or, AD 1480-1950]*	medium
event CH-3	DUZ-3	AD 1680-1950 *[or, not constrained]*	medium-high
Trench CIN 40.765541, 31.111827 (WGS84)			
Most recent (CIN-1)	DUZ-1	AD 1999	100%
penultimate (CIN-2)	DUZ-2	AD 1675-1900 *[possibly close to AD1900*]*	medium-high
event CIN-3	DUZ-3	AD 1270-1700 *[possibly close to AD1700*]*	medium-high
Trench AKSU 40.7569, 30.9562 (WGS84)			
Most recent (AKSU-1)	DUZ-1	AD 1999	100%
penultimate (AKSU-2)	DUZ-2	after AD 1670-1950, shortly before AD 1880-1940**	high
event AKSU-3	DUZ-?	close to AD 890-1020	low

Table 1. Summary of the results from the seven paleoseismological trenches investigated along the Düzce fault during the RELIEF project. The first column lists the surface faulting events recognized at each trench. The second column shows the correlation of paleo-earthquakes between different locations along the fault naming them DUZ1 to DUZ5 where DUZ1 is the 1999 earthquake. In column three the age interval of occurrence of the event is given based on radiocarbon, 210Pb dating (indicated with *), or archaeological evaluations (indicated with **). In column four we attributed confidence level (empirical) based on the constraints existing on the recognition of the event itself.

Table 1 contains the age ranges of the paleoearthquakes recognized in each trench; the event of the Düzce fault obtained by the correlations is indicated in the second column, with DUZ1 being the 1999 event. By integrating the results obtained in the different trenches we can summarize the recent seismic history of the Düzce fault as:

event DÜZCE 1: 1999;
event DÜZCE 2: AD1685-1900, possibly end of 19th century;
event DÜZCE 3: AD 1685-1900, possibly close to AD 1700;
event DÜZCE 4: AD 1185-1640;
event DÜZCE 5: AD 685-1220.

It is interesting to notice that, according to the paleoseismological results, both the AD1719 and AD1878, which are considered to have occurred on different faults, may have ruptured the Düzce fault instead or, alternatively, a cascade of events occurred on the Düzce and nearby faults at that time (as in the case of the Izmit and Düzce 1999 earthquakes).

Five events since AD 685-1220 yield an average recurrence for the Düzce fault in the range of 200-325 yr. However, the three most recent events, including 1999, occurred within 300 yr and may be suggestive of clustering. Assuming that the ca. 3 m average slip produced by the 1999 earthquake is characteristic for this fault, these recurrence times yield slip rates in the order of 9-15 mm/yr. This is in agreement with the estimates of slip rates obtained from cumulative offsets and dating of Late Pleistocene-Holocene geomorphic features (ca. 14 mm/yr) as well as with GPS estimates.

6.3.3. Paleoseismology of the Mudurnu valley fault (contribution to deliverables 6, 8, 10, 22)

The paleoseismic interpretation of a trench located at the central part of the July 22, 1967 earthquake segment (Mudurnu valley), yielded preliminary constraints on the recurrence of recent surface-rupturing earthquakes at the southern branch of the NAFZ, W of the Bolu basin. The trench was excavated on a Holocene terrace of the Mudurnu River (Figure 15), across a N-facing scarp and a very subtle pressure ridge (push-up) about 12 m wide, superimposed on the scarp. The internal structure of the pressure ridge consisted of two bounding fault zones that were reaching the present surface and a sealed fault zone in-between them (Figure 16). Three (possibly four) paleoearthquakes –before 1967- were identified in the trench (I to IV). The most conservative interpretation of the radiocarbon dating results suggests that at least two (possibly three) paleoearthquakes have occurred since AD 1394. This translates to a maximum average recurrence interval of 286 yrs (possibly 191 yrs), whereas the oldest recognised event (IV) is unconstrained. An unpaired radiocarbon age suggests that the penultimate event occurred after ca. AD1700, but one date may not be sufficient to exclude the possibility that it may have been one of the earthquakes that occurred in 1668, as suggested by Ikeda et al (1991). A second interpretation, which we cannot exclude with the available data, can be based on very young ages obtained from a unit affected by the oldest event recognised (IV). Two ages from different materials suggest that paleoearthquake IV and the two (possibly three) younger ones occurred since ca. AD1668 (max. average recurrence interval 100 yrs, possibly 75 yrs). An implication of this second scenario is that the 1967 earthquake rupture may not be characteristic. This is so because a minimum value for the slip during this earthquake multiplied by (maximum) average recurrence intervals of 100-75 yrs, yields minimum values for the slip rate of the southern branch of the NAFZ that may be too high compared to those we can infer from GPS measurements (ca. 20 mm/yr across the whole zone apparently equally distributed across the Mudurnu and Düzce faults).

