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ESF-FWF Conference in Partnership with LFUI

# Submarine Paleoseismology: The Offshore Search of Large Holocene Earthquakes

Universitätszentrum Obergurgl (Ötz Valley, near Innsbruck) • Austria
11-16 September 2010

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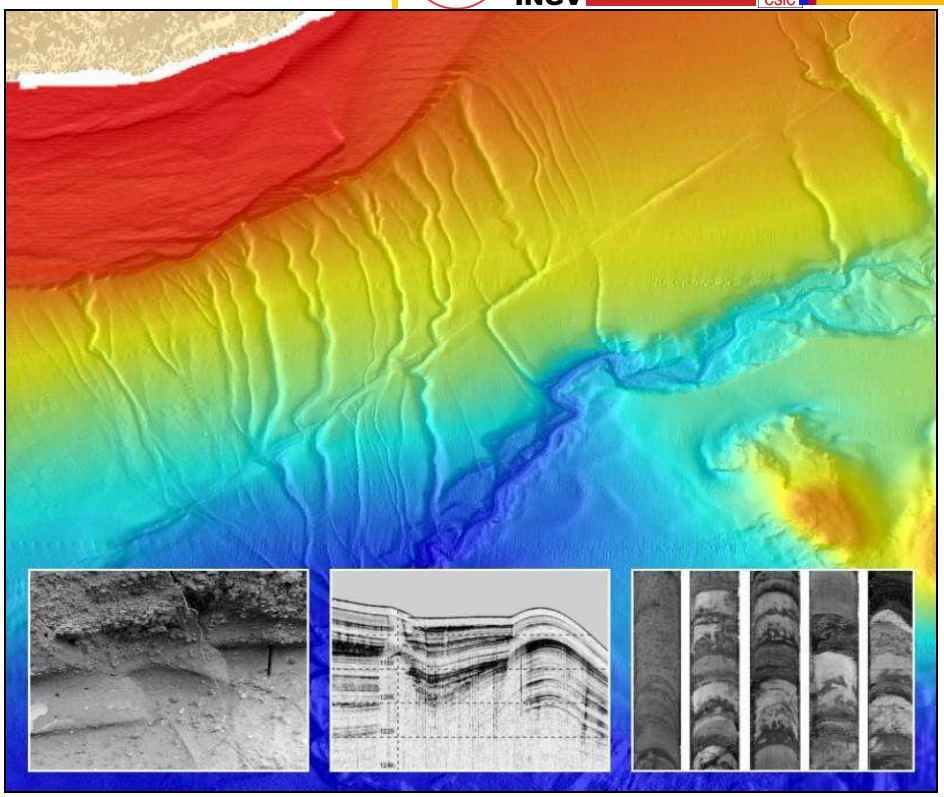

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# Conference Highlights

*Please provide a brief summary of the conference and its highlights in non-specialist terms (especially for highly technical subjects) for communication and publicity purposes. (ca. 400-500 words)*

The study of earthquakes of the past is a major priority for preparing reliable and updated seismicity models of use for modern seismic hazard assessment. These models are traditionally based on archaeological, historical, and instrumental seismicity records, but during the past decades the geological records of past earthquakes were used too. Similarly to the findings that historians derive from books, documents and reports, geologists can read and date through geological layers, tectonic and geomorphological settings, the signatures left by moderate and large earthquakes of the past. This is paleoseismology. The strength of paleoseismology is that the geological record can go back in time for periods much longer than the 100 or 1000 yrs covered by the instrumental or historical records, respectively.

During this conference we have explored and tested how much of the work done until now in paleoseismology in a terrestrial environment can be exported to a subaqueous environment. This is a very important issue because there is a concentration of population in the coastal areas that is seriously threatened by major earthquakes and tsunamis that are generated along offshore faults, which are poorly known. Despite the limitation of not being freely able to hands-on observe, sample and measure the fault at its intersection with the Earth surface, working in the subaqueous environment has clear advantages as the continuous sedimentation, minimized erosion, very limited human modification, and the consequent possibility to image through geophysical techniques extensive areas.

