EUG XI

Theme LS

Lithospheric Structure and Tectonics

EUG XI

Symposium LS01

Earthquake Deformation
and Related Surface Processes

Convenors

M. Meghraoui
G. Michel

Sunday PO Session

LS01 : SUpo01 : PO
Fluid-Driven Seismicity in a Stable Tectonic Context: The Remiremont-Epinal Fault Zone, Vosges, France

Laurence Audin (audin@dase.bruyeres.cea.fr) &
Jean Philippe Avouac
(avouac@dase.bruyeres.cea.fr)
Dase/ldg, bp 12, 91680, Bruyeres le Chatel, France

A better understanding of the significance of microseismic activity in stable tectonic domains might provide guidelines to help seismic hazard assessment. Along that line, we analyze the seismicity of the southern Vosges (France). The relocated events, which have all small magnitudes (ML<4.8), are found to align along a 40 km long fault zone flanking the southern Vosges Massif to the west. It joins to the south with the epicentral area of the 1682 historical earthquake (Io=8 MSK; Ms~5.3). Over the last 30 years, the seismic activity shows a characteristic migration-clustering pattern dominated by two swarms, first near Epinal to the north (1970-1980) and next near Remiremont (1983-1990). The Remiremont cluster was preceded by a period of seismic coalescence and triggered outward bilateral seismic migration. The seismic crisis developed along a well defined 3 km long vertical plane. In both case migration rates of the order of 5-10 km/yr over 30 km long distances are determined. This pattern requires some mechanism of stress interaction which must act over distances of the order of a 1 to 20 km within years. Given the low tectonic activity and the small magnitudes of the events the stress transfer cannot result from co-seismic elastic loading or from transient strain at depth. We therefore suggest that the seismic activity reflect rupture of asperities driven by fluid-flow in a zone of relatively high permeability.

LS01 : SUpo02 : PO
Palaeosecular Variation Recorded in a Recent Travertine Fissure Fill from Central Turkey: Implications to Rate of Growth and Earthquake Frequency

Halil Gürsoy (gursoy@cumhuriyet.edu.tr)[1],
Orhan Tatar[1],
John D. A. Piper (sg04@liverpool.ac.uk)[2] &
M. Alyaroubi[2]
[1] Department of Geology, Cumhuriyet University, TR-58140 Sivas, Turkey
[2] Geomagnetism Laboratory, Department of Earth Sciences, University of Liverpool, Liverpool L69 7ZE, United Kingdom

The palaeomagnetism of a young metre-wide and symmetrically-banded travertine fissure fill from the Sicak Cermik geothermal region near Sivas has been studied to evaluate the potential of travertine as a recorder of the past geomagnetic field. Magnetic intensity and susceptibility vary in a systematic way outwards from the fissure axis but show no close relationship to colour. Weak magnetisations of high coercivity are carried by goethite and/or hematite but iron complexes, probably including the former mineral, are altered during heating experiments to form magnetite. Compared with the fissure fill, adjoining layered travertines have higher intensities of magnetisation and lower coercivities reflecting the inclusion of air borne dust incorporating magnetite. Directions of magnetisation execute a clockwise path from the extremities to the axis of the fissure. This record can be matched using correlative bands on either side of the axis and is found to be symmetrical. It appears to record most of a single cycle of secular variation and on the assumption that approximately 1500 years of deposition are represented, the growth rate is found to be 0.4 mm/year. Approximately 50 discernible bands imply that earthquakes periodically reset the hydrothermal system depositing the travertine. They match the frequency of magnitude 4.0-4.5 earthquake events within 70 km of the geothermal site during historic times.

LS01 : SUpo03 : PO
Seismic-Induced Conjugated Deformation Bands in the Early Devonian Muth Formation (Spiti, NW Himalayas)

Erich Draganits (erich.draganits@univie.ac.at) &
Bernhard Grasemann
Institüt für Geologie, Universität Wien, Althanstrasse 14, A-1090 Wien, Austria

In the Early Devonian Muth Formation conjugate dilatational shear fractures show evidence of effective porosity reduction and compaction by cataclastic processes as well as reorganisation of quartz grains. These faults develop cluster zones rather than discrete fault zones and are interpreted as deformation bands (Aydin, 1977). It has been shown that deformation bands typically form in porous sandstone (Aydin & Johnson, 1984), thus their older age limit is constrained by the depositional age of the sediment and the younger age limit by the timing of thorough cementation.

Liquefaction features (e.g. sand volcanoes, sand volcano vents and slumped beds) have been documented at a discrete level that can be correlated across three sections that have a total restored distance of 31 km in normal direction to the overall facies trend (Draganits, 2000). Due to the regional scale of these liquefaction structures and the observation that the formation of deformation bands can be related to seismic slip events on nearby faults (Cashman and Cashman, 2000), paleo-seismicity is a probable mechanism that triggered liquefaction. Cashman & Cashman (2000) have shown, that deformation bands can form at "essentially surface conditions"; additionally, the susceptibility for liquefaction decreases nearly to nil in depth exceeding 10 m (Obermeier, 1996), therefore both, deformation bands and liquefaction features, may have formed under hydrostatic pressure at shallow levels.

Conjugated faults in the arenaceous dolomites of the underlying broadly Silurian Pin Formation show identical palaeo-strain orientations as the conjugated deformation bands in the quartz arenite of the Muth Formation, but the former with considerable higher acute angles than the latter. The nearly vertical orientations of the conjugated faults and deformation bands suggest a subvertical intermediate principal stress direction. Both structures are interpreted to belong to the same strike slip deformation. The differences in the acute angles can be explained by the higher confining pressure in the stratigraphically deeper Pin Formation during the generation of the faults, while the synchronous formation of the deformation bands occurred at shallower levels (Mandl, 2000). Assuming near surface conditions for the generation of deformation bands and related sand volcanoes, the depth of the Pin Formation during that time has been reconstructed by lithological sections.

These conjugated fault systems record a previously unknown pre-Himalayan deformation stage in the NW Himalayas. They document seismic oblique contraction in a transcurrent tectonic setting at the northern passive margin of the Indian continent during the Early Devonian.

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LS01 : SUpo04 : PO
Drainage Development and Cumulative Offset on the Gowk Strike-Slip Fault, Kerman, Eastern Iran

Richard T. Walker (rwalker@esc.cam.ac.uk) &
James A. Jackson (jackson@esc.cam.ac.uk)
Bullard Laboratories, Madingley Road, Cambridge, UK

The Gowk fault in Kerman province, eastern Iran is one of several major north-south strike-slip faults accommodating right-lateral shear along the eastern margin of Iran. Offset drainage networks are used to restore movement on this ~200 km long fault. The drainage reconstruction was aided by the unusual topography around the fault. Mountains flank the fault on both sides such that the course of drainage flowing eastwards across the fault zone is restricted to several deep gorges and cannot re-adjust to incremental fault movements. Total cumulative right-lateral offsets on the fault are shown to be ~12 km. Study of the geomorphology of the fault zone and identification of uplifted and abandoned drainage systems show active uplift to the east of the fault. The rocks on the uplifting eastern side of the fault control the preservation of geomorphic features. In the north, drainage incises through soft Quaternary alluvium and the preservation of subtle geomorphic features allows detailed reconstruction of the last ~3 km of fault movement, with processes of stream capture forcing repeated phases of drainage re-organisation. Further south, harder Mesozoic rocks have been uplifted and many drainage channels have been abandoned, leaving only one active gorge. Because of this, the processes of stream capture and drainage re-organisation seen in the north cannot operate and so the drainage still retains information on the total cumulative fault offset. The ~12 km total offset is small compared to the >100 km of right-lateral shear expected to have occurred in eastern Iran in the last ~5 Ma, and suggests a possible slip-rate of only ~2 mm per year. The abundance of recent earthquakes on this fault is therefore probably not representative of the longer-term activity.

LS01 : SUpo05 : PO
Fast Extrusion of the Tibet Plateau: A 3 cm/yr, 100kyr Slip-Rate on the Altyn Tagh Fault

A. S. Meriaux[1], **F. J. Ryerson**[2],
P. Tapponnier (tappon@ipgp.jussieu.fr)[1],
J. Vanderwoerd[1], **R. Finkel**[2], **M. Caffee**[2],
C. Lasserre[1], **X. Xiwei**[3], **L. Haibing**[4] &
X. Zhiqin[4]
[1] Institut de Physique du Globe de Paris, 4, place Jussieu, Paris 75005, France
[2] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[3] Insitute of Crustal Dynamics, SSB, Beijing 100085, P.R. China
[4] Insitute of Geology, Ministry of land and Ressources, Beijing, P.R. China

Total station offset measurements and age constraints of geomorphic features along the central segment of the Altyn Tagh Fault confirm Tibet's fast escape towards the Northeast. At two sites, between 85 and 89°E, we collected 90 samples for in situ cosmogenic dating. West of Tura, ^{10}Be and ^{26}Al dating of quartz pebbles from one fill and one strath terrace yields statistical model exposure ages of 13±2.5 ka and 5.7±0.5 ka. One depth profile on the strath terrace implies that inheritance is negligible. The ages of the terraces constrain those of a channel and a riser offset by 415±35 m and 150±15 m, respectively. Such offsets and ages yield a slip rate of 2.7±0.4 cm/yr. East of Tura, a broad glacial confluence and a narrow glacial valley, both now abandoned south of large contemporaneous valley glaciers north of the fault, are offset by 3660±100 m and 1020±10 m, respectively. Sampling of morainic ridges permits to reconstruct the paleoglacial morphology during the entire last glacial cycle. Quartz cobbles yield ^{10}Be and ^{26}Al model ages ranging from 6 ka to 107 ka, with distinct peaks at ~44 ka and. ~66 ka The ages and displacements are consistent with a slip-rate of 3.3±0.3 cm/yr integrated over 110 ka. Our surfaces ages distribution is correlated with the δ^{18}O record from the Gulyia ice cap in the western Kunlun (Thompson et al, 1997), demonstrating the impact of climate on moraine and terrace emplacement. The average 3.2±0.3 cm/yr slip-rate on the Tura segment of the central Altyn Tagh Fault implies that it plays a role equivalent to that of the Himalayas in absorbing the current convergence between India and Asia. Such fast left-lateral motion is consistent with models in which strike slip faulting governs the northwards growth of the Tibet plateau.

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LS01 : SUpo06 : PO
A 3-D Fault Interaction Model to Investigate the Topographical Process Associated with Active Tectonics

Delphine Fitzenz (fitzenz@erdw.ethz.ch) &
Stephen A. Miller (miller@erdw.ethz.ch)
Swiss Federal Institute of Technology, Engineering Geology, ETH Hoenggerberg, Zurich, 8093, Switzerland

An important and unresolved issue in earth science is what controls topographic development, and specifically, why topography is fractal. Most geomorphologic models focus on erosion effects and river networks that display certain power law scaling relationships (Turcotte, 1992), and do

indeed produce some space-filling fractal structures. However, models of erosion either start with an assumed periodic topography, or with an assumed fractal structure generated by non-linear diffusion models (Amar and Family, 1989). These models produce fractal structures but with fractal dimensions different from that observed in real topography. In this project, we are interested in the forward, building process associated with active tectonics. As a basis for this study, we have constructed a generalized 3-dimensional earthquake model that includes stress transfer, fault valve behavior, and poroelastic effects in undrained conditions. The model generalizes that of Miller et al. (JGR, 1999) to a fully 3-D system in which fault systems of any geometry can interact through an elastic matrix. The model is driven by large scale plate motion loading constrained by plate motion vectors, and includes pore pressure increases from fault compaction (or other source terms), and poroelastic effects. In-plane fault valve behavior is modeled as large co-seismic permeability changes at rupture and porosity creation through dilatant slip. We consider hydraulic property changes within the rupture area only, resulting in compartmentalization of fluid pressures, and brittle faulting is modeled with the elastic dislocation analytical results of Okada (BSSA, 1992). We present model results of the long-term (~ 2000 yr.) fault interaction between a blind thrust fault and a vertical strike-slip fault in a transpressional environment. We show the evolution of the complex fault zone stress state along both faults, seismicity time-lines and recurrence intervals, quasi-static rupture propagation, regional stress build-up and rotations, and static and dynamic fault interactions. For the chosen initial conditions, we find that the blind thrust fault evolves to a highly overpressured fault while the stress state on the sub-vertical strike-slip fault is more complex and changes dramatically with each large rupture (M_w>7). Co-seismic pore pressure changes within the rupture region result in large compartments of different overpressures along the fault plane. We show fault interaction and rake angle changes during rupture, and elastic co-seismic surface displacements within the model fault system. The model can be used to study many aspects of the earthquake process, including long-term behavior of complex fault systems, and transient topographic changes due to the generated seismicity. Model results imply that topographical signatures around active faults could be used to infer the state of slip complexity at depth.

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LS01 : SUpo07 : PO
The Thickness of the Elastic-Brittle Layer of the Lithosphere and Experience of the Prediction of the Earthquakes in the Caspian Sea Region

Leonid Levin (moscow@geon.msk.su) &
Leonid Solodilov (moscow@geon.msk.su)
GEON, 4, Chisty pereulok, Moscow 119034, Russia

The Caspian region is located in the central part of the Alpine belt of Eurasia where destructive earthquakes occurred repeatedly. Seismicity was caused by a combination of geodynamic processes, namely: collision of plates; subduction of above – asthenospheric layer of mantle; upwelling of the asthenosphere above old and recent zones of subduction; horizontal displacements of blocks along regional lineaments and faults; processes of mud volcanism. In the GEON Centre, a study of seismicity accompanied by long-term and middle-term prediction of earthquakes is based on the pricipally new technology, which includes the following sections: regional seismicity and local seismicity for long-term prediction of coordinates of high seismic potential sites. Such a technique requires a number of complex operations with geophysical data and earthquake focus area parameters, namely: determination of a lithosphere thickness through the level of an acute dropping in seismic wave energy, differentiation of the lithosphere into elastic-brittle and plastic-viscous layers using a ratio of magnitudes of various wave types, calculation of thickness of the elastic-brittle layer (depth of isotherm 6000ºC) on data of heat flow; identification of directions of seismo-hazardous zones on the base of calculating forces applied within the crust of seismoactive orogens and migration of centres of earthquakes in the plastic-viscous layer of the lithosphere. The Caspian region is characterized by complex distribution of thickness of the elastic-brittle layer of the lithosphere and epicentres of earthquakes. A thickness decreases in two regional directions - towards the axial zones of orogens and, on the contrary, to the deep-sea basins. In the first case, minimum thickness of less than 29-30 km is typical of the regions of intracrustal zones of partial melting, in the second case - of the deepest grabens, where a thickness of the sedimentary cover exceeds 15-20 km. Concentrations of earthquakes epicentres is established, predominantly, in the zones of complex structure of the elastic-brittle layer where gradient of its thickness is about 20-30 km. In the period from the first half of 1998 to September 1999, four earthquakes were registered which confirmed a prediction of intensity and coordinates of high seismic sites. A difference between predicted and observed coordinates ranges from 5 (northern site) and 22 (southern site) kilometers. This value does not exceeded the volume of the earthquake focus.

LS01 : SUpo08 : PO
Geomorphometry and Seismotectonics: Intraplate and Strike-Slip Zone Case Studies

Marianne Font (marianne.font@geos.unicaen.fr),
Daniel Amorese (daniel.amorese@geos.unicaen.fr),
Jean-Louis Lagarde (jean-louis.lagarde@geos.unicaen.fr) &
Bernard Delcaillau (bernard.delcaillau@geos.unicaen.fr)
UMR CNRS 6143 M2C, Université de Caen, 24, rue des Tilleuls, 14 032 Caen Cedex, France

Combined approaches including tectonics, seismotectonics and geomorphology can provide important information concerning crustal deformation and active tectonics. In these studies geomorphic systems are analysed with the aim of detecting the various responses of landforms to crustal deformation. Landform descriptions using Digital Elevation Models (D.E.M) bring a lot of new information. We have built automatic tools which allow to identify geometrically the drainage pattern computing (i) length, orientation of streams, (ii) distribution, elevation and angles of confluences, (iii) slope ruptures on river profiles. Watershed morphologies are characterised computing (i) average slope, elevation, orientation, (ii) maturity degree with the use of hypsometric curve, drainage density and average erosion volume. This methodology is a valuable tool for discriminating (i) discontinuities along topographic profiles, (ii) residual surface map, (iii) relation between local slope and drainage area on both side of suspected relief. In intraplate zones, considering a time interval greater than 10^5 years, morphodynamics seem to be highly controlled by tectonic uplift that induces relative variations of base level. For example, in NW of France (Normandy), tectonic and geomorphic investigations have been used to show that topography and landform discontinuities reflect the plio-quaternary dislocation of a late Cenozoic platform (Amorese et al., 1999; Lagarde et al., 2000). In these zones, quantitative morphometry and seismotectonic analyses of recent earthquakes provide useful information for identifying active faults and for constraining the present-day stress field. The relationship between geomorphometry and active tectonics is also examined in strike-slip zones (Hector Mine epicentral area, South California) where active faults are marked by densely aligned epicenters.