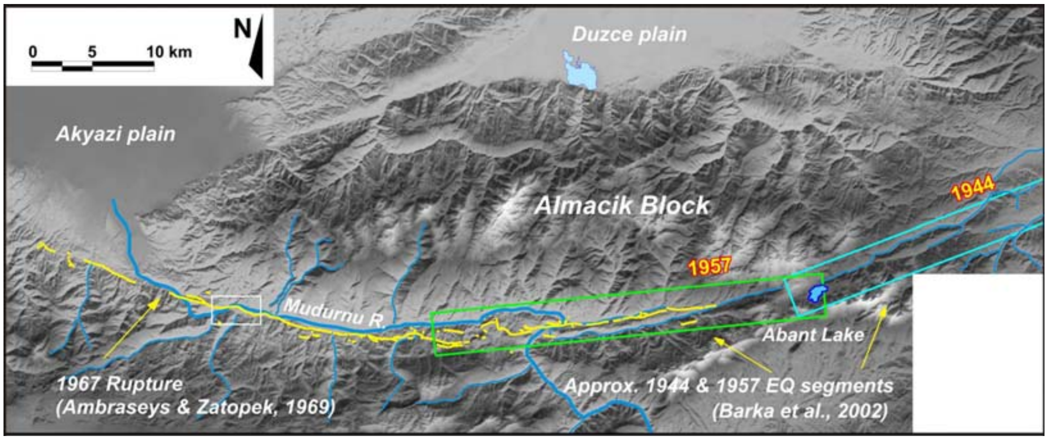


Figure 15. Location of the trench excavated across the Mudurnu valley fault.

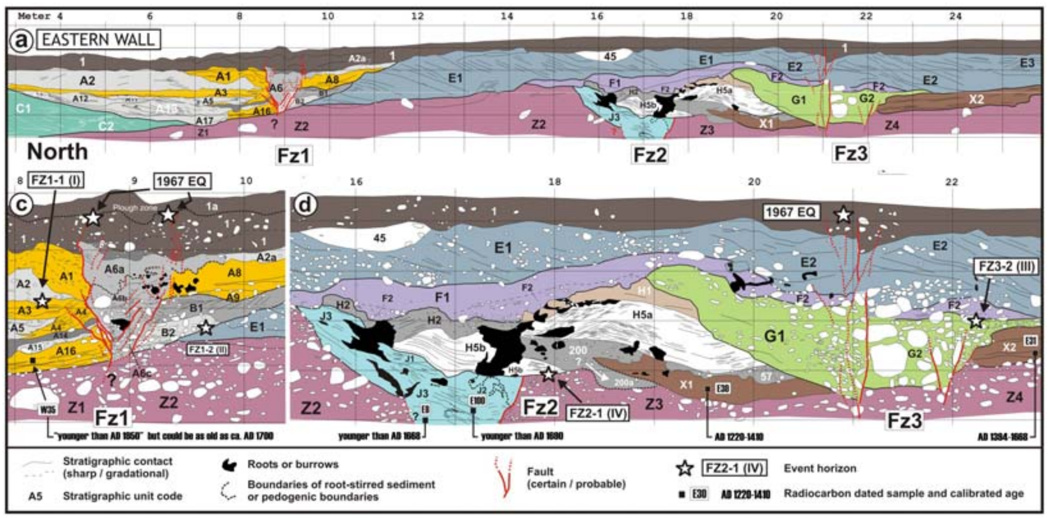


Figure 16. Simplified log of the E wall of the Mudurnu trench. Stars indicate locations of recognized event horizons.

6.3.4. Dendrochronology (deliverable 9)

With the aim of testing dendro-seismology in different localities of the North Anatolian fault, in collaboration with R. Fantucci (subcontractor) we performed dendrocronological sampling along the 1999 earthquake rupture of the Düzce fault and in the Mudurnu valley. For each one of these areas we collected samples at three sites. Dendrochronological sampling was *not destructive*. It was carried out by means of *incremental cores* taken using a *Swedish increment borer* from living trees that were located along or more or less far (control trees) from the fault trace. 41 trees were analysed, from different altitudes and geological environments; the species of sampled trees were: *Phyrus*(1), *Prunus* (3), *Pinus* (12), *Morus alba* (2), *Juglans regia* (4), *Castanea sativa* (2), *Fraxinus* (2), *Platanus orientalis* (6), *Alnus glutinosa* (1), *Tilia cordata* (1), *Quercus cerris* (3), *Quercus petraea*(2)

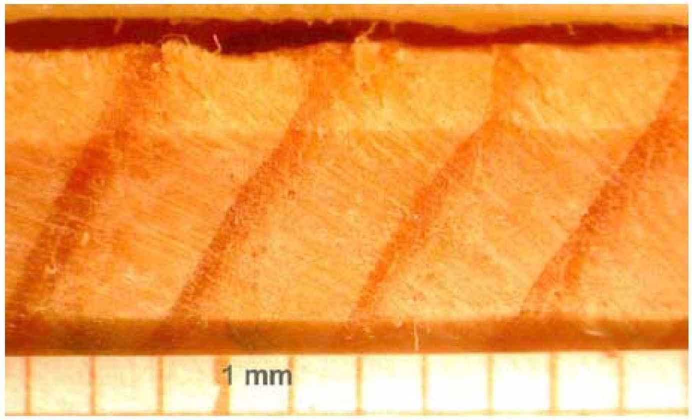


Figure 17. Example of core from a *Pinus* showing clearly the tree rings.