The aim of this conference to integrate the paleoseismological and marine geology communities in the common project of studying offshore, lacustrine and coastal structures with the potential of producing damaging earthquakes in the future, was successfully met. After having shared the basis for a common platform and language, we had the opportunity to learn how some pioneering studies have already developed sub-aqueous paleoseismology although, only rarely, the results were used as input to seismic hazard assessment studies. Subaqueous or coastal co-seismic and post-seismic effects of past earthquakes and tsunamis were discussed and the best approaches to survey, investigate, and date them were analysed and formalized.

Overall we discovered the advantages and the incredible potential hidden under the water and in coastal areas to better characterise our seismic regions. Being one of the most populated and high risk region, the Mediterranean area represents a fantastic natural laboratory for developing and formalizing approaches in Subaqueous Paleoseismology.

**X** I hereby authorize ESF – and the conference partners to use the information contained in the above section on ‘Conference Highlights’ in their communication on the scheme.

# Scientific Report

## Executive Summary

*(2 pages max)*

The aim of this conference was to integrate a number of existing lines of research and to give an official start and international recognition to Subaqueous Paleoseismology (Note that during the conference we agreed that, because we are dealing with lakes and coastal areas, the term subaqueous is more appropriate than submarine and thus it will be used hereinafter). This new field of study is essentially the merge and integration of the strength of two disciplines: paleoseismology on the one side, and marine geosciences on the other. Thus, we have learned first about both approaches, languages, and techniques to proceed afterward to the understanding of how and under which circumstances it is possible to recognize, image, and characterize submerged active faults and how to recognize and date individual moderate and large paleo-earthquakes from their submarine signature. To achieve this ambitious goal we have invited the most relevant worldwide professionals acting in both fields, with different expertise and the manifested interest in enlarging their perspective of research. Also the conference participants were selected with the aim of giving a precious opportunity to individuals that could benefit and maximize what learned and discussed in the conference for their future career.

Therefore, during the conference we devoted time first to explore paleoseismology, that is the investigation of individual earthquakes from their geological signatures: those produced directly along the rupture plane, and those produced indirectly, such as liquefaction, landslides and, in general, mass wasting in the vicinity of faults. Then, we explored the potential of marine geosciences in contributing to the imaging of active structures and in the assessment of the paleoseismological record. Rapid technological developments in seafloor and sub-seafloor imaging and sampling methods of use in marine geosciences have now increased the likelihood of being able to contribute in this sense. Worldwide examples of pioneering marine and lacustrine investigations presented at the conference have highlighted the true potential for a future development of subaqueous paleoseismology. Examples from different tectonic and geomorphic environments were presented: subduction zones, megathrusts, continental margins, lakes and coastal areas. For each environment we stressed the difficulties, limitations and benefits. Dating of depositional or tectonic events remains a difficult and crucial part of the process as it is for terrestrial studies. Different dating techniques have been discussed too. All this was very important to:

1) Establish the contacts between these two groups of researchers and build a common collaborative platform to move paleoseismology offshore;
2) Start the process of formalizing what Subaqueous Paleoseismology means and set its standards, what are the approaches of use for obtaining results that can be shared by the community, which are the research and technological areas that are promising and those that are more difficult or financially unaffordable yet;
3) Pose the basis for an international recognition of these efforts.

From the discussion developed during the conference it was clear that Subaqueous Paleoseismology represents a unique and powerful integration to the Holocene faulting and paleoseismicity knowledge already existing on land. Despite the limitation of not being freely able to hands-on observe, sample and measure the fault at its intersection with the Earth surface, and traditional paleoseismological techniques onland, such as trenching, are not feasible under water yet, Subaqueous Paleoseismology has the following clear advantages: (i) marine sedimentation is generally continuous in time and space, allowing for regional stratigraphic correlations and for the reconstruction of a complete record of events; (ii) seafloor mapping and marine geophysical imaging allows us to explore (at different degrees of

resolution) extensive areas in a relatively short time, (iii) offshore regions are essentially free of human modification and of large settlements that prevent the full application of paleoseismology.