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LS01 : SUpo09 : PO
Post Messinian Movement along Nimes Fault: Implications for the Sismotectonic of Provence (France)

Antoine Schlupp (schlupp@dase.bruyeres.cea.fr)[1], **Georges Clauzon** (clauzon@cerege.fr)[2] & **Jean-Philippe Avouac** (avouac@dase.bruyeres.cea.fr)[1]
[1] CEA/DIF/DASE/LDG/TRS, BP 12, 91680 Bruyeres le Chatel, France
[2] CEREGE, Europole Méditerranéen de l'Arbois, BP80, 13545 Aix en Provence Cedex 04, France

The Nimes Fault is one of the potentially active fault in Provence (South East France). Evidence for paleoseismic events were found nearby and, although the signal is tenuous, the fault seems to cut trough the quaternary deposits of the Rhone valley. Here, we quantify the fault activity since the Messinian. We take advantage of the fact that the Messinian crisis has had a strong geomorphological impact well preserved in the geology of Provence. The lowering of the Mediterranee has in particular induced river incision and the formation of several hundred meters deep canyons fossilized at 5.32 Ma. We show that such a canyon was formed across the Nimes fault south of the Roquemaure cliff. The sub-surface geometry was constrained from seismic profile and microseismic measurements using the Nakamura technique. The results shows a 440 m left-lateral offset of the southern edge of the canyon near the fault trace, which we interpret to reflect post-Messinian fault motion. Given that the tectonic regime of Provence has not varied significantly since then, we assume that the slip rate has been constant, between 0.06 and 0.09 mm/yr. Kinematic compatibility with the thrust faults along the Ventoux, Alpilles, Trevaresse and the Moyenne Durance strike-slip fault requires similar slip rates on these faults.

LS01 : SUpo10 : PO
Active Faults at the Boundary between Central and Southern Apennines (Isernia, Italy)

Daniela Di Bucci (daniela.dibucci@dstn.it)[1],
Giuseppe Naso (giuseppe.naso@dstn.it)[1] &
Sveva Corrado (corrado@uniroma3.it)[2]
[1] Servizio Sismico Nazionale, Via Curtatone n. 3, Roma, 00185, Italy
[2] Dipartimento di Scienze Geologiche, Università Roma Tre, L.go S. L. Murialdo n. 1 - oo146 Roma, Italy

Active faults and strong earthquakes along the Italian peninsula show different patterns of distribution, being spread all along the Northern-Central Apennines chain and concentrated along a narrow belt in the Southern Apennines. The degree of detail about the active faults in Italy is highly variable; as a result, the spatial distribution of the seismogenic structures of the Northern-Central and Southern Apennines is still matter of debate, and only a fraction of all potential source zones has already been fully investigated and characterised. In particular, a remarkable lack of data can be observed at the boundary between these two patterns of distribution. Therefore, in this work we focus on the boundary area between the Northern-Central and Southern Apennine thrust belt, which is presently undergoing NE-SW extension at a relatively low rate of about 1 mm/yr. The studied area extends between two regions well known from a seismotectonic point of view: the Boiano Basin active extensional system to the SE (Southern Apennines; 1805 earthquake) and the seismogenic structures of Sangro River Valley (Central Apennines; 1984 earthquake) and of Aremogna-Cinque Miglia Plains (Central Apennines; three paleoseismic events for the last 7000 years) to the NW. In this context, we studied the Isernia Basins, two sizeable Quaternary intermountain depressions located in this part of the Apennines in order to fill the gap of data. The research was based on original data, consisting of about 50 well logs drilled in the Isernia Basins, integrated with detailed field surveys (scale 1:10,000) and mesoscale structural analysis. This study allowed at defining the Isernia Basins geometry and kinematics. These basins are asymmetric half-graben partially filled with fluvio-lacustrine deposits, whose sedimentation is ruled by the activity of a set of normal faults striking N30°W and dipping toward the NE. This set of faults, which has been mainly developing during Late Pleistocene-Holocene, is about 15 km long and is located closed to the north-western end of the Boiano extensional system. The identification of the Isernia active fault system fills only part of the lack of data at the boundary between Northern-Central and Southern Apennines; the relationship with the surrounding active faults and with the regional seismicity is discussed.

LS01 : SUpo11 : PO
The Seismogenic Faults in the Umbria Region (Central Italy): An Integrated Geological and Geophysical Approach

Maria Grazia Ciaccio (ciaccio@ingv.it),
Francesco Mirabella (mirabell@unipg.it),
Alessandro Amato (amato@ingv.it),
Massimiliano Barchi (mbarchi@unipg.it) &
Saverio Merlini (saverio.merlini@agip.it)
Via di Vigna Murata, 605 Rome, 00143, Italy

We have investigated the seismogenic structures of the Northern part of the Umbria region-central Italy (Perugia-Gubbio area), by using data from seismic reflection lines, surface geology and seismology: the comparison between geological and geophysical data helps to constrain the geometries of active faults and then to understand seismogenic processes, fault interactions and to obtain more realistic seismic hazard estimates. In the past centuries, this area was struck by earthquakes of magnitudes (from Intensities data) up to 6.3, which define a NW-SE alignment. The distribution of recent seismicity shows that the Umbria region is characterised by a high level of background activity. In the last years several seismic sequences have occurred in this area with main shocks of magnitude up to Mw 6.0. Aftershock distribution and focal solutions suggest normal faulting mechanisms driven by a process of NE-SW extension. The set of seismic profiles analysed in this study (provided by Eni-Agip Division) consists of ten lines crossing the Apenninic belt and six tie lines which cover an area of nearly 800 km^2. The analysis of this data set allowed us to reconstruct the isochronous maps of the most important lithological markers, i.e. the top of the Evaporites and the top of the Basement, which is involved in the Miocene-Pliocene thrust sheets, and to delineate the geometry of two major extensional structures with a great detail, namely the low-angle east-dipping Altotiberina fault (ATF) and the west-dipping Gubbio fault (GF), antithetic to the ATF. The GF geometry can be effectively traced in the seismic reflection profiles for nearly 25 km from NW to SE to depths ranging between 1.5 s TWT (North), to 2.0s (South), which corresponds well with the nucleation depth of the main shocks of the region (~5-6 km). The intersection between the GF and the ATF deepens towards SE and is located within the Triassic Evaporites in the Northern sector and in the Phyllitic Basement in the Southern sector. The ATF, that is observed for nearly 35 km from NW to SE, cuts the Basement at greater depths from North (1.8 s TWT) to South (2.5 s TWT). Along this trend, we have identified an area where this intersection shows an offset of about 2 km towards SW and we have interpreted this feature with the presence of a ~E-W trending transfer zone which dissects the seismogenic system and possibly marks the southern boundary of the GF.

LS01 : SUpo12 : PO
Semi-Permanent GPS Network for Active Faults Survey and for Seismic Hazard Assessment in France. Technical Aspects, Objectives and First Installation in Jura

Stéphane Baize (baize@ipsn.fr)[1],
Franck Mathieu (mathieu@ipsn.fr)[1],
Eric Calais (eric.calais@unice.fr)[2],
Oona Scotti (scotti@ipsn.fr)[1],
François Jouanne (jouanne@univ-savoie.fr)[3],
Edward Marc Cushing (cushing@ipsn.fr)[1] &
Gérard Peyridieu (peyridieu@ipsn.fr)[1]
[1] IPSN/DPRE, B. P. 6, 92265 Fontenay-aux-Roses, France
[2] CNRS-Géosciences Azur, 250, rue A. Einstein, 06560 Valbonne, France
[3] LGCA, Université de Savoie, 73376 Le Bourget du Lac, France

On the basis of geological and geomorphologic data, it has been possible to identify potentially active structures in France : deformation rates are estimated at around 10^{-1} mm/y for the Durance Fault (Baroux, 2000) and the Nimes Fault (Schlupp et al., 2000) for time scale from 10^5 to 10^6 years. Preliminary results from the permanent network REGAL (Calais et al., 2000) indicate slip rates on the Durance fault on the order of 1.0±0.8 mm/yr. Another example is the Jura Mountains, the youngest thrust-and-fold belt related to French alpine orogeny. Several evidences (geology, seismicity) suggest that transverse strike-slip faults that characterize the most recent deformations are there still active (Baize et al., in press). This study aims at testing this hypothesis using GPS measurements.

Permanent geodetic networks involve a limited number of sites, which yields continuous geodetic data with a high precision, but implies tedious data analysis and relatively high costs (instrumentation, maintenance, technical interventions). Campaign measurements, repeated every 5 years for example, can measure a lot of sites but imply many field operators, and result in a lower precision than for continuous measurements at permanent sites. For instance, recent results show that two campaigns 5-years apart are necessary to detect the deformation rates expected in the Alps (Vigny et al., submitted). One reason for this is the non-random characteristics of the noise in GPS position time series, another one is systematic errors related to the tripod-antenna set-up at temporary sites.

An alternate way to achieve high precision measurements and reduce operation costs is the semi-permanent strategy. It consists in measuring temporary sites equipped with a specific geodetic monumentation during 10 to 15 days consecutively every 1 to 2 months. A single antenna is sufficient to measure a 6-10 site network, thanks to nearby permanent GPS stations. A key element is that the GPS antenna be repositioned very precisely for each session. The IPSN/BERSSIN developed a new mast-pillar ensemble composed of (1) a perennial pedestal anchored into the bedrock, (2) and a removable mast supporting the GPS antenna. This equipment is specifically designed to allow for a repositioning of the GPS antenna within 1/10 mm horizontally and 3/10 mm vertically. We started a test measurement phase in spring 2000, with the installation of 6 semi-permanent sites in Jura mountains. The first series of measurements was performed to establish the initial positions of each point. The next series of measurements is planned for the beginning of April 2001.

Installation of such networks is underway in different locations (Northern Jura, Provence area). It is hoped that results from such experiments will improve our understanding of deformation rates along individual faults which are important in seismic hazard assessment. See http://kreiz.unice.fr/regal/ for more information.

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LS01 : SUpo13 : PO
Horizontal Surface Displacements Induced by the Chi-Chi Earthquake, 1999 (Central Taiwan) Insight from SPOT Images Analyses

Stephane Dominguez
(domingue@ldg.bruyeres.cea.fr),
Remy Michel (michel@ldg.bruyeres.cea.fr) &
Jean-Philippe Avouac
(avouac@ldg.bruyeres.cea.fr)
CEA/DIF/DASE LDG-TRS, BP 12, 91680 Bruyeres-le-Chatel, France

The Chi-Chi earthquake (Ml=7.3) which occurred in Taiwan on September 21, 1999 is one of the best documented seismic rupture of thrust type. Numerous GPS and geodetic data have been recorded and field investigations have collected detailed measures of local fault scarps along the Chelungpu fault. However, due to complex deformations along the 80 km of the surface fault and the heterogeneous distribution of geodetic data, some difficulties remains to quantify the displacement gradients around the fault and to derive an accurate model of regional surface deformation. Unfortunately, SAR interferometry does not bring significant insight about the deformation because the dense vegetation covering the hanging wall of the fault yields near-total signal decorrelation. New data are then necessary to better constrain the kinematic of coseismic slip and to study in more details the mechanisms of seismic faulting in this region. With this objective, we used a new technique based on sub-pixel correlation of SPOT panchromatic images (offsets) acquired before and after the earthquake. This method has been already successfully applied to the Ms=7.4, 1999, Izmit earthquake (Michel, R. and Avouac, J.P., submitted to nature). We have obtained a detailed cartography (with a grid spacing of 40 m) of the surface rupture and the amplitude of associated displacements that are in good agreement with the field observations. Residual bias on displacement gradients measured from offsets were next compensated by comparison with GPS data using a least square approach. Based on those calibrated data, we generated a detailed model of horizontal ground surface displacements over a large area covering nearly 100% of the surface rupture and including the foot wall and the hanging wall of the Chelungpu fault. This model, together with geological and geophysical data available, is used to investigate the fault plane geometry at depth and is of interest to better constrain the source models of the Chi-Chi earthquake. Visible satellite imagery analyses is a powerfull tool to better constrain the geometry of the surface rupture in complement of the field observations. It provides reliable mesures of horizontal ground deformations associated with coseismic slip and new data for the determination of the regional surface displacement field.

LS01 : SUpo14 : PO
The Azambuja Fault (Portugal): An Example of Active Tectonics at a Seismic Intrapalte Region

João Cabral (jcabral@fc.ul.pt)[1],
Paulo Ribeiro (pribeiro@fc.ul.pt)[1],
Nuno Pimentel (pimentel@fc.ul.pt)[1] &
Antonio Martins[2]
[1] Faculdade de Ciências de Lisboa, Departamento de Geologia, Ed. C2, 51/4 piso, Campo Grande, 1700 Lisboa, Portugal
[2] Universidade de Évora, Departamento de Geociências, R. Romão Ramalho, 59, 7000 Évora-671 Évora, Portugal

The Azambuja fault is located NNE of Lisbon (Portugal, Western Iberia), in the Lower Tagus Valley (LTV), an area of important seismicity that represents a serious seismic hazard to this densely populated area. The LTV is located in the Lower Tagus Sedimentary Basin (LTB), a NNE-SSW trending tectonic basin where up to 2000 m of Cenozoic sediments are preserved. The LTB was structured in the Neogene, consisting in a foreland basin related to tectonic inversion of the extensional Mesozoic Lusitanian Basin, in response to a NNW-SSE Miocene compression. Major uncertainties on the regional tectonic structure have subsisted until now, due to the sedimentary cover that conceals many of the faults rooted in the Mesozoic and Paleozoic basement.

Seismotectonic studies are presently being conducted in the LTV region, using different approaches as aerial photographs and satellite imagery analysis, reinterpretation of seismic reflection lines, geomorphologic analysis based on digital terrain models, and field research. Several structures affecting the LTB Cenozoic sediments were already recognized.

So far, the Azambuja fault is one of the better-characterized regional neotectonic structures. It appears as a lineament on Landsat 5 TM satellite imagery and shows a clear morphological signature, presenting a NNE-SSW trending, East facing, 12 km long fault scarp, which displaces a Lower Pleistocene erosion surface with a maximum vertical offset of approximately 70 m. The fault is crossed by a seismic line, where it shows: an upthrust geometry displacing the Cenozoic sedimentary column, downthrown to the East, an upwards branched geometry leading to a distributed strain at the surface, a progressive upwards reduction of the vertical offsets indicating continuous movement during the Neogene, and displacement of the uppermost reflectors.

The field data are in agreement with the seismic reflection data. The fault is expressed at the surface by a zone of distributed deformation, where predominantly sandy Miocene and Pliocene sediments are tilted Eastwards and cut by several steeply dipping meso-scale faults presenting reverse and normal offsets, with a net downthrow to the East. This pattern is compatible with a sub-vertical fault (upthrust) in the basement that tilts and branches through the overlying Cenozoic sedimentary cover. The preservation of SSW-wards tilted Pliocene sands on the downthrown block, and the displacement, by the fault, of a Lower Pleistocene erosion surface that truncates the Pliocene sediments on the upper block, indicates slip on the fault predating the Quaternary erosion surface and after its development.

The Azambuja fault continues southwards under the Recent alluvium of the Tagus river, where it was identified on another seismic line, entering the epicentral area of important historical earthquakes and totaling more than 20 km in length.