All the cores were placed on a wood support, cut, sanded and cross-dated through the standard dendrochronological methods known as *skeleton plots*, then measured with a 0.01 mm accuracy through a micrometer (Figure 17). Then, they were subjected to the visual analysis to find abrupt growth anomalies as sudden decrease (suppression) or increase (release), possibly related to local disturbance like earthquakes, comparing these growth with the "normal" one of control trees. For each tree a growth curve was created which shows all the measured rings in each core sampled (Figure 18). In most of the cases, we found a sudden growth reduction (suppression) that could last for a few years, decades or longer.

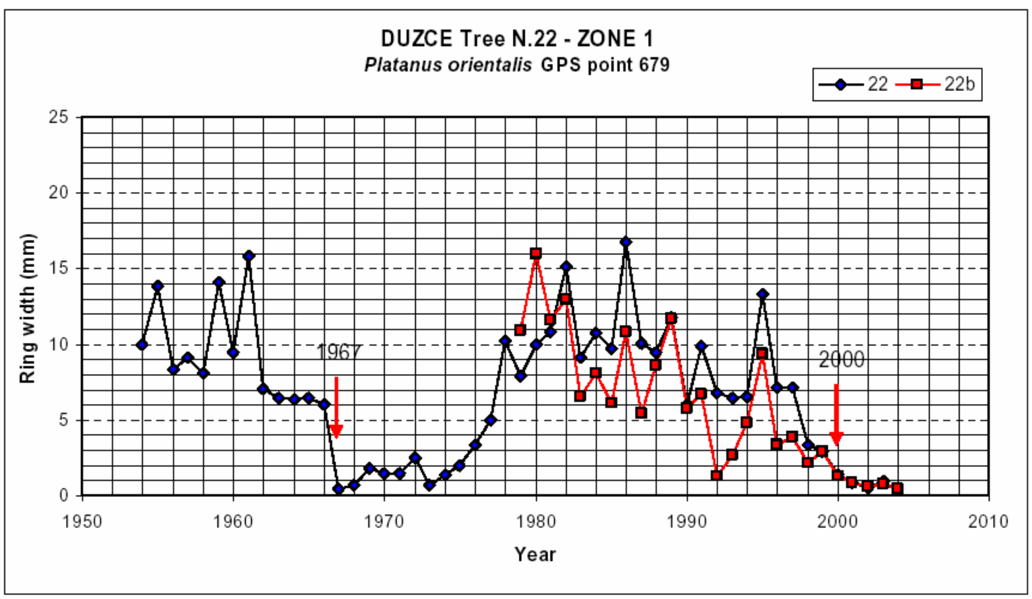


Figure 18. Example of tree ring suppression. The red arrows indicates the year of occurrence of the suppression. Notice that the 1967 disturbance lasted several years before the ring growth reaches back a normal value.

Summary of results from the Düzce fault

Because of the low elevations and intense agricultural activities, the Düzce fault generally runs in areas with a low density of trees, and these are generally young. Most of the trees sampled on the fault trace show anomalies in year 2000 and 2001 that are likely related to the 1999 earthquake. Two trees (N.22 and N.27 – *Platanus orientalis*) in the western part of the fault have also shown a growth anomaly similar to the 2000 one in 1967. Whether this is related to root rupture, root exposure, or change in hydrological conditions triggered by the Mudurnu 1967 earthquake is still a matter of investigation.

Summary of results from the Mudurnu valley

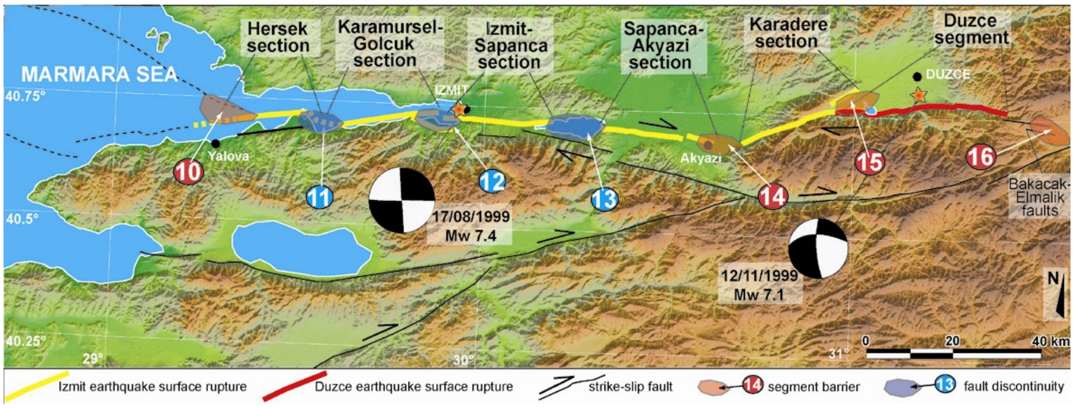
The Mudurnu valley splay of the North Anatolian fault ruptured during the 1957 and 1967 earthquakes. These two ruptures have a long zone of overlap. We applied tree ring analysis not only to recognize and date earthquakes of the past, but also with the aim of constraining better the 1957 and 1967 rupture extent.