Recent results in the field of Subaqueous Paleoseismology from different areas of the World show its potential to enrich the past earthquake record by assessing the paleoseismicity of submarine and coastal faults, with greater spatial and temporal resolution than that is now possible on land only. The scientific and societal benefits are evident, as most of the largest earthquakes/tsunamis are generated in submarine areas essentially along subduction zones and other plate boundaries, which are virtually unknown from the traditional paleoseismological viewpoint.

Until now, only terrestrial paleoseismology has been integrated into the seismic hazard assessment studies, which may be underestimated. During the conference we have verified that most of the geological parameters of use for seismic hazard assessment can be derived also from sub-aqueous environments and thus that there is a true perspective for the future of this science. The integration of pre-existing and new data and their correlation with paleoseismologically-studied areas on land, will better constrain seismic hazard and risk to coastal communities. The Mediterranean area is certainly the best natural laboratory to develop this new field of research given (i) the wealth of geological and seismological data available, (ii) the knowledge of the onland historical seismicity and paleoseismicity, (iii) the high-qualified knowledge and activity both in paleoseismology and marine geology, (iv) the high seismic risk.

In summary, the main goal of the conference was certainly met, the multidisciplinary international community convened in Obergurgl is now tuned up and well connected to start working together to formalize, build up the standards for Subaqueous Paleoseismology, and develop common projects to test approaches and perspective to gather new precious data.

The conference lasted for 6 days, for the 11$^{th}$ to the 16$^{th}$ September. The total number of participants was 66 of which 26 invited speakers (See Annex I for List of Participants). On the 11$^{th}$ September afternoon, there was the arrival to the University Center in Obergurgl and registration of participants. From 12$^{th}$ to the 15$^{th}$ September, the scientific sessions were held. The scientific program was organized based on a series of 27 invited talks (30 minutes each) grouped in 6 sessions, and given by senior scientists specialists in the fields of paleoseismology, marine geology and geophysics, stratigraphy, chronology and modelling. A total of 15 short talks (15 minutes each) were given by participants and integrated into the different sessions depending on the topic. A total of 52 posters were displayed during the conference, and presented during the evenings of the 12$^{th}$ and 13$^{th}$ September. The evening of the 14$^{th}$ September was dedicated to a plenary discussion, in which the main difficulties and advantages of subaqueous paleoseismology were raised. A forward look was already introduced. On the 15$^{th}$ September, the final discussions and conclusions were presented, closing the scientific part of the conference. On the morning of 16$^{th}$ September participants left the centre. (See Annexes II and III for Final Programme and List of Poster presentations, respectively). The conference web page is at www.esf.org/conferences/10313

# Scientific Content of the Conference

*(1 page min.)*

▪ *Summary of the conference sessions focusing on the scientific highlights*

The Subaqueous Paleoseismology conference was organized in three main parts: the first dealing, on the one side, with Paleoseismology, the discovery of the techniques and results for on-fault and off-fault investigations and, on the other, with an overview of the most advanced methodologies in mapping, imaging and dating used in marine geosciences that may be applied to subaqueous paleoseismology. The second part was devoted to the presentation of case studies that have already developed experience in Subaqueous Paleoseismology. The third part was devoted to the understanding of the true contribution that Subaqueous Paleoseismology could provide to seismic hazard assessment and this was also the main subject of the conclusion and Plenary discussion. The recurring question was "how many of the parameters needed for Seismic Hazard Assessment (SHA) is this subaqueous paleoseismology community able to provide"?