LS01 : SUpo15 : PO
The 1999 Chichi Earthquake, Taiwan: Balanced Cross-Sections Highlight the Role of Structural Inheritance

Frederic Mouthereau (frederic.mouthereau@lgs.jussieu.fr),
Jacques Angelier (jacques.angelier@lgs.jussieu.fr) &
Jian-Cheng Lee
University Pierre et Marie Curie, 4 place Jussieu, Lab. Tectonique, E1, T.25-26, Case 129, 75252 Cedex 05, France

The Chichi earthquake (Mw=7.6) occurred on September 21st, 1999, in the frontal portion of the active Taiwan collision belt. All data, from geology, geodesy and seismology, reveal large coseismic thrust motion along the Chelungpu thrust. This major earthquake in the frontal foreland thrust wedge is in geometrical and mechanical good agreement with the NW-trending regional compression induced by the arc-continent collision (see also abstract by Angelier et al., this symposium). The seismological analysis of the Chi-chi earthquake sequence indicates that the main shocks occurred at depth of about 10 km along a thrust fault plane dipping 25°E (Chen and Kao, 2000). The depth distribution of aftershocks revealed the presence of two east-dipping seismogenic surfaces at 10 km and 25 km on average. Stratigraphic and structural subsurface data independently showed that the Chinese continental shelf entering the collision at the belt front (i.e. near the Chelungpu thrust area) is widely pre-fractured by a set of ENE-trending normal faults cutting the Late Cenozoic sedimentary cover down to the metamorphic basement. Structural inheritance and geometry of heterogeneities in the basement, i.e. normal faulting, has been already invoked to interpret the shape and kinematics of the thrust front in this region (Mouthereau et al., 1999). Further observations of the 80-km long fault trace of the Chelungpu thrust show that the fault turns abruptly to the ENE-direction at its northern tip. This curvature is also observed for other adjacent active thrusts. This is not only interpreted as a consequence of the proximity of the major Sanyi-Puli transfer fault zone, but also as a result of the blocking of thrust propagation onto pre-existing ENE-trending normal faults. Based on these observations and the available subsurface data, several balanced cross-sections are constructed across the Chelungpu thrust. Particular attention is paid to reconcile the seismological data indicating the attitude of the earthquake fault at depth and the geometrical demand for consistency in the Late Cenozoic finite deformation, taking the direction of deformation into account. We conclude that to understand the structure and behavior of the Chelungpu Fault in the thick sedimentary cover and the upper crust it is not enough to consider the seismological and geodetic information. It is also necessary to integrate in a rigorous geometrical way the earlier evolution of this region, which was strongly influenced by tectonic-controlled stratigraphic changes influencing the distribution of later décollement levels and by pre-existing zones of weakness resulting from widespread normal faulting that had occurred prior to collision.

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LS01 : SUpo16 : PO
Typology of the Earthquake Related Surface Traces of the 17 and 21 June 2000 Icelandic Earthquakes

Françoise Bergerat (bergerat@lgs.jussieu.fr) &
Jacques Angelier (jacques.angelier@lgs.jussieu.fr)
Laboratoire de Tectonique, boîte 129, UPMC, 4 place Jussieu, 75252 Paris cedex 05, France

Two major earthquakes (M=6.6) occurred on 17 and 21 June 2000 in southern Iceland, ending nearly 100 years of relative seismic quietness. In the South Iceland Seismic Zone (SISZ), the last sequences of major earthquakes took place in 1912 (at the eastern tip of the zone) and in 1896 (in its eastern and central parts). Since the 11th century and prior to June 2000, a total of 33 earthquakes with complete collapse of houses had occurred in the SISZ. These major historical earthquakes were located on N-S faults. For some of them, the surface traces are visible in aa or pahoehoe lavas and have been mapped in more or less detail. Although the appearance of the fractures depends on the nature of the surface, characteristic features can be observed on most of them, especially en-échelon open fractures, push-up and pull-apart structures. The same features have also been recognised along the surface traces of the June 2000 earthquakes, mainly observable in soils. The fault traces of the June 17 and 21 earthquake trend are N-S and are about 25 km long. The analysis of focal mechanisms indicate dextral strike-slip motion for both these earthquakes, although a more complicated model can be considered (R.Stefansson, http://www.vedur.is). We studied in the field five segments of the surface traces of the two seismic faults, carrying out (1) geometrical measurements of these structures, such as for width of open fractures, height of push-ups, throws of normal faults, and (2) mapping of selected main structures with a kinematic GPS system. These observations show that despite the dextral motion of the main N-S trending seismic faults, WNW-ESE trending sinistral faults are also present. The five fault segments studied illustrate contrasting aspects of the mechanisms of the two faults: (1) Bitra (sinistral segment with en-échelon open fractures and push-ups), (2) Road n°1 near Bitra (pressure ridges, strike-slip fractures) (3) Mykjunes (dextral and sinistral conjugate segments), (4) Eyvik (normal fault), and (5) Hestfjall (en échelon fractures). The surface displacement data collected for the two June 2000 earthquakes show that the actual active fault pattern is not restricted to the N-S trending dextral strike-slip revealed by focal mechanisms of earthquakes but also includes WSW-ENE trending sinistral strike-slip, thus forming a conjugate system consistent with the structural pattern of the SISZ.

LS01 : SUpo17 : PO
What is the Source of the 1909 Provence Earthquake? Historical and Morphotectonic Evidences

Robin Lacassin (lacassin@ipgp.jussieu.fr),
Paul Tapponnier, **Bertrand Meyer** &
Rolando Armijo
Laboratoire de Tectonique, IPG Paris, 4 place Jussieu, 75252 Paris Cedex 05, 75252, France

The destructive earthquake that affected south-eastern France on 11 June 1909 is the largest event instrumentally recorded in the metropolitan territory. Magnitude estimates range between 5.5 and 6.3 for a relatively shallow epicenter (Levret et al. 1996). The MSK intensity reached a maximum of IX, 20 km NW of Aix en Provence, between the Trevaresse and Costes anticlines (syn to post-Miocene). Despite detailed descriptions of the damage, there were no reports of coseismic surface breaks and the fault responsible for the earthquake has not yet been identified unambiguously.

We revaluate the near-field macroseismic observations (MSK intensities at every localities, damages in Francs/inhabitant given by Lemoine, 1910) and show that isoseismal contours VII and VIII surround the Trevaresse range and are elongated in the same direction (N110°E) as the range. The Costes range, by contrast, trends N70° on average and lies along the boundary or outside of the isoseismal area VIII.

The Trevaresse range is a ~15 km long, anticline with a 'whale-back' morphology. The topographic envelope delineates the shape of the anticline whose southern limb in steeper than the northern one. The southern flank is marked by a steep, convex slope of several tenths of meters high. The base of that slope has a straight cartographic trace, with two main segments about 9 and 6 km long. Locally, steeper scarps with relatively fresh scarplets may be interpreted as remnants of coseismic surface breaks. We infer that the 1909 Lambesc earthquake has activated a north-dipping thrust ramp underlying the Trevaresse anticline and that the scarp marks the surface emergence of that ramp. Scaling laws (Wells and Copersmith, 1994) and different hypotheses on fault segment activation during earthquake are compatible with magnitude ranging between 5.8 and 6.2.

In the absence of dated Quaternary geomorphic or geological marker, and of paleoseismological trenching, we cannot assess average slip-rates and recurrence intervals for the Trevaresse thrust. We note however that several of the alpine anticlines of western Provence (e.g., Luberon, Manosque, Alpilles, Trevaresse...) have young morphology. Some of these structures might possibly host events comparable to the 1909 earthquake and should be taken into account for regional seismic hazard assessment.

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LS01 : SUpo18 : PO
The Seismogenic Structure of the 1857 Lucania Earthquake (Southern Apennines, Italy)

Emanuele Tondi (etondi@camserv.unicam.it),
Giuseppe Cello (peppe@camserv.unicam.it),
Luca Mattioni (lmattioni@katamail.com) &
Luca Micarelli (lucamic@camserv.unicam.it)
Via Gentile II da Varano, 62032 Camerino (MC), Italy

The 1857 Lucania earthquake is one of the most destructive events in Peninsular Italy; its destructive effects were recorded over a large area, in the southern Apennines, extending from the Vallo di Diano to the Val d'Agri (Boschi et al., 1995; Benedetti et al., 1998). Ongoing tectonic activity, in the area, is expressed by the occurrence of large earthquakes distributed within an about 20-30 km wide belt extending, in a NW-SE direction, within the high-topography zone of the Apennines. Here, a Quaternary fault network, overprinting older structures of the Neogene fold and thrust belt, is well exposed. In the epicentral area of the 1857 Lucania earthquake we recognized two fault systems which were active since, at least, early Pleistocene times. Both the systems accomodate the brittle strain stored during the latest stages of deformation of these sectors of the peri-Mediterranean orogen. The first system (the Val d'Agri Fault System: VAFS, in Cello et al., 2000) is characterized by geometrically complex fault zones of different size; it is a kinematically coherent system which consists mainly of roughly N120° trending left-lateral strike-slip faults and N090°-N100° trending, left-lateral transtensional faults. The second system (the Vallo di Diano Fault System, DIFS) is characterized by NW-SE trending faults displaying long-term displacements of a few hundred metres. Fault slip data show a kinematic behaviour ranging from dip-slip (normal) motion on roughly NW-SE trending planes, to transtensional motion on WNW-ESE oriented faults. Structural and morphological data acquired from the two areas show that the VAFS and DIFS have also been active during the Holocene; they record, therefore, the paleoearthquake response of the area to the current stress conditions. The geometry of the stress fields responsible for the genesis and evolution of the two fault systems are quite different. The maximum stress component for the VAFS is subhorizontal (WNW-ESE trending), whereas the s1 axis for the DIFS is subvertical. Both the systems are, instead, characterized by a WNW-ESE-oriented extension and by R values comprised between 0.66 and 1.00. This means that s1@s2>>s3, hence suggesting the possibility that, in these areas, permutations between stress axes may occur. In this note, we discuss: (i) the nature of these processes, (ii) the possible interactions between the two fault systems, (iii) their implications for seismic hazard analyses and for estimating the seismic potential of the active fault zone which was responsible of the 1857 Lucania earthquake.

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LS01 : SUpo19 : PO
Surface Rupture for the Study of Earthquake Deformation: The October 1, 1995 (Mw=6.2) Dinar Earthquake, SW Turkey

Hayrettin Koral (hkoral@istanbul.edu.tr)
Istanbul University, Faculty of Engineering, Department of Geological Engineering, Avcilar-Istanbul, 34850, Turkey

A moderate earthquake (Mw= 6.2) caused substantial damage in the town of Dinar at 17:57 UT, on October 1, 1995 and was characterized by a 10-km long surface rupture that has been investigated for the study of coseismic earthquake deformation. The surface rupture has been observed to be discontinuous along the NW-trending Dinar fault segments. It has consisted of nearly vertical cracks up to several tens of meters long and a meter wide that display linear, sigmoidal and anastomosing geometries indicating the mechanism of deformation on the fault plane. Most of these cracks display a dip-slip component of deformation (0.05-0.6 m); those with anastomosing geometries indicate a large dip-slip (>0.25 m). Sigmoidal crack patterns show both right and left strike-slip (rotational) component of deformation and a small dip-slip (<0.25 m). The geometry of the cracks and related modes of slip suggest a 325° oriented horizontal principal stress direction. This direction

makes an acute angle with the NW-trending plane of the Dinar fault. This angular difference is the cause of the strike-slip (rotational) deformation manifested in the surface rupture and indicated by the focal mechanism solution of the earthquake. Under the influence of this horizontal principal stress direction of compression, firstly en echelon cracks were formed. Then these cracks were modified by a predominantly dip-slip (extensional) deformation on the Dinar fault; the initial cracks were connected to each other by anastomosing cracks of a second rotational phase. The rotation led the hanging-wall block of the Dinar fault to depart from its dip-slip orientation to an oblique south-westerly direction towards the Mediterranean Sea as suggested by strike and dip-slip indicating cracks.

LS01 : SUpo20 : PO
The Quaternary Stratigraphy and Tectonic Analyses of the Izmit Bay Basin, the Easternmost Part of the Sea of Marmara Basin System (NW Anatolia, Kocaeli-Turkey)

Bülent Dogan
Istanbul Tecnical University

The zmit Bay basin comprises the easternmost part of the E-W trending basin system of the Sea of Marmara. The basin has been studied to document the tectonic analyses of the surface ruptures that control the Quaternary stratigraphy of the northern and southern parts of the zmit Bay.The area has been investigated as two different zones; namely the northern and southern zones. In the northern zone, laminated marine lagune deposit of Tirrenien sediments, namely the Sirintepe formation, rest uncomformably on the basement litologies. The Sirintepe formation is tectonically overlain by alluvial fan deposits of Yenikent formation. This litological unit is composed mainly of large, angular, sand matrix-supported gravels, although the abundance of silt and clay material increase gradually towards the northern cost of the Bay. In the southern part, the alluvial fan deposits of Arslanbey formation dominate the Quaternary stratigraphy. The major Earthquake (with MS = 7.6 and focal depth of 18 km) occurred on 17th August 1999 in the area led to the formation of oblique surface ruptures, along with the major right lateral rupturing. Both of these rupturing control the Quaternary stratigraphy of the northern and southern zones.In the southern zone, the main oblique rupture has been found to be in an orientation of N41ºW / 78ºEW with a 38 cm normal and 12 cm right lateral offset. This main rupture seems to control the deposition of the Arslanbey formation. The orientation of the fault changes in same places to be N62ºW/79ºNE, E-W/80ºN. The tensional fissures formed parallel to the main fault plane has maximum length of 2 m. The fault observed along the coastal part of the town of Gölcük is a synthetic fault of the main fault. It extends with an orientation of N38ºW/86ºNE. The normal and right-lateral offset of this fault have been determined to be 190 cm and 18 cm respectively.The main oblique rupture of the northern zone formed around the town of Derince. This fault extends in an orientation of N80ºW/84ºSW, E-W/82S with a total relative right-lateral displacement of 10 cm. The fault controls the formation of the Yenikent unit. The tensional fissures observed on this fault are mostly sub-parallel to the fault plane and are interpreted to be indicative for a potential extensional stress.The geological and tectonic characteristics indicate that the zmit Bay basin is an asymmetric pull-apart basin formed between two approximately E-W trending right-lateral main fault segments and bordered by oblique faults with significantly high normal offset components.

LS01 : SUpo21 : PO
Active Faults and Earthquakes in the Eastern Marmara Sea: A High-Resolution Marine Geophysical and Geological Survey

Alina Polonia (alina.polonia@igm.bo.cnr.it)[1], **Milene Cormier** (cormier@ldeo.columbia.edu)[2], **Namik Cagatay** (cagatay@itu.edu.tr)[3], **Enrico Bonatti** (enrico.bonatti@igm.bo.cnr.it)[1], **Leonardo Seeber** (nano@ldeo.columbia.edu)[2], **Omer Emre** (emre@mta.gov.tr)[4], **Giovanni Bortoluzzi** (giovanni.bortoluzzi@igm.bo.cnr.it)[1], **Luca Gasperini** (luca.gasperini@igm.bo.cnr.it)[1] & **Naci Gorur** (baskan@posta.mam.gov.tr)[3]
[1] Istituto Geologia Marina, Via Gobetti, 101, 40129, Bologna, Italy
[2] Lamont-Doherty Earth Observatory of Columbia University, New York, USA
[3] Istanbul Technical University, Istanbul, Turkey
[4] MTA, Ankara, Turkey

A geological/geophysical survey has been carried out in the Marmara Sea in October/November 2000, with the R/V Odin Finder. We have obtained a data-base of very accurate multibeam sea-bottom topography and reflectivity, and shallow sub-bottom profiles over key portions of the eastern Marmara Sea, including the Izmit Gulf west of Hersek promontory, the shelf between the Prince's Islands and Tuzla and west of Istanbul between Bakirkoy and Kumburgaz. We have successfully located faults and sampled sediments with an accuracy of 1-2 m. We will thus be able to correlate subtle structures and displaced sedimentary/erosional features in the sediment column with active faults. These data will allow us to determine Holocene slip rates and, we hope, to identify individual earthquakes on submarine fault segments of the North Anatolian plate boundary. Northwest striking Holocene faults were identified on the shelf south of Istanbul. Their slip rates are probably low, but they may play an important role in the complex tectonic environment of the eastern Marmara. A major right-lateral branch of the North Anatolian transform boundary bisects the western Gulf of Izmit. This branch splays between two strands bounding a down-dropped block a few Km across. Each strand consists of a series of en-enchelon left-stepping fault segments, each approximately 1 km long. Other faults in the western Gulf of Izmit and on the shelf south of Prince's Islands and Tuzla probably play secondary roles in the plate motion but may affect the behavior of the major faults. These new findings will help to characterize fault interaction over times of hundreds or thousands of years. A comparison between such long-term interactions and the much observed short-term interactions is important to evaluate possible non-stationary aseismic components of the strain. The bathymetric, chirp and core data will be analyzed and interpreted within the next two months, in time for the planning of a second expedition by R/V CNR-Urania tentatively scheduled in Spring 2001. During this expedition side-scan sonar mapping, sub-bottom and high resolution multi-channel profiling will be done and carefully positioned sediment cores will be recovered to understand the shallow geometry and kinematics of portions of the fault system in the northeastern Marmara Sea. We will thus test the potential of "submarine paleo-seismology" approach to identify individual slip events, such as the 1509 and 1894 earthquakes, on fault segments of the North Anatolian plate boundary in the eastern part of the eastern Marmara Sea. This data-set can then be used to infer the future behaviour of the faults.