The main problem in this area is that, because of the decades elapsed since the earthquakes, the exact location of the earthquake ruptures is not well constrained. On the other hand, the Mudurnu valley area, especially to the east, is highly vegetated, and thus contains good potential for tree ring analysis.

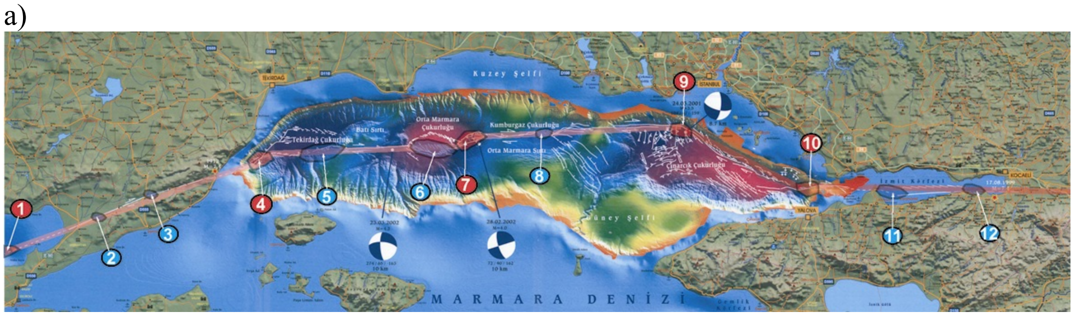
Trees were sampled where we thought to have evidence for earthquake surface faulting. Unexpectedly, the preliminary analysis of the sampled trees do not show clear evidence neither for the 1967 nor the 1957 events. However, some other events of disturbance have been recognized (i.e., 1973-75, 1951-52, 1947, 1919, 1902 and 1885) but more investigations are needed for an interpretation to be proposed.

6.3.5. Segmentation of the NAFZ in the Marmara region (contribution to deliverable 21)

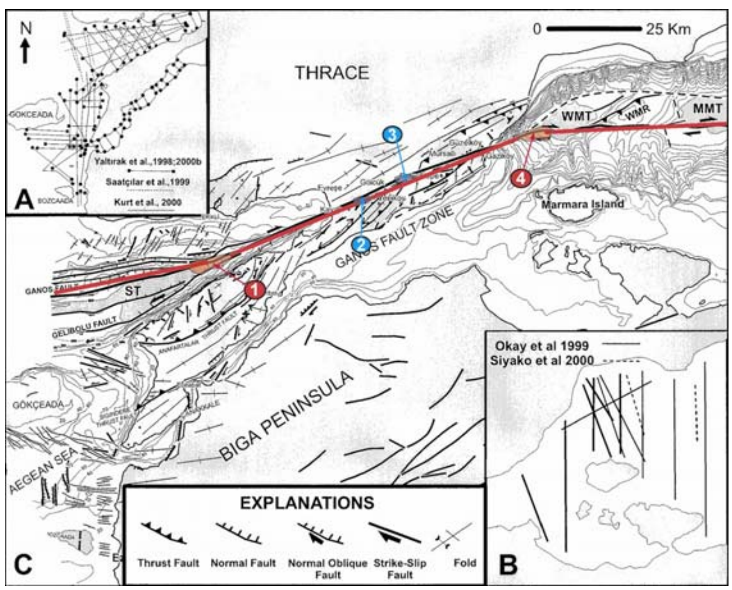
We analyzed the discontinuities (i.e., fault bends, step-over, fault junctions etc.) in the Marmara Region by the systematic collection from literature of the different types and characteristics of potential barriers to rupture propagation. Factors controlling rupture propagation have been studied in the literature from a purely geometrical or geometrical/dynamic point of view. First we divided the types of discontinuities into two families on the basis of their extensional or compressional setting. Then, for each family we defined classes depending on parameters that may influence rupture propagation (e.g., angle between two adjacent fault sections, width, rupture delay). The classes are defined from A to D depending on the efficiency of the parameter to stop rupture propagation (A for highest efficiency) but also on the possibility to directly define the parameter itself (e.g., fluid pressure is hard to be defined, classes C or D). References from the literature are given to each class. We attributed a name, typology and class to each discontinuity we encountered along the northern branch of the NAFZ in the Marmara region. For each class we attributed a positive or negative tag depending if the class specific parameter would prevent or allow rupture propagation. When the classes preventing fault propagation exceed the ones allowing it, we interpret the discontinuity as a segment boundary. The results of this process are reported in Figure 19, where red and blue circles indicate potential segment boundaries and through going discontinuities, respectively. It is interesting to notice that although this classification does not use as input data the fault segmentation revealed by the 1999 earthquakes it independently predicts it. This fact stress the potential for the use of tectonic/geologic/geomorphic data to develop reliable segmentation models.