First Part

The first session entitled "**Introduction to Paleoseismology, paleoseismic field methods and results**" was aimed at the construction of a basic knowledge about Paleoseismology, from the concepts to the techniques and results. This was done through the presentation of the conceptual path that is at the basis of Earthquake Geology and Paleoseismology and of on-fault and off-fault case studies. Emphasis was given to the advantages and limitations in this field and on the possibility of transferring these concepts to the subaqueous environment.

The second session was "**Potential, methods and concepts applicable to submarine paleoseismology**" and comprised a number of presentations that where looking at the applications of marine geosciences methods to paleoseismology. Presentations were focusing on acoustic mapping and seismic imaging using different techniques including also the use of remotely operated vehicles (ROVs) for the in situ recognition and characterization of surface ruptures of active faults. The exceptional possibility of recognizing individual paleoearthquakes in high-resolution seismic records as in terrestrial paleoseismological trenches was shown too. Stratigraphic and environmental reconstruction techniques in sediment cores based on micropaleontological analyses as well as dating techniques and problems were also an important subject of this session.

The contribution of historical seismicity was analyzed too, as another important input to the buildup and test of the results of these investigations, in fact, as in terrestrial studies a reciprocal feedback is expected between geological and historical results.

Second Part

The third session was devoted to the presentation of the studies already performed or underway on "**Submarine Paleoseismology in Subduction Zones / Megathrusts".** This comprised the presentation of different methodologies that may be of use in these environments from turbidites and mass transport deposits analyses to high-resolution seismic stratigraphy, sedimentology and geomorphology for mapping active fault seafloor traces. Examples came from West-US margin, New Zealand, Lesser Antilles, Chile and Japan.

Session four focused on "**Submarine Paleoseismology in Continental Margins**", and included approaches that were spacing from the long-term monitoring to seismic imaging, geomorphology and coring for the recognition and characterization of submerged active faults, or of the most recent coseismic breaks of the seafloor. Interesting comparisons between inland and offshore results were presented. Turbidite deposits were also used as a powerful tool to recognize individual shaking events and obtaining regional earthquake recurrence intervals, and their depositional pattern was also presented as investigated though numerical modeling. Examples were from Greece, Turkey, Algeria, Italy, Haiti, Spain, and Canada.

An exceptional case of a post-emergency investigation (Haiti) was presented too. This was for the recognition of the offshore portion of the earthquake fault and for the establishment of a turbidite stratigraphy to understand the frequency of shaking in the epicentral area.

The fifth session was on **"Submarine Paleoseismology of lakes and lagoons**". The study of earthquake evidence in lakes and lagoons probably represents the beginning of subaqueous paleoseismology. The long lasting experience acquired in the Alpine lakes was clearly emerging from the presentations but many promising studies from other regions of the World were presented too. Seismic stratigraphy, geomorphology of the lake floor, mass wasting deposits recognition and coring are the key approaches for this environment.
To complete this overview, session 6 was designed for presentation of evidence for tsunamis of the past. Being originated offshore both from earthquake displacement or landslides and leaving signatures both in coastal areas and on the seafloor, we considered this field as a further branch of subaqueous paleoseismology. Examples from Sicily, Portugal, Greece and Turkey, regions mostly struck by tsunamis in the historical period, were presented.

Third Part
This part comprises a unique presentation on the input of geological data from Subaqueous Paleoseismology into Seismic Hazard Modeling. This subject represented the key input for the discussion and for the future development of this research.

▪ *Assessment of the results and their potential impact on future research or applications*

The main results of the conference can be summarized as follows:

1. Subaqueous paleosismology is the study of the timing, location and size of pre-historical earthquakes (Holocene or Quaternary, depending on the area we are studying) occurred under water (at sea, lakes or coastal areas). We have learned that there are many evidences of seismic activity underwater as presented in different tectonic environments, and this is represented by fault displacement and earthquake associated processes, such as submarine landslides, turbidity currents and tsunamis. Subaqueous paleoseismology has an enormous potential to develop worldwide and to provide important and essential input to seismic hazard assessment of coastal areas threatened by the effects of local and distant earthquakes.