LS01 : SUpo22 : PO
17 August 1999 Kocaeli and 12 November 1999 Düzce Earthquakes in NW Anatolia (Turkey)

Süha Özden (sozden@cumhuriyet.edu.tr)[1], **K. Sevki Kavak** (kaank@cumhuriyet.edu.tr)[1], **Orhan Tatar** (tatar@cumhuriyet.edu.tr)[1], **B. Levent Mesci** (mesci@cumhuriyet.edu.tr)[1], **Fikret Koçbulut** (fkocbulut@cumhuriyet.edu.tr)[1], **S. Zeki Tutkun**[2] & **Bülent Doĝan**[2]
[1] Department of Geology, Cumhuriyet University, TR-58140 Sivas, Turkey
[2] Department of Geology, Kocaeli University, TR-41100, Turkey

The destructive earthquake of 17 August 1999 at 03 02 (Ms=7.4) in the densely populated Marmara region of NW Turkey along the North Anatolian Fault Zone (NAFZ) resulted in almost 20.000 deaths, left at least tens of thousands people homeless and injured and widespread destruction of buildings and industrial sites. The main area of surface ruptures were observed approximately 130 km-long extending between Yalova in the west and Gölyaka (Bolu) in the east. The epicenter of the Kocaeli earthquake located in the Gölcük area but maximum dextral strike-slip displacement on the surface rupture was observed in the town of Arifiye with 480 cm to the east of the epicentre area.

Only after two months, an earthquake also taken place on the western part of the NAFZ around Bolu, Düzce and Kaynasli villages on the 12 November 1999 at 18 57. The earthquake affected very large areas resulted in more than 700 deaths, left over 2500 people wounded, around 1500 buildings damaged. It was notable that Bolu tunnel and viaducts were also severely damaged. According to USGS data, epicenter of the Duzce earthquake falls at 40.768 North latitude and 31.148 East longitude where coincides N-NE of the Çinarli Village of Düzce. The magnitude was determined as 7.1 Mw and started at 14 km deep from surface. This event created about 40 km surface rupture between Gölyaka in the west and Dip village in the east on the Düzce Fault. The observed dextral strike-slip displacements yield around 25-400 cm along the surface rupture. This seismic event was also significant with the morphological and geometrical aspects. The features related to the strike-slip faulting such as anastomosing structures, horse tails, pressure ridges, small scale sag ponds, liquefaction structures, huge landslides of around 4-5 m, collapsed and subsided were observed on the surface rupture.

The aftershock distribution following the first event was mainly concentrated in two different regions around Yalova and the southern part of Adapazari. These two regions fall the both ends of the surface rupture of the Kocaeli earthquake. Finally, the seismic activity emerged around the Düzce area indicates that the failure stress migrated towards east along the Düzce fault on northern strand of the NAFZ. Whereas, in the western part, the existence of seismic risk along the northern strand on the Adalar-İstanbul-Thrace segment is still remain.

LS01 : SUpo23 : PO
Results of Paleoseismic Studies after the 1999 Izmit Earthquake: Implications for Seismic Hazard to Istanbul

T. K. Rockwell (trockwel@geology.sdsu.edu)[1], **E. Aksoy G. Ucarkus**[2], **A. Barka**[2], **D. Ragona D. Dier**[1], **M. Ferry**[3], **Y. Klinger**[4], **R. Langridge**[5], **M. Meghaoroui**[3], **A. Meltzner**[4] & **G. Seitz**[6]
[1] Dept. of Geological Sciences, San Diego State University, San Diego, CA 92182, USA
[2] Dept. of Geology, Istanbul Tech. Univ., Istanbul, Turkey
[3] 3EOST-Intitut de Physique du Globe de Strasbourg, Strasbourg, France
[4] , Caltech, Pasadena, CA, USA
[5] IGNS, P.O. Box 30-368, Lower Hutt, New Zealand
[6] LLNL, Livermore, CA, USA

We excavated 25 trenches across the 1912 rupture of the North Anatolian fault near the Gulf of Saros in Turkey to resolve slip and earthquake history on a channel-fan complex that crosses the fault at a high angle. A distinctive well-sorted fine sand channel served as a marker unit that was exposed in 21 trenches totaling over 300 m in length. Isopach mapping shows that the sand is channelized north of the fault, and flowed as a fan complex across a broad fault scarp to the south. Reconstruction of the feeder channel to the fan apex resolves about 8.5 m of dextral slip. Study of the rupture history in several exposures demonstrates that this displacement occurred principally as two large events and a smaller, fissuring event. The age of the sand channel is radiocarbon dated as post-1600 A.D., so we attribute the two larger events to the large regional earthquakes of 1766 and 1912. A third event, which is expressed only as a small fissure filling in one trench exposure, occurred between the two large events and may be the result of minor bleed-over slip from the 1893 M6.9 earthquake in the Gulf of Saros to the west. We conclude from these observations that most of the slip likely results from the 1766 and 1912 earthquakes. If each was similar in size, then about 4 m of slip can be attributed to each event. We also excavated six trenches at two sites along the 1999 Izmit rupture to study past earthquake history along that segment of the North Anatolian fault. One site, located in the township of Kosekoy east of Izmit, revealed evidence for two and probably three surface ruptures during the past 400 years. The other trench was sited in an Ottoman canal that was excavated (but never completed) in 1591. There is evidence of only two large surface rupturing events at that site, located only a few kilometers from the Kosekoy site.

One of the past events is almost certainly the large earthquake of 1719, but the presence of a probable third event during the past 400 years leaves open the possibility that either 1754 or 1894 also ruptured the onshore portion of the fault zone. Release of about 4 m of seismic slip both west and east of the Marmara Sea this past century (1912, 1999) support the contention that Istanbul is at high risk from a pending large earthquake. In that historical records suggest that the last central large Marmara event occurred in 1766, there may be a similar 4 m of accumulated strain across the Marmara basin segment of the North Anatolian fault.

LS01 : SUpo24 : PO
Geomorphology, Paleoseismology and Effects of the M=7.4 August 17, 1999 Izmit Earthquake on Auxiliary Strands of the Yalova Fault

Christian Walls (cwalls@earthconsultants.com)[1], **Kerry Sieh** (sieh@gps.caltech.edu)[2], **Yann Klinger**[2], **Aykut Barka** (barka@itu.edu.tr)[3], **Serdar Akyuz** (akyuz@itu.edu.tr)[3] & **Erhan Altunel** (ealtunel@ogu.edu.tr)[4]
[1] 2522 N. Santiago Blvd, Suite B, Orange, CA 92867, United States
[2] 1200 E. California Blvd, California Institute of Technology, Pasadena, CA 91125, United States
[3] Eurasian Earth Science Institute, Istanbul Technical University, Istanbul, 80626, Turkey
[4] Osmangazi University, Department of Geology, Eskisehir, Turkey

The principal surface rupture from the M=7.4 August 17, 1999 Izmit earthquake terminated east of the Hersek peninsula at the segment boundary between the Izmit and Yalova faults. However, geodetic studies indicate that up to 0.6 m of coseismic surface slip occurred along the eastern Yalova segment (Reilinger et al., 2000). A portion of this calculated slip is evident as decimeter scale normal sense offsets that occurred 7-12 km west of the Hersek Peninsula on secondary faults of the Yalova segment on the Kilic delta. In this research we integrate aerial photo analysis, geomorphic mapping, paleoseismic trenching, borings and cpt transects to locate and determine timing of past ruptures on auxiliary faults of the Yalova segment.

Near the Karamursel pull-apart basin, the Yalova segment consists of several splays. Two faults bound the Hersek Peninsula (Lindvall et al., 2000) and extend west to form the main sidewall fault along the southern margin of the transtensional basin under the Marmara Sea (Aksu et a., 2000). South of the Hersek Peninsula triangular facets along three distinct 9-12 km segments delineate right stepping en echelon N60-80E north dipping normal faults. The westernmost fault forms the boundary between a 200 m escarpment and the Kilic delta where 2.5 km of the range front fault produced discontinuous 10-15 cm scarps during the August 1999 earthquake. A paleoseismic trench placed across a 4 m curvilinear scarp 100 m north of the main fault, exposed structures that formed during multiple faulting and slumping events before 27.5 ka.

The August 1999 earthquake produced two 0.5 km E-W linear fracture zones on the Kilic delta. Radiocarbon dating of detrital charcoal from paleoseismic trenches across the faults revealed that the penultimate event occurred during the time of the great Marmara earthquake in 1509 with 15-30 cm of vertical offset, approximately twice that of 1999. Implications of the contrast in offset during the 1509 and 1999 events and the absence of the 1894 event will be discussed.

One fracture zone is collinear with a 13-m-high, 70 m wide and 1 km long asymmetric ridge with a north-facing scarp that did not rupture in 1999. Four trenches, four continuous core borings and two cpt transects placed across the width of the structure revealed a fault bound rotated block comprised of gently south dipping 24.8-28.0 ka terrigeneous sediments flanked on the north by marine, colluvial and slump material. The stratigraphic relationships coupled with radiocarbon analyses of detrital charcoal and articulated marine shells demonstrate multiple stages of block rotation, faulting, slumping and seawater inundation that occurred primarily before 5,295 B.P.

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LS01 : SUpo25 : PO
The Lower Tagus Fault, Portugal: Investigating Active Transpressional Deformation in a Major River Valley

Vittorio Bosi (vittorio.bosi@dstn.it)[1], **Susana Vilanova** (fonseca@alfa.ist.utl.pt)[2], **Mustapha Meghraoui** (mustapha@eost.u-strasbg.fr)[3] & **Joao. F. B. D. Fonseca**[2]
[1] National Seismic Survey of Italy, via Curtatone 3, 00185 Roma, Italy
[2] Earthquake Engineering and Seismology Division, ICIST, IST Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal
[3] EOST-Institut de Physique du Globe de Strasbourg, 5 rue Rene Descartes, 67084 Strasbourg, France

The city of Lisbon and the lower Tagus Valley (LTV) experienced large offshore (1755) and onshore historical earthquakes (M 6.8 - 7), the best studied being those of 1531 and 1909 (Moreira, 1984). Using geomorphic, geophysics and structural geology analyses, we investigate the northern flank of the valley identified as a possible source for large earthquakes. Although the existence of an active fault following the strike of the valley has been inferred by several authors (e.g., Choffat and Bensaude, 1912; Andrade, 1938; Fonseca, 1989; Cabral, 1995), no evidence of such structure - other than the occurrence of these large earthquakes - was previously documented. along the LTV. The active structure corresponds to a segmented transpressive strike slip fault and we fosused on a (minimum) length of 20 km of the fault section near Santarem. Folded and faulted Quaternary units (also visible in seismic profiles), uplifted alluvial terraces and inferred drainage control by vertical movements illustrate the recent tectonics of this area. We selected a site along the fault scarp and excavated two trenches across the fault (parallel and perpendicular to the main scarp). The deformation observed in trenches shows clear thrusts planes with gouge zone and shear fabrics which affect late Quaternary formations. The Holocene age of thrusting was firstly obtained by dating of archaeological samples (bronze and calcolithic age) which were found in the soils affected by the faults and after confirmed by radiocarbon ages. The complex pattern of deformation in trenches suggest multiple events after 2865 BC - 2490 BC, with at least one event post-dating 365 AD - 655 AD. Beside the offshore seismogenic sources, the LTV active fault near Lisbon implies necessarily a reevaluation of the regional seismotectonics and the related seismic hazard.

LS01 : SUpo26 : PO
Ground-Penetrating Radar (GPR) in Paleoseismological Investigations- Examples from Active Fault Zones of the Betic Cordilleras

Klaus Reicherter (reicherter@geowiss.uni-hamburg.de), **Stefan Reiss** & **Claus-Dieter Reuther**
Geological Institute, Bundesstr. 55, D-20146 Hamburg, Germany

Ground Penetrating Radar (GPR) survey of recent faults and fault systems is a geophysical method applied in paleoseismology and, especially, in pre-treching studies. We apply GPR techniques in different Quaternary tectonic and depositional environments in several seismically active regions within the Ibero-Maghrebian convergence zone (Betic Cordilleras, southern Spain). The main purposes are to detect active fault traces in depth, and to obtain subsurface information of the faulting history, e.g. the influence of faults on the sedimentary architecture in the hanging wall. A SIR-10-B system (GSSI) was employed using 200 and 400 MHz antennas. Geological and netotectonic structures in Quaternary deposits revealed interpretable data sets up to 15 m depth in the investigated sites of major active regions in the central Betic Cordilleras: (1) the Ventas de Zafarraya Fault (VZF) in the Granada Depression. The GPR imaging has been applied to survey Quaternary and Jurassic limestone deposits across the fault scarp and revealed high-resolution data sets up to 5 m depth. The faults truncate and warp the reflections, commonly juxtapose strata with different dips and contrasting intensities. Radargrams of the hanging wall show a significant change into concave-up patterns, which are interpreted as faulting-related halfgraben sediments. Three major normal faults are identified, which are traceable in depth and distance. Different reflection patterns suggest a multiple faulting history along the VZF. (2) the Carboneras Fault Zone (CFZ) in the Betic Cordilleras near the Cabo de Gata (S Spain). Three sites along the CFZ were examined with GPR surveying, which was complemented by mapping of fault scarps and paleostress analysis. Shallow-depth high-resolution imaging of Tyrrhenian beach terraces exhibited both vertical and horizontal offsets in the Rambla Morales site in the South of the CFZ. A sinistral strike-slip fault associated with minor thrust faults in a positive flower structure was detected in the middle segment along the La Serrata ridge, sealed by a caliche of latest Pleistocene age (<85 ka). The Playa de Bolmayor section in the North yielded sub-surface evidence for several faults probably related to coseismic slip and recent activity of individual fault strands. To conclude the results of our GPR investigations in the central Betic Cordilleras, important sub-surface information was acquired. The studied faults, fault scarps and associate minor faults are traceable in depth and distance. The faults truncate and warp the reflections, faults juxtapose strata with different dips and contrasting intensities. The fault planes and associated minor faults are characterized by continous reflector terminations, whereas continous reflectors are interpreted as bedding planes. GPR studies provide a geophysical method to study and map buried active faults and fault systems, and is applicable to image the architecture of fault-related Quaternary colluvial and alluvial deposits in semi-arid to arid climates or adequate settings.

LS01 : SUpo27 : PO
Slump Deposits as a Paleoseismological Tool: Reconstructing Holocene Earthquake History of Central Switzerland

Michael Schnellmann (schnell@erdw.ethz.ch), **Katrin Monecke** (katrin.monecke@erdw.ethz.ch), **Flavio Anselmetti** (flavio@erdw.ethz.ch), **Arnfried Becker** (becker@seismo.ifg.ethz.ch) & **Domenico Giardini** (giardini@seismo.ifg.ethz.ch)
ETH Zürich, Institut für Geophysik, CH-8093 Zürich, Switzerland

High resolution seismic profiling in Lake Lucerne, Central Switzerland, indicates that large slump deposits occur in the subsurface of the different lake basins. Five seismic stratigraphic horizons can be identified at which persistent slumping occurred, pointing to a common regional trigger mechanism. These units are interpreted as a result of earthquakes that occurred in central Switzerland during the last 12,000 years. The region is known to be seismically active. Chronicles describe an earthquake, which occurred in 1601 in great detail. Shore-collapses and huge water movements, in particular an 8 days lasting seiche, were observed. This specific earthquake has previously been linked to a slump unit in the lake. In order to study the subsurface with all slump units in quasi 3D, a dense grid of approximately 200 kilometres of 3.5 kHz seismic lines has been acquired. To minimise the influence of floods the study focused on basins without major deltas and with low detrital input. Eight Kullenberg cores each of approximately 10 metres have been taken to date the critical units and to characterise the sediments deformed by seismic shaking and slumping. The seismic data images numerous slump deposits up to 10 metres thick, down to a maximum depth of 30 metres. In some areas, the profiles show clearly the back scar and the internal structure of the slumped sediments with intense folding and thrusting. More frequently, the slumps show only chaotic reflections. The top of these disturbed units occasionally correlates with a seismically transparent unit in the basin plain, characterised by a smooth flat top. This feature is interpreted as a homogenite, originated when mud-sized sediment was brought into suspension during slumping and settled slowly in the deepest part of the basin. Dating of the cores should yield ages for all the 5 horizons, at which persistent slumping has been observed.