a)



b)



c)

Figure 19. Location of the fault discontinuities of the eastern (a), central (b) and western (c) parts of the study area. Red circles indicate the potential segment boundaries, whereas blue ones indicate potential through-going discontinuities. (Surface ruptures traces of figure 19a from Akyuz et al. [Barka Ed. 2000]; figure 19b modified from Le Pichon [EPSL, 2001]; figure 19c modified from Yaltirak [Marin Geology, 2002])

6.3.6. Ground Motion Scaling in the Marmara Region (contribution to deliverable 18)

In the last few years increasing attention has been paid to regional ground motion studies, where the regional background seismicity is used to produce predictive relationships for the ground motion to be used in hazard studies. In this study, horizontal component velocity seismograms from the different networks deployed for the aftershocks studies after the M_w =7.4 Kocaeli earthquake of August 17, 1999 and M_w=7.2 Düzce earthquake of November 12, 1999, are used to measure and quantify high frequency ground motion scaling for the seismically hazardous Marmara region, located in the western part of the North Anatolian Fault Zone (NAFZ). This study analyzed a data set consisting of 2031 waveform from 53 stations and 462 regional earthquakes related seismic events in the range of the 5 - 200 kilometer hypocentral distance and with moment magnitudes between 2.8 and 7.2. The signals were processed to examine the peak ground velocity and Fourier velocity spectra in the frequency range of 0.4 - 15 Hz. Random vibration theory (RVT) is used to test estimates of the peak ground motion in the time domain and duration defined by the limits of 5% - 75% seismic energy that follows the onset of the S-waves used. Comparison of the two regressions indicated that our RVT related duration term for band pass filtered spectra is quite good and both regression results display consistent shapes.

Both the Fourier velocity and peak filtered time domain regression results are characterized by rapid decreases of amplitude at short distance. Results are given in terms of excitation, attenuation and specific site for the horizontal ground motion. Fourier velocity spectra for the combined horizontal motion are best fit by a hinged quadri-linear geometrical spreading function for observations in the 10 – 200 km hypocentral distances range as a function of frequency: ***$f \leq$ 2.0 Hz,*** $r^{-1.1}$ for $r \leq 30$ km; $r^{-0.8}$ for $30 < r \leq 60$ km; $r^{-1.2}$ for $60 < r \leq 100$ km; $r^{-0.2}$ for $r > 100$, ***$f >$ 2.0Hz,*** $r^{-1.0}$ for $r \leq 30$ km; $r^{-0.4}$ for $30 < r \leq 60$ km; $r^{-0.6}$ for $60 < r \leq 90$ km; $r^{-0.8}$ for $90 < r \leq 100$ km; $r^{1.0}$ for $100 < r \leq 110$ km; $r^{-0.5}$ for $r > 110$. The frequency dependent crustal shear-wave quality factor Q (f) coefficient $Q(f) = 180 f^{0.45}$.

The excitation spectra of larger events were modeled by using the regional propagation, a single-corner frequency Brune spectral model characterized by an effective stress parameter, □□= 80 bar, and by a regional estimate of the near-surface, distance-independent, network averaged attenuation parameter, $□_o$= 0.055 sec that as estimated from the rolloff the empirical source spectra obtained from the regressions.

Predictions for peak ground acceleration (PGA) and spectral pseudo-spectral velocity (PSV) (5% damping) were computed through the use of the random vibration theory (RVT), with the parameters obtained from the regressions of this study.

6.3.7. Seismicity along the North-Anatolian fault between the Gulf of Saros and Bolu from the 5th century B.C. to the 15th century A.D. (contribution to deliverable 16)

This contribution was subcontracted to Storia Geofisica Ambiente (SGA).

A revised parametric catalogue form the antiquity to the XV century the study was organised including a review of the pre-existing catalogues and new research.

The first step was the identification of the catalogues that contain data concerning the area. We have taken into account the catalogues starting from 1904 until 2002. In order to maximise the results the analysis has focused on the more recent catalogues. Such catalogues present substantial problems of non-homogeneity for the criteria both of localisation and evaluation of the parameters. This selection has provided a state of the art on the seismicity of the area, highlighting the diversity of evaluation according to the various authors who have dealt with the matter.

The identification and the selection of the ancient and Byzantine sources has been carried out through the critical review of the catalogues by Guidoboni *et al.* [INGV and SGA pubbl., 1994] for the part before the year 1000, and by Guidoboni and Comastri [INGV and SGA pubbl., 2005], for the part from 11th to 15th century.