2. The survey methods in subaqueous paleoseismology are based on the most advanced methodological and technological developments in marine geosciences, covering different scales of resolution. Acoustic mapping techniques allow to identify the geomorphic evidence of active faults and to map fault traces along large areas relatively fast. When the swath-bathymetric systems are installed in a remotely operated vehicle (ROV) or autonomous operated vehicle (AUV), which run near the seafloor, a cm-resolution comparable to the microtopography inland may be achieved, allowing to map the surface rupture of a given earthquake. Seismic imaging techniques allow to detect the stratigraphic evidence of seismic activity, such as folded and faulted reflectors and discontinuities, and may give a long temporal record of the fault activity (*i.e.*, slip rates may be more robust). In shallow water depth, very high-resolution seismic systems may get near to resolutions achieved by trenching on land, being able to detect the offset produced by a single event. In addition, survey grids may allow sub-surface "3D" mapping. Sediment sampling allows characterizing and dating sediment layers and mass transport deposits triggered during earthquakes. A key issue rose during the conference concerned sediment dating. Although radiocarbon is the most widely used dating method for the marine environment, there are important uncertainties that need to be taken into account. These are mainly due to the temporal and local variability of the reservoir age, an essential parameter during the age calibration process.

3. A review of the main on-fault achievements, based on direct fault investigations, was presented. Fault morphology and segmentation is well expressed underwater, as erosion is minimized and scarps can be better preserved. Examples of cross-cutting relationships are revealed in map view (*e.g.* offset channels for strike-slip faults) or in depth-section (*e.g.* faulted horizons for dip-slip faults). Several examples of successful fault characterization (slip rate, length and kinematics) and identification of segment boundaries were presented, although

difficulties appear when dealing with slow-moving faults, great water-depths and reactivated faults. In only very few cases (Marmara Sea and New Zealand), earthquake ruptures were identified and vertical and strike-slip components per event (*i.e.* coseismic slip) were obtained, as this is based on the ability to recognize and date individual event horizons (*i.e.* as in trenches onland). This is a topic for future research and technological development as it essentially depends on the vertical resolution of the underwater acoustic and seismic imaging methods. Another difficulty rose regarded to assign historical and instrumental earthquakes to identified faults, as earthquake location in oceanic areas has large uncertainties. Future implementation of **long-term deployment of broadband seismic stations** in active continental margins is needed.

4. The off-fault studies are based on seismically triggered landslides, turbidites and tsunamites, which may give information on earthquakes and allow obtaining recurrence intervals of large magnitude earthquakes, essential for seismic hazard assessment. However, the use of mass transport deposits as paleoseismic indicators requires demonstrating that earthquakes are the most plausible triggering mechanism. Synchronicity tests are based on coeval turbidites that can be correlated among widely separated depositional areas, at least during Holocene when the sea level stabilized. Several key points were raised regarding off-fault studies, for instance the selection of sampling site, as events may be missing or under-represented depending on the depositional location. Another issue was related to the link between thickness of a mass transport deposit and the magnitude (and intensity) of the earthquake, which correspondence is not straightforward.

5. Suggestions for refining chronologies were proposed regarding other dating methods a part from radionuclides $^{210}$Pb and $^{14}$C. For instance, the use of paleomagnetic curves and oxygen isotopes for better constraining the age of sedimentary records. Future lines of research may go in the line of **monitoring sediment pore pressure and other geotechnical properties of sediments** to investigate under which earthquake magnitude sediment failure occur, as well as **modeling underwater active processes**, such as turbidity flows, to better understand and tie paleoseismic observations.

6. Paleoseismic parameters derived from subaqueous on-fault studies as well as recurrence intervals (regional or related to an individual fault) derived from off-fault earthquake triggered underwater mass transport deposits should be taken into account in any future seismic hazard assessment. This is especially important in active margins near highly populated areas, such as the Mediterranean Sea.