LS01 : SUpo28 : PO
Sedimentary Patterns in Lake Lungern, Central Switzerland: A Potential Archive of the Regional Holocene Earthquake History

Katrin Monecke (katrin.monecke@erdw.ethz.ch), **Michael Schnellmann** (schnell@erdw.ethz.ch), **Flavio Anselmetti** (flavio@erdw.ethz.ch), **Arnfried Becker** (becker@seismo.ifg.ethz.ch) & **Domenico Giardini** (giardini@seismo.ifg.ethz.ch)
ETH Zürich, Institut für Geophysik, CH-8093 Zürich, Switzerland

The sedimentary patterns of Lake Lungern as mapped by high-resolution seismic sections and recovered by long sediment cores indicate a large potential to reveal paleoseismic events. Lake Lungern is situated in a tectonically active area of the Alpine belt in Central Switzerland. The historical record since AD 1300 and the instrumental record since 1974 show significant levels of seismicity in Central Switzerland, including seven major earthquakes with an intensity (MSK) of VII to IX. The aim of this study is to reconstruct the effects of the historically reported earthquakes on the lake sediments and to extend the earthquake history back further into the Holocene. Lake Lungern lies within a NNE-SSW trending valley within the Helvetian nappes. The valley follows a shear zone cutting obliquely through the Alpine structures. The shear zone is characterised by a system of steeply dipping valley-parallel trending strike slip faults with an overall sinistral movement. Remarkable are several gas escapes along the presumed fault traces. The lacustrine sedimentation is controlled mainly by clastic input from several small rivers entering the lake and from landslides occurring on the relatively steep valley sides. During recent investigations a dense grid of 3.5 kHz seismic profiles and 6 Kullenberg cores varying in length between 2.5 m to 6.6 m were collected. The seismic lines show at least four event horizons, including slump deposits and inclined layers. The slumps could have been triggered by earthquakes, as indicated by the occurrence of different slump units within one stratigraphic horizon. The inclined layers can be interpreted as the result of faulting within the underlying lake sediments. Tracing of the inclined structure indicates a N-S trending, steeply dipping fault, which coincides well with the regional fault system. The gravity cores reach at least the three uppermost event horizons. They should provide more information about the processes and timing of the large-scale sedimentation and small-scale in situ deformation of the lake deposits

LS01 : SUpo29 : PO
Updating of Neotectonic and Paleoseismological Catalogue in France and Adjacent Area. Application to Seismic Hazard Assessment

Stéphane Baize (baize@ipsn.fr)[1],
Edward Marc Cushing[1], **Francis Lemeille**[1],
Christian Hibsch
(christian.hibsch@g2r.uhp-nancy.fr)[2] &
Bertrand Grellet (geoter@mnet.fr)[3]
[1] IPSN/DPRE, BP 6, 92 265 Fontenay-aux-Roses, France
[2] G2R - UMR 7566, Université Henri Poincaré, BP 239, 54 506 Vandoeuvre-les-Nancy, France
[3] GEO-TER, 3 rue Jean Monnet, 34 830 Clapiers, France

In French regulation for nuclear safety, seismic hazard assessment now contains recommendation for geological and paleoseismological consideration of past earthquakes. Because of geodynamic context, major seismic events have occurrence period larger than a thousand years, which is the larger period for historical observations in France. Then, geological and geomorphologic investigations are very interesting in order to find major events in a given area.

The aim of the work was to create an updated catalogue of neotectonic and paleoseismological evidences in France and adjacent area. A discussion about origin of surface-rupture faults known in France has been undertaken from a heterogeneous bibliographic catalogues. After a first selection then controlled by new field investigations, various origins of deformation were recognized among the initial list : gravity or karstic collapses, landslides, periglacial deformations, glaciotectonism... This catalogue is the result of a long-term work started in the early nineties (Cushing et al., 1993; Grellet et al., 1993).

Finally, only 31 sites are described from a former list of 120 ‘deformation’ indications. For the authors, a few reveal a demonstrated neotectonic origin (18). Only one site is recognized as a proved paleoseismic event (Bree in Belgium) (Camelbeeck & Meghraoui, 1998), even if several are suspected to be linked with seismic activity: Courthézon on the Nimes Fault (Combes et al., 1993), Valveranne on the Durance Fault (Ghafiri, 1995), La Balme on the Vuache Fault, Jülich in Germany, on the Rurrand Fault (Vanneste &Verbeeck, 2000). Particular care was kept to correlate each surface rupture with regional faults then suspected to be active. Such a proceeding was followed with classical geologic investigations, but also with geomorphologic approaches (DEM analysis: linear features, relief and scarps) which gives indications about the size of the active fault. Thus, the major seismogenic faults of France (and neighbouring area) correlate with such neotectonic evidence (Nimes fault, Durance fault, Vuache fault, Feldbiss fault...). However, for some sites, the crustal fault able to generate seismic event with surface failure is not yet known.

A complementary work is necessary to include these punctual observations in seismic hazard assessment. For example, quantitative geomorphologic analysis is planned to enlarge the French active faults review. Moreover, interseismic deformation rates along active faults, available with long-term geodetic measurements (GPS), could be acquired in order to evaluate the stress accumulation on the faults. Thus, in addition with classical neotectonic analysis (displacement, fault length, dating of events), evaluating seismogenic potentialities and recurrence period for major events will be possible.

Actually, this updating work permitted to include directly palaeo-earthquakes in seismic hazard assessment and seismic motion expected for a few industrial sites. It allowed too a better definition of sismotectonic zones and active faults, together with instrumental and historical seismicity.

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LS01 : SUpo30 : PO
Petrology and Kinetics of a Pseudotachylyte from the High Tatras (Western Carpathians, Slovakia)

Igor Petrik (geolpetr@savba.savba.sk)
Geological Institute, Slovak Academy of Sciences, Dubravska 9, 84226 Bratislava, Slovakia

A fault-related pseudotachylyte (pt) was found in the High Tatra granitic basement in a NNE oriented fault-system. Samples from three places were studied in detail showing different aspects of pt formation, injection and solidification. The pt occurs either as veins (up to 1 cm thick) or as an anastomosing vein network. With the growing share of lithic clasts the network may change into breccia cemented by the crystallized frictional melt. The pt matrix consists of well-crystallized hematite needles (6-35 vol%), anhedral K-feldspar, albite and subordinate quartz. The pt mineral composition suggests an origin due to preferential dehydration melting of biotite and/or chlorite which provided water for further melting of the quartzo-feldspathic component. Highly oxidizing conditions in the melt originated probably due to high temperature water dissociation followed by hydrogen escape. The escape was greatly facilitated by a very high surface/volume ratio of the melt in the network vein system. The composition of matrix is controlled by the proportions of biotite + feldspars + quartz undergoing melting rather than by Qz-Ab-Or-An equilibria suggesting that equilibrium was not attained.

The hematite brightness in BSE images enables an easy image analysis. This was utilized for measuring of crystal size distributions (CSD). Hematite lengths were measured in 42 images from 10 thin sections (200-2000 crystals per image). Profiles across pt veins show average hematite lengths 3-20 µm (max 25) with crystal sizes decreasing towards rims confirming the injection origin of the vein. The clast-laden pt and the injections into very thin tension fractures (100 µm) crystallized the smallest crystals about 2-6 µm suggesting high cooling rates in these large-surface domains. By contrast, the largest hematite crystals (14-20 µm) grew in melt pools accumulated in extensionally formed pockets. In accordance with Marsh (1998) the CSDs show loglinear patterns, and the hematite is interpreted as having grown in a batch system with constant growth rate (G) and exponentially growing nucleation rate. As crystal G are not known for such highly non-equilibrium environments the solidification times were estimated from heat conduction equations (Jaeger 1968): a 1 cm thick vein will solidify in ca. 60 sec (including the latent heat of crystallization). Such a crystallization time requires hematite G ca. $2x10^{-5}$ cm/sec which is about 5 orders of magnitude faster than values typical of nearly equilibrium conditions. The maximum lengths (Lmax) of hematite in measured domains vary by a factor of 8 corresponding to crystallization times (t=Lmax/G) between 15-120 sec.

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Monday AM Session

LS01 : MOam01 : F2
Seismic Activity and Fault Segmentation of the NAF in the Bolu Mountain: Relationship between the November 12, 1999 and the February 1, 1944 Earthquakes

Aykut Barka (barka@itu.edu.tr)[1],
Erhan Altunel (ealtunel@ogu.edu.tr)[2],
Serdar Akyuz (akyuz@itu.edu.tr)[1],
Ziyadin Cakir (cakirz@itu.edu.tr)[1],
Ozgur Kozaci[1], **William Lettis**[3],
Jeff Bachhuber[3], **Chris Hitchcock**[3] &
John Helms[3]
[1] Istanbul Technical University, Eurasian Earth Science Institute, Ayazaga, Istanbul, Turkey
[2] Osmangazi University, Engineering Faculty, Department of Geology, Eskisehir, Turkey
[3] William Lettis & Associates, 1777 Botelho Dr., Suite 262, Walnut Creek, CA 94520, USA

The North Anatolian fault (NAF) zone splays into two major branches around the Bolu mountains. The southern strand extends through the Mudurnu Valley and it ruptured during the February 1, 1944 Bolu (M=7.5), 1957 Abant (M=7.0) and 1967 Mudurnu Valley (M 7.1) earthquakes with average dextral offset of 2.5 m. The northern strand, Düzce fault, ruptured during the November 12, 1999 (M=7.2) earthquake with an average right-lateral offset of about 3 m. The Düzce fault joins the southern branch of the NAF via a right-releasing stepover including the Elmalik, Bakacak and Zekidagi faults. The 1944 earthquake rupture apparently decreased from about 3.5 m near Bolu, to 1.9 m or less near Abant Lake. The dextral offset on the 1999 Düzce rupture decreases eastwards and it terminates in Bolu mountains. The rupture data is well documented for the November 12, 1999 earthquake but the 1944 event is not well documented. Thus, it is possible that some coseismic slip may have occurred along the Elmalik and Bakacak faults. Paleoseismic trench data show that the Bakacak and Elmalik faults have produced distinct surface faulting earthquakes during the Holocene. The recurrence interval between earthquakes on these faults appears to be much longer than the average repeat time for earthquakes on the main North Anatolian fault. The southern and northern strands of the NAF are structurally and kinematically linked through a right stepover but the Bakacak and/or Elmalik faults may rupture independently.

LS01 : MOam02 : F2
Large Earthquakes and Creep in a Collision Zone: The Chelungpu and Chihshang Faults, Taiwan

Jacques Angelier
(jacques.angelier@lgs.jussieu.fr)[1],
Lee Jian-Cheng[2], **Hu Jyr-Ching**[3] &
Chu Hao-Tsu[4]
[1] Universite Pierre et Marie Curie, 75252 Paris Cedex 05, France
[2] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
[3] Institute for secondary School teachers, Taichung, Taiwan
[4] Central Geological Survey, Taipei, Taiwan

The destructive Chichi earthquake (Mw=7.6), September 21th 1999, hit central west Taiwan and killed about 2,400 people. The focus was located at a shallow crust level (7-10 km). It reactivated a major west-verging thrust near the front of the fold and thrust belt of Taiwan, the Chelungpu Fault. Along the rupture trace of the Chelungpu Fault, the vertical seismic offsets and the horizontal shortening generally average 2-4 metres along the central and southern segments of the fault, but commonly reach 5-7 metres and even 8-10 metres in the northern segment. At several localities, the geometrical relationships between the horizontal thrust component of displacement, the left-lateral component and the vertical component could thus be determined. The deformation remained commonly negligible on the footwall side, whereas the upthrust block was often heavily deformed, with fissuring and pop-up structures with anticlines bounded by thrusts and backthrusts. The active fault scarp of the Chichi earthquake represents a very small portion of a much larger, and partly eroded, scarp which progressively developed during the recent Quaternary times, as a result of a succession of thrusting events. On the eastern side of the collision belt, creep has occurred for several tens of years along the west-verging Chihshang Fault, a segment of the active suture zone of eastern Taiwan. Annual records of displacement revealed concentration of shear on a single fault, with a rather constant velocity (nearly 30 cm in 12 years). Our creepmeters now provide daily records of deformation at two main sites, revealing the influence of seasonal variations related to the water contents of the sediments. Large earthquakes have occurred in this region and the creep behaviour cannot be expected to be permanent. Adjacent segments of the Longitudinal Valley Fault did not show field evidence of present-day fault displacement although geodetic surveys revealed shortening: these segments are probably locked with increasing elastic strain. The Chichi earthquake and other major historical earthquakes that occurred along the western front of the belt indicate that very significant shortening presently occurs at the front of the Taiwan belt, although its main expression is a succession of large earthquakes separated by periods of "locking". Assuming that the Chelungpu Fault was locked during the last century, the averaged slip velocity is about 3 cm/yr, as for the Longitudinal Valley. We thus present a model of twin plate boundary. The Longitudinal Valley, or Eastern Plate Boundary, corresponds to a suture zone where shortening was permanent before and during the collision, representing a total of several hundreds kilometres. The Western Plate Boundary, where the Chichi earthquake occurred, developed more recently, as the probable result of northward propagation of the pre-existing Manila trench system into the continental foreland of the Taiwan belt.

LS01 : MOam03 : F2
The 1999 Hector Mine Earthquake: The Latest in a Cluster of Large Earthquakes in the Eastern California Shear Zone

Thomas Rockwell (trockwel@geology.sdsu.edu)
Dept. of Geological Sciences, San Diego State University, San Diego, CA 92182, USA

The Hector Mine earthquake produced up to 5.2 m of right-lateral rupture along the Lavic Lake fault, a previously mapped but unnamed fault in the Bullion Mountains of the Mojave desert of southern California (Hector Mine Geologic Working Group, 1999). Preliminary paleoseismic investigations indicate that the penultimate earthquake in the Bullion Mountains may have been as many as several tens of thousands of years ago, making this a pre-Holocene fault and one that would not have been expected to rupture in a large earthquake this past year. Paleoseismic investigations on many parallel faults that comprise the Eastern California Shear Zone (ECSZ) show that this is simply the latest in a cluster of large earthquakes that have now involved all but one of the faults under study. Prior to this cluster, there was a period of several thousand years during which no large earthquakes were produced on any of these faults, preceded by another cluster of ruptures. Furthermore, the much higher slip rate Garlock fault, that bounds the ECSZ on the north, appears to be in phase with these clusters of earthquakes. GPS measurements show high strain rates of about 10 mm/yr across the ECSZ. In contrast, slip rates estimated for individual faults with the ECSZ are typically a fraction of a mm/yr and do not sum to the observed geodetic motion. Thus, this recent, late Holocene cluster of earthquakes which coincides with GPS observations of high strain rates may suggest that strain accumulation and release is not uniform east of the San Andreas fault.

LS01 : MOam04 : F2
Slip-Rate and Earthquake Recurrence Time on the Hebgen Lake Fault (Montana, USA): Constraints from Surface Exposure Dating of Alluvial Terraces and Bedrock Fault Scarp

Jerome Van der Woerd (vanderwoerd2@llnl.gov),
L. Benedetti, **M. W. Caffee**, **R. Finkel**,
F. J. Ryerson & **Hebgen Lake Paleoseismology Working Group**
IGPP-LLNL, L202, 7000 East Avenue, CA94550 Livermore, USA

The August 1959 Hebgen Lake earthquake sequence, with two main shocks of magnitude Ms=6.0 and Ms=7.5, is one of the largest to have occurred on a normal fault north of the Basin and Range. The two earthquakes ruptured the Hebgen Lake and Red Canyon normal faults, whose traces were marked at the surface by an older, degraded scarp. Zreda and Noller (1998) reported the occurrence of 6 earthquakes around 0.4, 1.7, 2.6, 7.0, 20.3 and 23.8 ka by dating a limestone bedrock scarp along the Hebgen Lake Fault using the accumulation of cosmogenic Chlorine-36. These results of seismic activity and clustering are not supported by geomorphic studies of scarp degradation and alluvial terrace offsets. In order to better constrain slip-rate and recurrence time of earthquakes along the Hebgen Lake fault, we have selected three sites where abandoned stream terraces are clearly cut and offset vertically by the fault. We have dated these terraces using ^{26}Al and ^{10}Be cosmogenic nuclide surface exposure dating of quartz-rich samples. A terrace level with a cumulative offset of 5 to 6 m is found at the three sites with surface ages ranging from 11000 to 15000 yr. At the Grayling Creek site, older ages (20 to 30 kyrs) are found mixed with younger ones, a probable result of pre-exposure in the large catchment upstream. At the Cabin Creek site, the lowest terrace yields young ages (800-1400 yr) consistent with final abandonment after the 1959 earthquake, when the creek incised its bed in the uplifted terrace. Additional surface and sub-surface sampling at the three sites will help refine the chronology of terrace deposition and abandonment. The results suggest a minimum vertical slip-rate of 0.3-0.5 mm/yr on the Hebgen Lake fault. Moreover, since the cumulative offset is due to 2 or 3 earthquakes, a recurrence time of 5 to 10 kyr for large earthquakes comparable to the August 1959 event is plausible. These results will be interpreted along with additional cosmogenic ^{36}Cl ages and with data from several trenches to better assess the time-magnitude series of earthquakes on this fault.