A particular sector of the research has concerned the acquisition of recent critical editions, which have contributed to improving and better detailing the already known texts, now reviewed more critically. In particular, these analyses have concerned the dating and the localisation of the effects, the splitting of some earthquakes, previously grouped together in a single event, the pinpointing of the date.

The *corpus* of the sources used is made up of 113 works by authors most of whom are only coeval to the various events.

We have also taken into account the historiographic, antique and Byzantine production, in order to better understand the local historical situations contextual to the events being examined, or to better localise particular defensive structures cited by the sources as damaged.

The attention to the historical contexts has thus allowed us to improve some localisations and to better clarify some previously unresolved dating problems. This analysis has also shown the limits of the sources, due to their objective scarcity and their orientation to the large urban cultural centres.

For each earthquake known in the literature in the period and in the area under examination a complete chart has been filled in, which summarises the critical analysis carried out and it motivates the changes made to the parameters.

Overall 26 maps have been drafted on a territorial scale and 18 on an urban scale; the earthquake effects at Constantinople have been localised on the grounds of indications drawn from the sources of the various monuments hit.

The products of this study can be summarized as follows:

- Descriptive catalogue of the reviewed earthquakes;
- Parametric catalogue;
- List of the localised tsunamis;
- Catalogue of the effects felt in Constantinople;
- List of the monumental buildings in Istanbul damaged by the earthquakes in the period under examination;
- List of the sources.

6.4 Conclusions including socio-economic relevance, strategic aspects and policy

INGV mainly focussed attention in the study of the eastern part of the RELIEF study area. The main contribution derives from tectonic, geological, geomorphic and paleoseismological studies although also ground motion and historical seismicity studies have been performed.

The main results of these studies are listed below:

- reconstruction of the geometry, evolution and internal complexity of the Düzce fault zone,

- recognition of the relations between the fault at depth and its surface expression;
- recognition and dating of the paleoearthquakes of the Düzce fault;
- estimates of the geological slip rates of the Düzce fault;
- recognition and dating of the paleoearthquakes of the Mudurnu fault;
- model of segmentation for the Marmara region
- signature of earthquakes of the past in the tree ring growth
- ground motion scaling in the Marmara Region
- reappraisal of the historical seismicity between 5th century B.C. and 15th century A.D.

From a social-economic point of view the knowledge acquired during the project is an important contribution to future planning of social and economic activities in the area. This is particularly true for the Düzce area where development is still ongoing and the completion of the new freeway, connecting Ankara with Istanbul, may substantially push it. The new knowledge about fault behaviour, location of future earthquake ruptures and location of potential maximum energy release area is certainly a relevant contribution, along with the knowledge of characteristics of energy propagation, to hazard assessment.

6.5 Dissemination and exploitation of the results

6.5.1 RELIEF web site (deliverable 29)

Figure 20 Indicative screen captures from the RELIEF Web Site from the public access section (cover page and project overview).

The website of the RELIEF project is intended for the on-line dissemination of the project results to the public but also among the project participants, during the course of the research activities as well as after the end of the project. The Website structure was designed, implemented and put on-line in fully functional form, at the web server of INGV (**http://www.ingv.it/paleo/RELIEF/index.html**). The website consists of a public access area (Figure 20) and an area where access is restricted to RELIEF participants only. The pages are optimized for Microsoft Internet Explorer 6 (PC version) and screen resolution of 1280x1024 pixels.

6.5.1.a. *Public access area*

The structure of the **public access area** can be seen at the site map given in figure 21. It is organised in a way that will provide the visitor with a detailed description of the RELIEF project goals, the way the work was organized and carried out (workpackages, activities, meetings), the partner institutions and personnel involved and, the project deliverables online (upon their release).

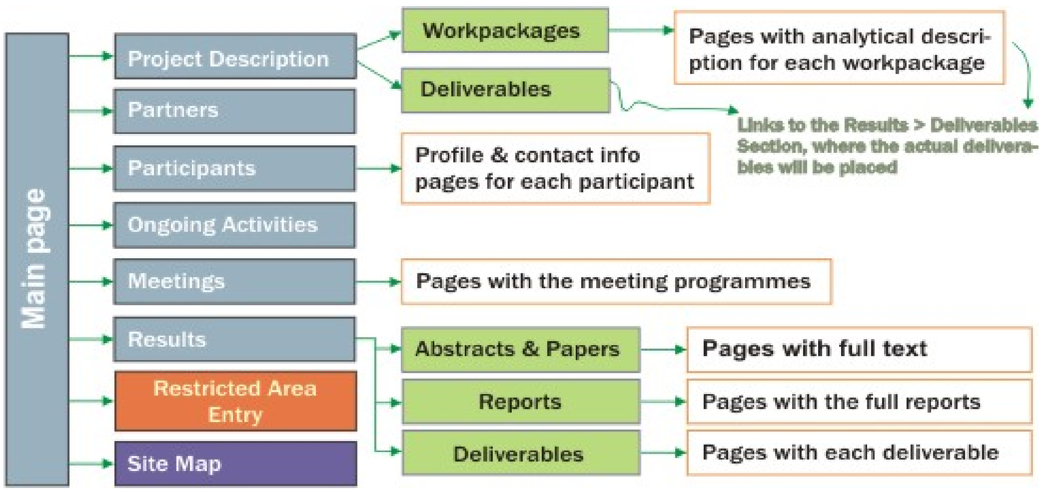


Figure 21. Site map of the RELIEF web site public access area.