## Forward Look

*(1 page min.)*

▪ *Assessment of the results*

The main results of the conference of relevance for future developments can be summarized as follows:

1. Underwater paleoseismology has an enormous potential to develop Worldwide and to provide an important input to improve the seismic hazard assessment of coastal areas threatened by the effects of local and distant earthquakes. This awareness has a very important social impact because coastal areas are intensely populated worldwide but there, seismic hazard assessment is generally missing critical information on the submerged seismogenic structures.
2. Nowadays Subaqueous Paleoseismology can benefit of the incredible technological advancements developed during the past decade. This is true for the tools of use in marine geosciences but also for improvements in computer geoscience, geochronology, etc. Based on this, we found a consensus among the conference participants on the fact that it is possible to reach a reasonable standard in the definition of the main seismogenic parameters of use for Seismic Hazard Assessment also for the subaqueous environment. Similarly to the terrestrial environment, each area has specific conditions that can favor or prevent the evaluation of a given parameter. Thus, there is a similar level of uncertainty related to works offshore and inland to be considered. The critical difference is related to the higher financial budget needed for the subaqueous research. However, the subaqueous environment has clear advantages with respect to the terrestrial one for the development of paleoseismological research that are (i) marine sedimentation is generally continuous in time and space, allowing for regional stratigraphic correlations and for the reconstruction of a complete record of events; (ii) seafloor imaging and marine geophysical instrumentation allows us to explore (at different degrees of resolution) extensive areas in a relatively short time, (iii) offshore regions are essentially free of human modification and of large settlements that prevent the full application of paleoseismology.
3. As regards the contribution of Subaqueous Paleoseismology to Seismic Hazard Assessment we have concluded that parameters describing the active fault characteristics, such as fault length, geometry (strike and dip), kinematics, complexity (segmentation) and slip-rate can be evaluated with a high level of confidence as their recognition is based on well-established techniques and extensive experience. Conversely, the approaches to obtain all the information regarding the individual paleoearthquakes such as slip per event and age and thus, recurrence time and elapsed time, are still in the process of being strengthened and to be consistently tested. However, the results presented at the conference are very promising and call for a common effort in this direction. A further approach to evaluate the frequency and possibly the size of earthquakes is based on off-fault studies (*i.e.,* the study of the effects of earthquake shaking as turbidites, mass transport deposits, etc.). This approach, is based on a longer experience developed both in marine and lacustrine environment and thus, at present it appears the more feasible. The problem here remains the establishment of the correct relation of the observed effect to the causative process. Are the effects we observe all related to earthquake shaking? An answer can be derived from the comparison with the historical seismic and tsunami record or through comparisons between onshore and offshore results although this is not always possible. Potential in the understanding of the processes of emplacement of turbidites or mass transport deposits, and thus of their causative mechanism, can be derived also through numerical modeling. Interesting examples were shown at the conference.
4. The formalization of the approaches to use in Subaqueous Paleoseismology and interpretations is the goal for the close future. There is also a need for setting the standards, so that results can be considered worldwide acceptable for input to seismic hazard assessment. To do so a strong collaboration and exchanges are needed in the community, and test areas to tune up different experiments should be commonly investigated.

▪ *Contribution to the future direction of the field – identification of issues in the 5-10 years & timeframe*

During the conference, the appraisal of the two independent approaches developed for identification and characterization of potentially seismogenic active faults in subaqueous and terrestrial environments was a very positive experience to understand where the two philosophies diverge or converge. In general, we have found a great convergence coupled with a serious will of researchers to cooperate to substantially develop and improve together Subaqueous Paleoseismology.