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LS01 : MOam05 : F2
Geodetic vs Seismic Strain Rates, Ways to Estimate the Amounts of Accumulated Seismic Moments in Central Asia?

Gero W. Michel (fault@gfz-potsdam.de),
Reigber Ch. & **Michajljow W.**
GFZ Potsdam, Division 1, Telegrafenberg, D-14473 Potsdam, Germany

Recent GPS results taken from a regional network covering the Tien Shan and adjacent areas along with historical and prehistorical seismicity data were used to 1) compare geodetic and seismic strain rates and 2) to assess the apparent amount of accumulated seismic moments. In order to do this we a) divided the study area into block units using 80 straight and easy to model fault segments, b) approximated block motions using the GPS results, c) estimated differential motions along faults assuming that these are fully coupled seismically, d) divided the area into seismotectonic regions, and e) approximated geodetic strain rates in these regions. Results were then compared to strain rates estimated using historical and prehistorical seismicity data of the area. This was done estimating maximum possible earthquakes from the historical and prehistorical records and using both, x) composite moment tensors that include the entire seismicity record and - taking into account that earthquakes may cluster in time and space - y) Gutenberg-Richter frequency-magnitude relations. High coincidence of seismic and geodetic strain rates were derived and extrapolated geodetic moments were taken as accumulated seismic moments. Changes in moments were then approximated taking into account both, deformation release during major earthquakes and associated redistribution of stresses and strains approximated using deformation in an elastic half-space.

LS01 : MOam06 : F2
The August 17, 1999 Turkey Earthquake Seen with INSAR Imagery and Tectonic Field Observations

Ziyadin Cakir (cakirz@itu.edu.tr)[1],
Jean Bernard De Chabalier
(dechabal@ipgp.jussieu.fr)[2],
Rolando Armijo (armijo@ipgp.jussieu.fr)[2],
Bertrand Meyer (meyer@ipgp.jussieu.fr)[2],
Aykut Barka (barka@itu.edu.tr)[1] &
Gilles Peltzer[3]
[1] ITU, Turkey
[2] IPGP, France
[3] JPL, USA

We mapped the coseismic surface deformation caused by the 1999 Izmit event at the entrance of the Marmara Sea using SAR Interferometry. The tectonic observations were used to gain a better understanding of the fault geometry and kinematics, as well as the slip distribution. The surface break consists of four distinct segments with variable right-lateral slip reaching 5 m. West of the city of Gölcük the

rupture goes offshore into the Gulf of Izmit and its western end cannot be observed directly. Besides, a new set of fissures was observed along the fault trace that had already ruptured in 1967, in the Mudurnu valley. We calculated several interferograms that span the event both in the descending and ascending modes of ESA ERS1 and ERS2 satellites. Of these, only two interferometric pairs have high coherence and give a good image of coseismic surface deformation. The two interferograms are formed by combining two pairs of tandem images of ERS1 and ERS2 acquired in August 12-13 and September 16-17, 1999, respectively. Both interferograms require that, west of Gölcük, a fifth offshore segment ruptured, bypassing 10 km the Hersek delta to the west. The ERS2 interferogram shows however more fringes than the ERS1 one, especially on the northern side of the fault rupture. The discrepancy seems mostly due to atmospheric artefacts seen in the interferogram obtained from the September tandem. Using the trace of the fault and offset measurements gathered in the field we modelled the two interferograms assuming dislocations on rectangular planes down to the depth of 20 km in elastic half space. Both models show similar slip distribution, except that the ERS2 model has more slip, particularly at deeper depths. It is likely that the atmospheric fringes observed in the interferogram of the September tandem pair are included in the ERS2 interferogram only. Subtracting the September tandem interferogram from the ERS2 one we can model both the ERS2 and ERS1 interferograms with the same parameters. To test our results we used the coseismic GPS measurements of Reilinger et al. (2000) and obtained a good agreement with our InSAR model although with uniformly less slip and less moment (~%25). Slip distribution obtained from both the InSAR and GPS modelling at depth mimics the surface slip distribution, suggesting that the segmentation of the fault observed at the surface reflects reasonably the deeper structure. The fringe pattern requires secondary fault motion where fissures were observed in the Mudurnu valley and also east of the Iznik lake. We modelled the former with 40-cm right-lateral slip on a steeply north-dipping fault and the later with 20-cm right-lateral slip on a vertical fault.

Reilinger, Ret al, *Science*, **289**, 1519-1524, (2000).

LS01 : MOam07 : F2
Active Faulting and Seismic Hazard in Lebanon

Paul Tapponnier (tappon@ipgp.jussieu.fr)[1],
M. Daeron[1], **G. King**[1],
E. Jacques (jacques@eost.u-strasbg.fr)[2],
A. Sursock[3] & **A. Elias**[3]
[1] IPG Paris, 4, place Jussieu, Paris, France
[2] EOST - IPG Strasbourg, 5 rue Rene Descartes, Strasbourg, France
[3] CNR Geophysiques, Bhanes, BP 16-5432, Beyrouth, France

Historically, the eastern shore of the Mediterranean has been repeatedly shaken by large earthquakes, but no such earthquake has occurred since the middle part of the nineteenth century. Although the most active seismogenic structure of the region is the Levant fault system, boundary between the African and Arabian plate, there is still no consensus on its present slip rate, its segmentation, the exact size of the earthquakes it can generate, and their return periods. Because Lebanon sits astride the main branches of the fault system, it stands particularly at risk It is thus urgent to catch up with nature, before the next disaster ends the present 160 years period of quiescence. We have undertaken a systematic study of geomorphic traces of Holocene faulting in Lebanon, in order to determine average slip rates, characteristic earthquake sizes and their recurrence times. The fastest slipping fault of Lebanon is clearly the sinistral Yammouneh fault, which appears to have offset stream channels or alluvial fans by 40 to 80 m in the last 10-14 Ka, on the west flanks of mounts Sannine and Saouda, or in the now shortcut Yammouneh pull-apart basin. The entire length of the fault most probably ruptured during the greatest known historical event, in 1202 AD. Comparison of seismic scarplet weathering suggests, however, that it may not have been this fault but the Serghaia fault, other main branch of the Levant system on the east side of the Bekaa valley, that broke during the largest of the shocks of 1759 AD. Since the 1837 AD earthquake probably ruptured the Yammouneh fault mostly south of the Litani junction, our interpretation suggests that much of the Lebanese stretch of that fault may represent a long-quiescent (800 years) seismic gap. Another major active fault is the large, crescent-shaped thrust, responsible for the current uplift of Mount Lebanon. Its 70 m-high cumulative scarp cuts the city of Tripoli in half and appears to be the most likely source of the great 551 AD damaging earthquake. The Tripoli-Saida thrust, which appears to merge with the Yammouneh fault, is probably the principal feature to absorb crustal-scale slip-partitioning in the Lebanese restraining bend. The earthquake potential of these faults will now be more thoroughly assessed by trenching and morphometry.

LS01 : MOam10 : F2
Paleoseismic Investigations along the February 5, 1783 Earthquake Ruptures (Cittanova Fault, Calabria, Southern Italy), and Methodological Observations

Vittorio Bosi (vittorio.bosi@dstn.it) &
Paolo Galli
National Seismic Survey of Italy, Via Curtatone 3, 00185 Roma, Italy

On February 5, 1783 a catastrophic earthquake struck southern Calabria, destroying tens of villages, causing more than 30.000 casualties and changing radically the physiography of the landscape. The physical effects induced by this event are far and away the strongest and the most extensive among those induced by earthquakes in Italy in the last millenium. In 48 villages of the area the estimated intensity is ≥X MCS (Mercalli, Cancani, Sieberg scale); among those 24 reached XI MCS. The estimated magnitude is very close to M = 7. This event was followed by other two large earthquakes on February 7 (Mesima Valley; Io X-XI MCS, M between 6.6 and 6.8) and on March 28 Catanzaro (Io XI MCS, M = 7), respectively. As for the seismic source of the February 5 event, the Cittanova Fault (Aspromonte Fault Auctorum) has been generally identified as the surficial expression of the seismogenetic fault, even if the geological constrains of its present activity have never been demonstrated. Our study of the 1783 surface rupture and of the Cittanova Fault has been achieved by means of a multidisciplinary approach, which includes a systematic re-analysis of all the available contemporary sources, a detailed aerophotographic study of the region, field and trench surveys, and a archaeoseismic investigation carried out in collaboration with the Soprintendenza alle Antichità della Calabria. The results obtained depict and characterize the seismogenic structure responsible for the 1783 (M>7) earthquake, focusing in particular on slip-rate and time recurrence along the fault and giving new insights on the seismic hazard assessment and seismotectonic of the region. We also discuss our multidisciplinary approach with respect to those applied previously.

LS01 : MOam11 : F2
Evidence for Holocene Normal Faulting in the Epicentral Area of the 1356 Basel Earthquake (Switzerland): New Paleoseismic Results from Trenching and Geophysical Prospecting

Matthieu Ferry
(matthieu.ferry@seismo.ifg.ethz.ch)[1],
Mustapha Meghraoui
(mustapha.meghraoui@eost.u-strasbg.fr)[2],
Bertrand Delouis
(bertrand.delouis@seismo.ifg.ethz.ch)[1],
Peter Huggenberger
(peter.hunggenberger@unibas.ch)[3],
Ina Spottke (ina.spottke@gmx.de)[3],
Domenico Giardini
(domenico.giardini@seismo.ifg.ethz.ch)[1] &
Michel Granet (michel.granet@eost.u-strasbg.fr)[2]
[1] ETH-Zurich, Institut fur Geophysik, HPP O13.2, 8093 Zurich, Switzerland
[2] E.O.S.T., 5, rue Descartes, 67084 Strasbourg, France
[3] Geologisches Institut, Bernoullistr. 16, 4056 Basel, Switzerland

We present results of geomorphologic analysis, geophysical prospecting and trenching along an active normal fault located in the epicentral area of the 18 October 1356 Basel earthquake (I=IX-X MKS, Mayer-Rosa & Cadiot, 1979). The fault is visible along the 7 km long NNE-SSW trending and prominent linear scarp which limits the Birs valley to the west. Small rivers incisions and late Pleistocene and Holocene alluvial terraces are uplifted along the fault scarp which forms a 30 - 40 m topographic relief. The presence of an active normal fault with at least two main branches reaching the surface is attested by resistivity profiles, reflection seismic data, and by direct observations in trenches. Faulted colluvial wedge deposits, with secondary ruptures of 0.20 to 0.45 m, and progressively tilted gravels and sandy-silt units illustrate the succession of faulting events. The main fault which ruptures colluvial deposits up to the present day soil layer documents the most recent seismic history of this fault zone, and its possible connection with the 1356 Basel earthquake. ^{14}C dating obtained from the new and previous exploratory trenches indicate that at least two or three seismic events would have occurred on that fault in the last 3500 years. The fault zone may also cross to the south the Jura mountains and show a total length reaching 10 to 15 km. This fault length and a minimum 10-km-depth for the seismogenic layer is compatible with a M 6.5 event in this area.

Mayer-Rosa D, Cadiot B, *Tectonophysics*, **53**, 325-333, (1979).

LS01 : MOam12 : F2
Investigation of the Surface Rupture of the April 14 and 18, 1928 Earthquakes in Bulgaria

Thierry Camelbeeck (cam@oma.be)[1],
Stefan Shanov (shanov@router.geology.bas.bg)[2],
Kris Vanneste (kris.vanneste@oma.be)[1],
Gabriel Nikolov (nikolov@router.geology.bas.bg)[2]
& **Koen Verbeeck** (koen.verbeeck@oma.be)[1]
[1] Observatoire Royal de Belgique, Avenue Circulaire, 3, B-1180 Bruxelles, Belgium
[2] B.A.S. - Geological Institute, Acad. G. Bonchev str., Bl. 24, 1113 Sofia, Bulgaria

Even if Bulgaria is not considered as a seismically very active country, some of Europe's strongest earthquakes occurred there: the Kresna-Krupnik earthquake of April 4, 1904 (M_S=7.0) and the Chirpan (M_S=6.8) and Plovdiv (M_S=7.0) earthquakes of April 14 and 18, 1928.

However, since 1928, no such large earthquake occurred in Bulgaria, which may induce an underestimation of the seismic hazard. A strong earthquake may have disastrous consequences in a country undergoing rapid economical development. Thus, it is important to evaluate as good as possible the return period of such events.

A preliminary survey has been undertaken in 2000 to determine the possibility to conduct paleoseismic investigations in the regions affected by these large earthquakes. In contrast to the region devastated by the 1904 earthquake, that of the 1928 earthquakes is characterised by geological conditions favourable for such investigations even if human activity already destroyed much evidence of the surface ruptures. It is also interesting to note the large amount of liquefaction features observed at the time of the earthquakes, suggesting a real possibility for the search of indirect evidence of past large events.

LS01 : MOam13 : F2
The 1904 Struma Earthquakes (SW Bulgaria)

Bertrand Meyer (meyer@ipgp.jussieu.fr)[1],
Rolando Armijo (armijo@ipgp.jussieu.fr) &
Dimitar Dimitrov (dimit@bgcict.acad.bg)[2]
[1] Institut de physique du Globe de Paris, Laboratoire de Tectonique, UMR 7578, 4 Place jussieu, 75252 Paris cedex 05, France
[2] Institute of Geodesy, Bulgarian Academy of Sciences, 1113, Sofia, Bulgaria

In April 1904, a sequence of two destructive earthquakes, a main shock preceded by a large foreshock 23 minutes earlier, occurred in the Balkans. The main event has long been recognized as the largest earthquake ever recorded in the region and has been assigned a magnitude up to 7,8. The region affected by shaking straddles the present border between Bulgaria and the Republic of Macedonia with the immediate epicentral area close to Krupnik in the Struma valley. Although subsequent and smaller earthquakes have produced surface faulting in neighboring areas, neither the surface break nor the source faults of the 1904 events have yet been identified. Using satellite imagery and topographic information, we searched and mapped active faults close to or within the epicentral area. The most prominent ones are three 20-35 km long normal faults: The Kocani fault in eastern Republic of Macedonia, and the two neighboring Krupnik and Bansko faults in south western Bulgaria. The latter two are the closest to the epicentral area and the most likely candidates to have produced the 1904 sequence. We studied these two faults in the field. Geologic and morphologic observations allow us to estimate the age (= 10 Ma) and the long-term slip-rate (= 0.1 mm/yr) of the Krupnik fault along which we found a 2 m high scarp whose youthfulness suggests recent reactivation, most probably in 1904. We did not find evidence of recent scarps along the Bansko fault. The rupture of the Krupnik fault with length, width and slip compatible with our observations accounts for a moment Mo=2.8 1019 N.m and a magnitude Ms=6.9. Although this might be attributed to the foreshock alone, it seems unlikely that we would have failed to find evidence of a much larger main shock. We conclude that the Krupnik fault is responsible for the 1904 main shock and that the earlier magnitude estimates were significantly exaggerated.