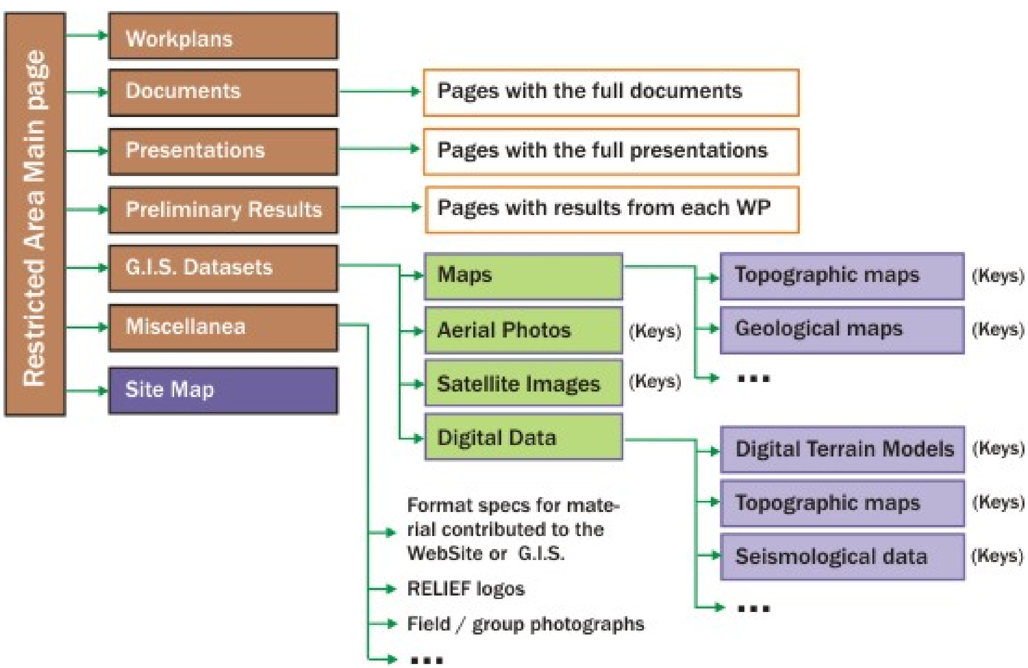


Figure 22. Site map of the RELIEF web site restricted access area (password-protected, for partners & participants only)

In the **project description** section, there are introductory pages with the project overview and information on the North Anatolian Fault, pages with detailed information on the workpackages and a page with the list of deliverables. The **partners** and **participants** pages include information on the project partners and an analytical list of participants (with a personal page for each one). The **ongoing activities** section contains a list of the work currently done by each partner and group, whereas the **meetings** section contains a list of RELIEF meetings, linked to pages with the analytical programmes. The **results** section includes pages with: 1) references and links to published scientific papers and abstracts, links to on-line resources, presentations, etc carried out in the frame of RELIEF, 2) RELIEF reports (will be put upon release) and 3) RELIEF deliverables (will be put upon release). The **site map** button at the main page links to a page with the site map.

The **site map** button at the main page links to a page with the site map.

6.5.1.b. *Restricted access area (only for participants)*

The structure of the **restricted access area** of the web site can be seen in figure 22. Its purpose was to provide the project participants with reference information/documents regarding the project and related administrative issues, circulars, work plans, presentations of preliminary results given in RELIEF meetings or any other workshop/conference, technical specifications for data contributions, descriptions and map keys for datasets available for dissemination among partners only, a section for miscellaneous content and, the finished deliverables.

6.5.2 Geographical Information System (GIS) (deliverable 30)

The RELIEF Geographical Information System is a means to integrate in a homogeneous and consistent way the diverse datasets relative to the identification and characterisation of seismic sources and, seismic hazard assessment, that were compiled, updated or produced in their entirety in the course of RELIEF research activities. Disseminating RELIEF results in the form of a GIS, aimed at delivering to the end-user a functional information system having the following advantages:

- Data Querying (based on spatial relations / attribute data that will be included)
- Visualisation and thematic mapping capabilities
- Updatability / expandability of data

The GIS was developed in the MapInfo 7 Professional software and came to include all the data collected by INGV during the RELIEF project and the data provided by the other partners, in layers of:

- Satellite images
- DEMs of various resolutions
- Topography at various scales
- Locations of study sites (trenches, dendrochronology sampling)
- Geological data (earthquake ruptures and coseismic slip measurements)
- Seismological data (instrumental / historical earthquakes)

Several data layers include attribute data (information attached to each geographic object) that allow for GIS functionality (querying, thematic mapping).