The main issues the new-born community will work on during the next years are mainly focused on the strengthening of the new discipline, the setting of standards and its recognition in the international scientific community. These issues can be summarized as follows:

- Development of consensus for methodological approaches and interpretations,
- Verification of the consistency of results obtained through different approaches,
- Establishment of the cause-effect relation and evaluation of actual uncertainty related to the interpretation of seismic vs. non-seismic causes,
- Integration with information derived from historical and instrumental seismicity and inland fault data,
- Provide data to the Seismic Hazard community.

A great opportunity to work on these issues is the establishment of test areas where to develop common and comparative studies, collaborations and experiments. The test areas should be set where the effects of known historical or instrumental events are well constrained or where there is the possibility of comparing onshore and offshore results in faults that have a submarine continuation.

▪ *Identification of emerging topics*

The fundamental result of this conference is the recognition of the potential to contribute with reliable data to a better assessment of the Seismic and Tsunami Hazard of coastal areas. This has a direct societal impact and will see this community working hard to bridge the lack of data still existing in this field.

The main topics emerging from the conference are:

- The great tuning of the paleoseismological and marine geosciences community.
- The awareness of the possibility to recognize individual paleoearthquakes both on-fault and off-fault also in subaqueous environments, which was not considered before. However, the need for the understanding of the cause of the off-fault effects needs to be better investigated.
- Dating remains a critical issue and needs attention
- The need for setting of test areas where to concentrate efforts in understanding the whole earthquake system in the subaqueous environment for providing the critical impulse to this new field of research.

▪ Is there a need for a foresight-type initiative?

The enthusiastic response of participants to the conference, but also from scientific community in general, convinced us that we should continue in the same direction with other activities making the studies in subaqueous paleoseismology more diffused and discussed and thus strengthened. To reach this goal, conferences, workshops, sessions to national and international meetings as well as the development of common projects in any of the topics treated in this conference (tsunamis,

turbidites, MTD, dating, seismic imaging, etc.) represent positive activities to be certainly supported.

A similar format conference on subaqueous paleoseismology will be organized every two years. The next conference will be held in Crete (Greece) and organized by HCMR of Athens. We are looking for sponsors supporting the initiative.

A special volume based on the contributions presented in the conference will be published by the end of 2011 or beginning of 2012. We are planning to publish in the Open Access Journal of the European Geosciences Union "Natural Hazards and Earth System Sciences (NHESS). This was considered the most suitable journal as it has the potential to reach both the on land paleoseismology and the marine community interested on hazards as well as seismologists and the seismic hazard modelers .

We are also investigating the possibility for launching a working group, a couple of options are under consideration: a focused ILP (International Lithosphere Program) Subaqueous paleoseismology WG or a wider Paleoseismology WG within the IUGS-UNESCO IGCP (International Geosciences Program).

Finally, a mailing list will be established by the end of this year to keep alive contacts among conference participants and to gather around this new subject all researchers that are willing to contribute with the diverse expertises.

## Atmosphere and Infrastructure

▪ *The reaction of the participants to the location and the organization, including networking, and any other relevant comments*

During the whole conference, there was an exciting and very positive atmosphere among junior and senior participants. Constructive comments were raised by scientists coming from different environments (i.e. geologists, physicists, paleontologists, geophysicists, modelers) using a similar language and approaches that may be easily extrapolated to different areas of study.

New collaborations were started; the intention of publishing together a volume collecting most of high quality of the work is a clear evidence for this.

Overall the location and organization was very good, the local staff had an excellent and collaborative attitude (i.e. discussions lasted very late at night and we were always late at dinner) and helped us to solve logistic problems.

The location was beautiful, great to concentrate in the conference and also to enjoy the panoramas and mountain walks. The only drawback was the fact that reaching to that remote place from most locations in Europe, took us a whole day trip. The time of the conference (11-16 September) was not the most convenient for university teachers (starting during that week) and also for the weather, which was unstable. Either in the middle of Summer or even Winter would have been better time.

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**Date & Author**: 30/09/2010 Daniela Pantosti and Eulàlia Gràcia