LS01 : MOam14 : F2
Long Paleoseismic and Paleogeodetic Records of Subduction from Sumatran Coral

Kerry Sieh (sieh@gps.caltech.edu)[1],
Danny Natawidjaja (danny@gps.caltech.edu)[1],
Luis Rivera (luis@sismo.u-strasbg.fr)[2],
Bambang Suwargadi[3] & **John Galetzka**[1]
[1] Seismolab #100-23, Caltech, Pasadena, CA 91125, USA
[2] EOST, 5, Rue Rene Descartes, 67000 Strasbourg, France
[3] Geoteknologi, LIPI, Bandung, Indonesia

The upward growth of massive coral heads is limited by lowest annual tidal levels. Thus the geomorphology and internal stratigraphy of coral heads growing at and just below lowest tides record annual sea-level fluctuations (Zachariasen et al., 2000). In western Sumatra, on the hangingwall block of the Sumatran subduction zone, these coral “microatolls” serve as long-lived natural paleoseismic and paleogeodetic recorders of subduction processes. Microatolls studied by Zachariasen et al. (1999), south of the Equator, show that subduction of the past few centuries is dominated by uplift of 1 to 2 m during the M9 earthquake of 1833. We have subsequently documented a sudden, less extensive emergence in 1797 and one or more extensive emergences during the 17th century. Interseismic periods south of the Equator have high averaged rates of submergence and exhibit trenchward tilt, but the submergence is episodic and quite probably associated with very large aseismic slip events. North of the Equator, the giant earthquake of 1861 dominates the seismic record (Newcomb and McCann, 1987), but we have not yet explored this region. In between the 1861 and 1833 ruptures, at the Equator, corals of the past three decades show that vertical emergence and submergence is accumulating in a manner and pattern consistent with elastic models of subduction, in which a portion of the subduction interface is locked and the remainder is slipping aseismically. Sieh, Ward et al. (1999) show that the down-dip limit of the locked patch is tightly constrained to a point 140 km from the trench, at 30 km depth. Our seismologic and paleoseismic data show that a 70-km-long patch coincident with this locked portion failed during a M 7.7 earthquake in 1935. A continuous 250-year-long coral record indicates that, above the 1935 rupture plane, submergence at high rates began right after the earthquake and diminished slowly in subsequent decades. Current rates of submergence are still higher, though, than rates in the 200 years prior to the earthquake. This 250-yr-long coral also records minor effects of the neighboring giant events 1833 and 1861 events and an emergence in the 18th century. Our hope is that the coral microatolls will continue to yield an exceptionally long and precise record of emergence and submergence that will illuminate seismic and aseismic subduction processes through several earthquake cycles.

Zachariasen, J, Sieh, K, Taylor, F & Hantoro, WS, *Bull. Seis. Soc. Am*, **90**, 897-913, (2000).
Zachariasen, J, Sieh, K, Taylor, F, Edwards, RL & Hantoro, WS, *J. Geophys. Res*, **104**, 895-919, (1999).
Newcomb, K & McCann, W, *J. Geophys. Res*, **92**, 421-439, (1987).
Sieh, K, Ward, S, Natawidjaja, D & Suwargadi, B, *Geophys. Res. Lett*, **26**, 3141-3144, (1999).

Monday PM Session

LS01 : MOpm21 : F2
Slip Histories of Hector Mine (Mw=7.1, October 1999), and Nazca Ridge Earthquakes (Mw=7.7, November 1996) Inferred from the Combination of INSAR and Teleseismic Data

Jerome Salichon (jerome@seismo.ifg.ethz.ch)[1],
Bertrand Delouis (bertrand@seismo.ifg.ethz.ch)[1],
Paul Lundgren[2] &
Domenico Giardini (giardini@seismo.ifg.ethz.ch)[1]
[1] Institu fuer Geophysik, ETH-Hoenggerberg, 8093 Zuerich, Switzerland
[2] Jet Propulsion Laboratory, Pasedena, United-states

The interferometric SAR and seismological data have been rarely combined to retrieve the source parameters and slip history for large earthquakes. We apply a fully non-linear approach using simulating annealing based algorithms to invert for rupture onset time, slip amplitude, and rake direction on discreet elementary faults. The spatial complexity of the rupture can be well constrained thanks to dense geodetic measurements of wide extent obtained with ERS1/2 satellites. The access to ground displacements helps to control the fault plan geometry and allows to limit the trade-off between space and time aspects with respect to the case where only seismological data are used. The timing history of the rupture is therefore better approached with the joint inversions. We study the November 12, 1996, Mw=7.7, Nazca ridge (Peru) subduction earthquake, where only part of the ground displacement is mapped, because of the offshore extent of the event, and the October 16, 1999, Mw=7.1, Hector Mine (USA) earthquake where the static ground deformation is mapped almost completely. We evaluate the resolution power of the InSAR and teleseismic data and analyse the benefits of their combination since single broad band inversion only rarely produces maps consistent with geodetic or strong motion data. An input from InSAR, even partial, is crucial for constraint to describe accurately the slip histories of earthquakes.

LS01 : MOpm22 : F2
The Earthquake in South Iceland on June 17, 2000: An INSAR Based Model Compared to GPS and Volumetric Strain Data

Rikke Pedersen (rikke@norvol.hi.is),
Freysteinn Sigmundsson (fs@norvol.hi.is),
Thora Árnad-Ttir (thora@norvol.hi.is),
Kristján Águstsson (kri@vedur.is) &
Kurt Feigl (kurt.feigl@cnes.fr)
Nordic Volcanological Institute, Grensasvegur 50, Reykjavik, 101, Iceland

In June 2000, two magnitude 6.5 earthquakes occurred in the South Iceland Seismic Zone (SISZ), a transform zone connecting the western and eastern volcanic zones in Iceland. Both earthquakes (June 17 and 21) were strike-slip events on N-S oriented faults. We have conducted an extensive InSAR study in the eastern volcanic zone, using ERS-data. The area studied includes the easternmost part of the SISZ, an area affected by the June 17 event, but little affected by the event on June 21. The hypocenter of the June 17 event was located at 63.97N and 20.37W at 6.3 km depth.

A series of 18 interferograms have been analysed, spanning 03/08/1993-29/09/2000. The interferograms hold pre-seismic, co-seismic and post-seismic image-pairs. A significant deformation signal, of at least six fringes (one fringe = 2.83 cm), appears in the co-seismic interferograms. The observed deformation fringes are located east of the June 17 rupture. A unit-vector from ground to satellite of [0.442, -0.116, 0.889] in east, north and up components, results in poor resolution of the dominant N-S displacements expected. Our interferograms are most sensitive to the secondary east, and vertical, displacement components. Forward search of a best-fitting model has been conducted using the RNGCHN program, assuming a rectangular fault in an elastic half space. The model fit was found to be very sensitive to the depth extent of the rupture. Our results show that distributed slip, rather than uniform, is required to create the deformation pattern observed, with maximum slip near the centre of the fault, and less slip near its ends. Average slip is 1 m. A preliminary model for distributed slip along a 16 km long fault plane was obtained from analysis of volumetric strain data. The model that best fits the InSAR data is similar to the distributed slip model found from volumetric strain data, though the rupture must extend to larger depth to fit the InSAR data. In the modelling there is a trade-off between the fault strike and amount of dip-slip, which make these parameters difficult to constrain by InSAR data.

The earthquakes were also captured by network GPS measurements, and the InSAR results will be evaluated against GPS results. A joint interpretation of InSAR, GPS and volumetric strain data has the potential to provide a very detailed image of the June 2000 earthquakes.

LS01 : MOpm23 : F2
Holocene Deformation Outside the Rift Zone of North Iceland

Olivier Dauteuil (dauteuil@univ-rennes1.fr)[1],
Fanny Tournat[1], **Jacques Bouffette**[1],
Jean-Christophe Embry[2], **Yves Quété**[1] &
Brigitte Van Vliet-Lano’[2]
[1] Géosciences Rennes - UMR-CNRS 6118, Campus Beaulieu, 35042 Rennes cedex, France
[2] URA 719 CNRS, Sédimentologie et Géodynamique, Université Sciences et Techniques de Lille, 59655 Villeneuve D’Ascq cedex, France

In Iceland, major present-day seismic activity is located in the volcanic zone affecting lava flows younger than 800,000 yr. Outside the active rift, recent deformation is assumed to be lack, except that appearing in the transform zones. However, recent sedimentologic, micro-seismicity and geodesic data evidence Holocene to present-day deformation affecting basalts older than 1 Ma located far away from the plate boundary. To constrain this low activity occurring outside the active zone, we studied the deformation of a lake shoreline formed during the last glaciation event. The surveyed paleolake is located in the northern part of Iceland, west of the north volcanic zone and south of the Tjörnes fracture zone, in the Flateyjarskagi peninsula. It was settled in north-south and east-west valleys surrounded by elevated relief formed by 3 to 10 Ma basalt flows. It is a 40-km-long trending north-south and 15-km-wide in east-west direction. In the landscape, the lake displays three discontinuous shorelines that can be easily mapped in the field and from SPOT images. The shorelines were formed at different lake levels corresponding to distinct glacier extend stages that closed the valleys. This ancient horizontal surface was used to record the vertical motion of this peninsula during the Holocene time. Several key-points of the shorelines were accurately located using a differential GPS system. A GPS receiver base was settled on the eastern border of the paleolake, and different features forming the shorelines were mapped with a rover GPS receiver. The mono-frequency receivers provided a horizontal accuracy of 13 cm and a vertical accuracy of 27 cm after a post-processing mixing the base information to the rover data. The number of visible satellites ranging from 7 to 10 provides this good accuracy. The correlation between the different key-points was realised from both SPOT images and field observations. The results show that the ancient shoreline is tilted towards the east-north-east (N060°) of 0.1°. This angle tilt corresponds to 43-to-45 m elevation differences depending on the shoreline. This deformation is both compatible with 1) the topographic anomaly of the peninsula that is higher at south and with 2) the very diffuse micro-seismicity of the northern Iceland. This tilt direction is surprising because the classical model of the vertical motion predicts a maximum uplift at north-east resulting from the transform zone and the rift. We suggest that the observed vertical displacement (ENE tilt) is a finite deformation resulting from a successive downlift induced by differential deglaciation and final uplift due to the rifting.

LS01 : MOpm24 : F2
Slip Behavior of the San Andreas Fault Through Several Earthquakes

Yann Klinger (yann@gps.caltech.edu)[1],
Jing Liu (jing@gps.caltech.edu)[1],
Kerry Sieh (sieh@gps.caltech.edu)[1] &
Charles Rubin (charlier@cwu.edu)[2]
[1] Seismolab #100-23, Caltech, Pasadena, CA 91125, USA
[2] Central Washington University, Ellensburg, WA 98926, USA

We are investigating the amount of offset for successive ruptures at a single location. Data of this sort is of primary interest both for theoretical purposes and practical applications. We chose a 100-meter section of the Carrizo segment of the San Andreas Fault, where small channels about a half-meter deep are cut by the simple, narrow, rectilinear

trace of the San Andreas Fault. The source channel cuts several meters into a Pleistocene alluvial fan NE of and upstream from the fault. On the SW side of the fault, several small gullies are offset dextrally from this upstream channel. This particular geometry is allowing us to determine the slip associated with 7 successive earthquakes. We have opened a latticework of trenches across the offset creeks on the both sides of the fault to locate accurately each offset channel and determine the amounts of motion. We cut the first trenches parallel to and about 4 to 5 meters from the fault. We then cut progressively closer to the fault in increments of 50 cm or less, enabling us to keep track of the shape and location of each buried channel. The trenches downstream from the fault show single, separated channels, partially infilled by fluvial and colluvial debris. In general, the subsurface channel locations are quite consistent with their subtle surface expression. The trench across the upstream part of the channel exposed a series of nested channels that indicate a succession of incision and deposition events. Lenses of silt and fine sand cap several of these channels. The lenses indicate several generations of ponding of water behind earthquake-generated shutter ridges. The elevation, shape and age of the successive channels allow us to correlate them with particular, singular channels across the fault, downstream. The last earthquake of 1857 offset the youngest channel pair 8.3 ±0.1 m. Our preliminary correlation of the 6 older channels yields offsets about the same size as the offset of 1857. If these correlations are confirmed, we will have demonstrated that serial ruptures at this location on the San Andreas fault have been nearly invariant over several cycles. The implications of such repetitive behavior both for theory and hazard assessment would be great.

LS01 : MOpm25 : F2
Arc-Parallel, Active Extensional Faulting in Guadeloupe (French West Indies)

Nathalie Feuillet (feuillet@ipgp.jussieu.fr)[1],
Paul Tapponnier (tappon@ipgp.jussieu.fr)[1],
Isabelle Manighetti (manig@ipgp.jussieu.fr)[1],
Benoit Villemant (villema@ipgp.jussieu.fr)[2] &
Geoffrey King (king@ipgp.jussieu.fr)[1]
[1] Laboratoire de Tectonique, IPGP, 4 place Jussieu, 75252 Paris cedex 05, France
[2] Laboratogéochimie des systèmes volcaniques, IPGP, 4 place Jussie, 75252 Paris cedex 05, France

The lesser Antilles volcanic arc results from subduction of Atlantic seafloor under the Caribbean plate. During the historical period, several large earthquakes (M > 7, 1690, 1843, 1897,1974), as well as smaller, more frequent events have struck several of the islands. The origin, in terms of faulting, of most of these events is poorly known. To better assess the seismic hazard near the French island of Guadeloupe, we document the existence and nature of active faults at several scales. In the field, and using aerial photographs, satellite SPOT images, topographic maps (1/25000) and DEMs, we mapped active and Mid to Late Pleistocene normal fault and crack systems that cut the uplifted coral platforms of Grande-Terre and Marie-Galante and the volcanic rocks of Basse-Terre. Using high-resolution bathymetry and seismic reflexion data acquired during the January 1999 Atalante cruise (AGUADOMAR), we show that the normal faults observed onland extend offshore and form two major sets. The first one, east of Guadeloupe, is mostly perpendicular to the arc and bounds grabens. The second one runs parallel to, or at a small angle with the volcanic arc. The two fault sets connect to form a large-scale, horsetail system, which we interpret to result from extension perpendicular to plate convergence and slip partitionning along the NAM/CAR boundary. We assessed rates of faulting on the Morne-Piton normal fault of Marie Galante, the largest in Guadeloupe, which uplifts a flight of Quaternary reef terraces on the island's eastern coast. U/Th dating of these terraces show that they correspond to Quaternary sealevel highstands (130±20 ky, 221±11 ky, 330±10 ky). Based on a detailed morphological study, we constrain quantitatively the uplift and flexure of these terraces. Mechanical modelling of the their shapes leads to estimate an average slip rate of 0.7-0.8 mm/year on the fault.

LS01 : MOpm26 : F2
The September 21, 1999 Chichi Earthquake (Taiwan): Contribution of INSAR Interferometry to Analyse Permanent Ground Deformations

Erwan Pathier (erwan.pathier@lgs.jussieu.fr)[1],
Bénédicte Fruneau (fruneau@dedale.univ-mlv.fr)[2],
Benoit Deffontaines (benoit.deffontaines@lgs.jussieu.fr)[1],
Daniel Raymond (daniel.raymond@lgs.jussieu.fr)[1] &
Jacques Angelier (jacques.angelier@lgs.jussieu.fr)[1]
[1] Laboratoire de Tectonique, Université P. & M. Curie (Paris 6), Case 129, T26, E1, 4 place Jussieu, 75252 Paris Cedex 05, France
[2] Institut Francilien des Géosciences, Université de Marne-le-Vallée (Paris 12), 5 bd. Descartes, 75454 Marne-la-Vallée Cedex, France

On September 21, 1999, the Mw=7.6 Chichi earthquake devastated Central Taiwan. The focus was located at a depth of 8-10 km. The rupture propagated along a thrust fault surface and reached the surface along a nearly North-South rupture trace, about 100 km long, reactivating the Chelougpu Fault, a major west-verging thrust of the fold and thrust belt of Taiwan. The coseismic thrust motion showed asymmetry between a footwall (western) block undergoing little displacement and a hangingwall block suffering an uplift of 3 m on average.

The permanent ground deformation is featured not only by the sudden changes in topography located along the rupture trace showing a variety of earthquake-related structures, but also by smooth changes at the regional scale. A description of structural changes along the fault trace, based on geological investigation in the field, is given elsewhere in this symposium (abstract by Angelier et al.). We show that the interferometry analysis using satellite Radar images (InSar) brings a powerful tool to reconstruct the ground displacement in the area affected by the earthquake, especially if local geodetic information from the GPS network is taken into account. Such a study, however, is mainly restricted to the western block, including the large Taichung Basin, because in the eastern block the dense vegetation makes the InSar analysis difficult. We thus focus on the footwall deformation using InSAR analysis, GPS and DEM data together, in order to define the displacement throughout this region. We then analyse the deformation field pattern in relation with the geometry of the fault trace and the damage distribution. Attention is paid to the consequences of topographic changes through time, as one of the keys to evaluate the seismic cycle during the last thousands years. However, although river and terrace profiles can provide valuable information on the deformation history, the lack of accurate age data on terraces still impedes this research in the ChiChi earthquake area. Large earthquakes, like the Chichi earthquake, are not the only expression of active deformation. Permanent ground deformation also plays a major role. We illustrate this aspect based on the case of the Tainan active compressional structure, in SW Taiwan, where InSar analysis combined with GPS-DEM data and field investigation allowed us to locate and characterize the ongoing deformation at the western front of the active Taiwan collision belt.