6.6 Main Literature produced

The papers listed below contain data totally or partially derived from this project.

- Akinci, A., L. Malagnini, R. B. Herrmann, R. Gok, and M. Sorensen, 2006. Ground Motion Scaling in the Marmara Region, Turkey (Geophysical Journal International, in press).
- Guidoboni E. and A. Comastri (2005), Catalogue of earthquakes and tsunamis in the Mediterranean area from the 11th to the 15th centuries, INGV and SGA, pp. 1037.
- Oglesby, D.D., P.M. Mai, K. Atakan, S. Pucci and D. Pantosti (2005), Dynamic rupture in the presence of fault discontinuities: an application to faults in the Marmara Sea, Turkey, *Fall AGU 2005 Abstracts*, December 5-9, San Francisco.
- Palyvos, N., Pantosti, D., Zabci, C., D'Addezio, G. (2005). Late Holocene earthquakes at the Mudurnu valley, 1967 earthquake segment of the North Anatolian Fault Zone, recorded in river channel deposits, *International Journal of Earth Sciences*, (submitted).
- Pantosti D., De Martini P.M., Pucci S., Palyvos N., D'Addezio G., Zabci C. Paleoearthquakes of the Düzce segment of the North Anatolian fault zone (Turkey), *BSSA,* (submitted).
- Pantosti D., S. Pucci, N. Palyvos, P.M. De Martini, C. Zabci, G. D'Addezio, P. Collins, Paleoearthquakes of the Düzce segment of the North Anatolian Fault Zone (Turkey), *abstract submitted to EGU General Assembly, Vienna, April 2006.*
- Pantosti, D., S. Pucci, N. Palyvos, C. Zabci, P.M. De Martini, G. Uçarkus, A. Dikbas, M. Meghraoui, S. Akyuz and P. Collins, Paleoearthquakes along the duzce fault segment of the North Anatolian Fault Zone (Turkey), *32nd International Geological Conference, Abstract Volume, Florence, August 2004.*
- Pucci S.(2005). Caratterizzazione geologico-strutturale e geomorfologica della faglia di Duzce (Turchia) per la comprensione del comportamento sismogenetico e lo sviluppo di modelli di ricorrenza, *PhD thesis of the Perugia University*, in prep.
- Pucci S., P.M. De Martini, D. Pantosti, Slip rate of the Düzce segment of the North Anatolian Fault Zone from offsets of geomorphic markers *abstract submitted to EGU General Assembly, Vienna, April 2006.*
- Pucci S.,D. Pantosti, M. Barchi, N. Palyvos, Evolution and complexity of the seismogenic Düzce Fault Zone (Turkey) depicted by coseismic ruptures, Plio-Quaternary structural pattern and geomorphology, *abstract submitted to EGU General Assembly, Vienna, April 2006.*
- Pucci, S., N. Palyvos, C. Zabci, D. Pantosti and M. Barchi (2005), Coseismic ruptures and tectonic landforms along the Düzce segment of the North Anatolian Fault Zone (Ms 7.1, Nov. 1999), *Journal of Geophysical Research-Solid Earth,* (in press).
- Pucci, S., D. Pantosti, M.R. Barchi and N. Palyvos (2005). Evolution and complexity of the seismogenic Düzce fault zone (Turkey) depicted by

coseismic ruptures, Plio-Quaternary structural pattern and geomorphology, *Earth Planetary Science Letters,* (submitted).

- Pucci S., D. Pantosti, N. Palyvos, and M. Barchi (2005), Evolution of the Düzce segment of the North Anatolian fault Zone (Turkey), *International Symposium on Active Faulting*, Hokudan, Japan, January 17-24, 2005.
- Pucci, S., D. Pantosti, N. Palyvos and M. Barchi (2005), Evolution of the Düzce segment of the North Anatolian Fault Zone (Turkey), *Geophysical Research Abstracts*, Vol. 7, 08728, 2005.
- Pucci, S., D. Pantosti, M. Barchi, and N. Palyvos, Evolution and complexity of the seismogenic Düzce Fault Zone (Turkey) depicted by coseismic ruptures, Plio-Quaternary structural pattern and geomorphology, *Tectonics of Strike-Slip Restraining and Releasing Bends in Continental and Oceanic Settings, Abstract Volume*, 28-30 *September 2005, Geological Society, Burlington House,Piccadilly, London.*
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- Pucci, S., N. Palyvos, C. Zabci, D. Pantosti and M. Barchi, Evoluzione del paesaggio legata a tettonica attiva: un esempio dalla faglia Nord Anatolica, *22° Convegno Nazionale GNGTS, Abstract Volume, November 2003.*