LS01 : MOpm27 : F2
Fault Structure in the Tip Region of the Chelungpu Fault, Taiwan; Initial Results from Drilling into the Tip of a Fault

Zoe Shipton (zshipton@cc.usu.edu)[1],
Richard Heermance (rheermance@cc.usu.edu),
Hidemi Tanaka[2] &
James Evans (jpevans@cc.usu.edu)[1]
[1] Dept. of Geology, Utah State Univ., Logan, UT 84322-4505, USA
[2] Dept. of Bio/Geosciences, Ehime University, Ehime, Japan

We present data from two 500-m drill holes through the tip region of an active shallowly-dipping thrust in order to address the nature of slip propagation in the near-surface region. The 1999 Mw 7.6 Chi-Chi earthquake ruptured on the east dipping Chelungpu thrust fault. The epicentre was near the centre of the fault trace but the maximum slip of 8.9 m was near the northern tip of the fault at a bend in the fault. Although the central portion of the rupture trace had relatively modest amounts of slip, this region experienced the greatest amount of ground shaking, resulting in large amounts of damage and fatalities. It is not clear if this is due to geometric irregularities on the fault surface, or to complexity of the rupture process. A Japanese funded group drilled two 500-m cored holes; one through the maximum ground shaking/moderate slip region, and one at the northern, high slip/moderate ground shaking region. The entire core has been structurally logged and the character of the fault zone recorded. Additionally borehole geophysical logs, including image logs, have been run along both holes,. The structures in the cores include 10 cm to > 2 m thick regions of foliated cataclasites, sheared and foliated mudstones, and breccias. Corrlelation with seismic reflection profiles across the fault zone suggest that while cosesimci slip appears to be localised to a narrow zone, off fault deformation creates a braod region of deformation in the hanging wall of the fault. This data has provided an opportunity to examine the structure and processes of a region where little is known about the structure and composition of the fault zone and its relationship to the radiation or dispersal of seismic energy.

LS01 : MOpm30 : F2
Earthquake Time-Slip Histories Determined from *In Situ* ^{36}Cl Cosmogenic Dating of Limestone Fault Scarps: The Sparta (Greece) and the Hebgen Lake (Montana) Normal Faults

Lucilla Benedetti (benedetti2@llnl.gov)[1],
Robert Finkel (rfinkel@llnl.gov)[1],
Geoffrey King (king@ipgp.jussieu.fr)[2],
Mark Caffee (caffee1@llnl.gov)[1],
Rolando Armijo (armijo@ipgp.jussieu.fr)[2],
Jerome Van Der Woerd (vanderwoerd2@llnl.gov)[1],
Dimitri Papanastassiou (d.papan@egelados.gein.noa.gr)[3],
Frederick Ryerson (ryerson1@popeye.llnl.gov)[1],
Frederic Flerit (flerit@ipgp.jussieu.fr)[2] &
Dan Farber[1]
[1] LLNL-IGPP, L-202 7000 East Av, CA 94541, USA
[2] IPGP, 4 place Jussieu, 75005 Paris, France
[3] National Observatory of Athens, P.O. Box 20048, Gr-118 10, Athens, Greece

Direct cosmogenic dating of exhumed earthquake scarps provides a potential method for determining earthquake time-slip histories and slip-rates. Here, we have applied *in situ* ^{36}Cl cosmic ray exposure dating to limestone scarps produced by active normal faults. Limestones (largely calcite) contains an abundance of calcium which is a major target element for cosmogenic ^{36}Cl production. In order to test this method we sampled the scarps produced by the Hebgen Lake fault in Montana, USA, and by the Sparta fault in Greece. The range front morphology of the Sparta fault is characterized by steep triangular facets, separated by V-shaped valleys and wineglass canyons, suggesting that the fault has been active for at least the last several hundred thousand years. At the base of the facets the fault cuts limestone bedrock to produce a 20-km-long, very well preserved normal fault scarp, which, in the central part, reaches a height of 10-12 m. Along the base of the best-preserved sections of this scarp, we sampled two 6-8 m vertical profiles separated by about 12 km. At those two sites we sampled continuous vertical profiles of the scarp with a resolution of 10 cm. The Hebgen Lake fault (Montana) was responsible for a sequence of two earthquakes that occurred in August 1959 (Ms=6.0 and 7.5). The fault exposes bedrock only at one location along its trace, at a site previously studied by Zreda and Noller (1998, Science 282). We extended this earlier study with denser sampling along an 8 m continuous vertical profile with 10 cm resolution. In the 80 samples collected on the Hebgen Lake fault and in the 66 and 82 samples collected on the two sites along the Sparta fault, the concentration of ^{36}Cl and of stable chlorine has been measured by accelerator mass spectrometry (AMS) at the LLNL-CAMS. The production of ^{36}Cl decreases exponentially with depth but varies little with height once a section of the scarp has been tectonically exhumed. As expected, the ^{36}Cl concentration for both sites of the Sparta fault displays a general increase with height along the scarp. We can distinguish at least three different groups of exposure ages, suggesting that this scarp has formed as a result of at least three events during the last 11000 years. Moreover the approximate measured uplift-rate of about 0.7 mm/yr is similar to that =1 mm/yr deduced from the morphological observations (Armijo et al. 1991, Nature, 351). Our preliminary results are consistent with the suggestion of Armijo et al. (1991) who proposed that an earthquake on this fault may have been responsible for the destruction of Sparta in 464 BC. Further analysis of our data and refinement of ^{36}Cl production rates will allow us to further test this hypothesis. The Hebgen Lake results will be interpreted along with additional cosmogenic ^{26}Al and ^{10}Be ages and with data from several trenches to better assess the time-magnitude series of earthquakes on this fault.

LS01 : MOpm31 : F2
Results from the PALEOSEIS-Project, Switzerland

Arnfried Becker (becker@seismo.ifg.ethz.ch)[1], **Colin A. Davenport** (c.davenport@uea.ac.uk)[2] & **Domenico Giardini** (giardini@seismo.ifg.ethz.ch)[1]
[1] Institut für Geophysik, ETH Zürich, CH-8093 Zürich, Switzerland
[2] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TG, Switzerland

In 1997, ETH Zürich in co-operation with the University of Zurich drilled the first borehole in lake deposits with the aim of identifying evidence of pre-historic earthquakes in the region around Basle. The earthquake catalogue for Switzerland covers the past 1000 years, including the largest historical event north of the Alps, i.e. AD 1356 Basle earthquake. This project is intended to extend the existing earthquake record throughout the Holocene into the late Pleistocene: deposits of these ages occur extensively throughout central and northern Switzerland within many lake basins and valleys. These varied deposits provide opportunities to study the evidence for paleo-earthquakes based upon the occurrence of slumped and liquefied lake sediments, landslides, rockfalls and cave damage. Accordingly, a project commenced in 2000 led by Geophysics and Limnogeology at ETHZ and Geography at UNIZ, with the objective of assembling reliable paleoseismic inventories by multi-disciplinary investigations of these natural archives (PALEOSEIS-Project). Results have been obtained from all these approaches, including investigations by trenching of a fault south of Basle, which is a possible source of large earthquakes in the region. The earlier results of seismite records from drill cores from Seewen and Bergsee indicate that at least two pre-historic large earthquakes have occurred in the past 12,000 years. Research by PALEOSEIS PhD students involving seismic profiling and drilling in the central Swiss lakes (Lucerne, Lungern, Sarnen etc.) is intended to identify events triggered by earthquakes, particularly slumps, turbidites and in situ deformation. Within the project a research program has been developed with speleologists in central Switzerland to investigate cave damage which may have resulted from earthquake shaking and displacement. These early results suggest that by combining such varied data sets, improved future earthquake assessments for Switzerland can be achieved.

LS01 : MOpm32 : F2
The Multiple Faulting History of the Ventas de Zafarraya Fault– Paleoseismology of the Granada Depression (Southern Spain)

Klaus Reicherter (reicherter@geowiss.uni-hamburg.de)[1], **Peter Becker-Heidmann**[2], **Antonio Jabaloy**[3], **Jesus Galindo-Zaldívar**[3] & **Gero Michel**[4]
[1] Geological Institute, Bundesstr. 55, D-20146 Hamburg, Germany
[2] Inst. f. Bodenkunde, Allende-Platz 2, D-20146 Hamburg, Germany
[3] Dept. de Geodinamica, Campus Fuentenueva, E-18002 Granada, Spain
[4] GFZ Potsdam, Telegrafenberg, D-14482 Potsdam, Germany

The Granada Depression is one of the Neogene intramontane basins in the Betic mountain chain situated in the Iberian-Maghrebian convergence zone. Its sedimentary infill documents various tectonic episodes and facies changes. Continental Plio-Quaternary sediments are deformed by a series of NW-SE and E-W striking faults, which correlate with centers of micro-earthquake activity. Extensive fault scarps may be attributed to coseismic surface rupturing and are characterized by classical paleoseismological investigations, as micromorphology, sedimentology and radiocarbon dating of displaced paleosols, complemented with Ground Penetrating Radar studies and remote sensing techniques in a joint interdisciplinary project. Evaluation of historic data shows that different parts of the Granada Depression experienced several strong earthquakes of a MSK intensity up to X during the last 2000 years. We study fault kinematics, the earthquake history of distinct active faults, recurrence rates of earthquakes, and, the seismic hazard and rsik in the Granada Depression. The Ventas de Zafarraya fault scarp in the southwestern part of the Granada Depression reflects recent activity along a major fault in the central Betics. The E-W striking and N-dipping normal fault scarp is exposed near the cemetery of Ventas de Zafarraya. Several paleosols are displaced by the normal fault, accompanied with liquefaction. Three scarp-derived colluvial wedges, the oldest of which revealed a ^{14}C-ages of 8720±130 years BP, consist of coarse limestone debris each forming a fining-up sequence, overlain by wash-element colluvium and paleosols. According to maximum displacement method, all three events during the last 9000 yearsmay be classified and related to earthquakes with M > 6 (6,5). The results of Ventas de Zafarraya show an important correlation with Holocene climate. The interval of soil formation found in the Ventas de Zafarraya scarp between 3000 and 2000 years BP correlates with a period of moderate humid climate and a beginning aridification phase. In summary, it is evident that, (1) seismic deformation in the Granada Basin and other parts of the Betics is distributed on several faults, (2) that the seismic cycle for the study area is incomplete. Clearly, the pre-historical earthquake history in southern Spain needs further scrutiny with particular attention to secondary effects that are preserved in such diverse geological phenomena, such as paleo-landslides. The existing bias that results from the preferred consideration of strong earthquakes in the seismic catalogues and calculations distort the risk assessment of this highly active seismic zone.

LS01 : MOpm33 : F2
Evidence of Recurrent Pre-Historic Seismicity of the Alhama de Murcia Fault (southeastern Spain)

Eulàlia Masana (eula@natura.geo.ub.es)[1], **Pere Santanach** (santanac@natura.geo.ub.es)[1], **José Martinez-Diaz** (jmdiaz@eucmax. sim.ucm.es)[2] & **José-Luis Hernández-Henrile**[2]
[1] Dept. Geodinàmica i Geof'sica. Facultat de Geologia, Universitat de Barcelona. Zona Universitaria de Pedralbes, Barcelona 08028, Spain
[2] Dept. Geodinámica. Facultat de Ciéncias Geol-gicas., Universidad Complutense de Madrid. Ciudad Universitaria., Madrid 28040, Spain

The Alhama de Murcia fault (eastern Betic Cordillera) is a NE-SW reverse-sinistral fault which constitutes the northwestern edge of the Quaternary Guadalent'n depression. Five earthquakes with I (MSK) VIII and a number of Mb<5 instrumental earthquakes linked to the fault have occurred in the last 500 years. Earlier neotectonic analyses of the Lorca-Totana segment have yielded a long-term vertical slip-rate of 0.2 mm/yr since the Tortonian. The first paleoseismic results along this sector are presented. The study consisted of: i) geomorphologic analysis, ii) site selection for trenching and, iii) trenching analysis. The analyzed fault dips to the SE and traps sediments from the La Tercia range (northwest of the fault). Within this Quaternary depositional area the geomorphologic analysis revealed: 1) three depositional units cut by the fault (two generations of alluvial fans and one of fluvial terraces), 2) a 9 km long fault scarp (probably longer since it reaches a human-modified area to the northeast) which constitutes the southeastern edge of the Quaternary deposits, and 3) a number of left-lateral creek offsets across the fault. Sites for trenching were selected where the youngest sediments cropped out and/or where there was a very recent trap of sediments along the fault. Microtopographic profiling and mapping of the selected sites were performed to better locate the trenches and to quantify the vertical offset of the alluvial fan deformed by the fault at each site. A calcrete soil observed on top of the youngest alluvial fans was correlated with a regional event of soil development, 125 ka in age. This age, together with a minimum of 8 m of vertical displacement of the fan, yields a provisional middle-term vertical slip-rate of this fault of 0.06 mm/yr. The 4 trenches analyzed provide evidence (unconformity, buried scarp, dammed sediments, differential tilting) of a minimum of two paleoearthquakes. Vertical displacement per event, which was possible to quantify only in trench 4, is approximately 0.9 m. Preliminary TL and Radiocarbon dating (to be confirmed by further dating) suggest that the seismic events occurred after 25 ka and that the most recent event took place in the late Holocene. This yields a mean recurrence period in the order of 10^4-10^3 yr and suggests a short elapsed time. Given the total vertical displacement in trench 4, which is 3.5 m, the short-term vertical slip-rate is 0.1 mm/yr. This is the minimum of the net slip-rate because the fault shows evidence of oblique-slip kinematics (slickensides with a pitch ranging from 351/4 to 651/4, left lateral deflection of creeks crossing the fault). Preliminary dating indicates, therefore, that this segment of the Alhama de Murcia fault is among the most active seismogenic faults in Spain.

LS01 : MOpm34 : F2
Geophysical Imaging of Concealed Active Faults in the Urban Area of Kobe, Japan

Takao Miyata (miyata@shida.planet.sci.kobe-u.ac.jp) & **Satoru Yamaguchi** (yanchi@kobe-u.ac.jp)
Department of Earth and Planetary Sciences, Kobe University, Nada-ku, Kobe, 657-8501, Japan

Urban concealed active faults caused terrific damages into Kobe megacity during the 1995 Kobe Earthquake. It is necessary to research the concealed active faults beneath the megacity for mitigation of earthquake disaster. We chose the Ishiya riverside park, Nada-ku, Kobe, Japan, as the test site to check the validity of geophysical method (GPR, VLF-MT, RM) in detecting the concealed active fault, because there are many earthquake-related works (co-seismic ground damage survey, seismic reflection survey, drillings, repetitious leveling etc.). In this paper, we discuss about a geophysical imaging of subsurface structures of the concealed active fault beneath Kobe, based on the GPR (Ground-Penetrating Radar), VLF-MT (Very Low Frequency Magnetotelluric) and RM (Resistivity Method) data.

For the GPR survey, we used a SIR-2 system (GSSI) with antennas of 200 MHz, 100 MHz and 35 MHz. Lengths of two survey lines are 244 and 220 m, respectively. The range from 100 ns to 250 ns was chosen for the survey. We changed the time profile to the depth profile by the wide-angle measurement. The VLF-MT survey was carried out along the survey line of 200 m, using VL-101 (Teratecnica). The signal from the station JJI (22.2 KHz), southern Kyushu, Japan, was used. For the RM, we used a McOHM21 (OYO) and 61 poles along the survey line of 120 m.

The following results were obtained: (1) the two GPR profiles have two discontinuities in the two horizontal strata of relative strong and weak reflections, respectively. The strong reflected signal was found as wedge structures at the two locations. (2) Low apparent resistivity zone (<200ωm, 30 m in width) was detected at the middle part of the VLF-MT survey line. (3) Low resistive zone of less than 1000ωm and 10 m in width were found in the 2D resistivity section. (4) These detected anomalies lay on a line, and these locations are just above the concealed fault, which have been detected at 1000-200 m deep by seismic reflection survey.

Judging from our obtained results, we think that faulting of the concealed active fault beneath Kobe reaches near the ground surface. This is supported by the results of the drillings and repetitious leveling.