Earthquake Hazard Zonation in The Lake Constance Area - Contribution of Satellite Radar (ERS-1, Sir-C) - Data
Barbara Theilen-Willige   Birkenweg 2, D-78333 Stockach, Tel. and Fax: 49 7771 1868

Abstract

The integrated analysis of geologic and seismologic data, field observations, lineament data derived from satellite radar images (ERS-1, SIR-C) data from Southwest-Germany, especially the Lake Constance Area, allows a better understanding of the tectonic setting and a more detailed identification of fault zones. Especially the lineament anlysis of satellite radar data contributes to the tectonic inventory. Comparisons of lineament maps with seismotectonic data suggest that some of the most prominant visible lineament zones are deap-seated structures. Determining the location of faults and main fracture zones and estimating their influence on seismic waves is an important component of seismic risk analysis. The lineament analysis of satellite radar contributes to a better knowledge of the influence of local structural conditions on seismic wave radiational propagation and on ground motions. As potentially hazardous secondary effect earthquake triggered landslides might occur as reported from the 16 Nov 1911- event. The detailed interpretation of satellite radar data allows the detection of lineaments that are coincident with fault and fracture systems influencing slope instabilities. Comparison of slope gradient maps of the northwestern Lake Constance Area with radar imageries derived lineament maps help to delineate areas objected to landslides.

Keywords: Earthquake Vulnerability, ERS-1, SIR-C, Lineament Analysis, Landslides, Hazard Map

Introduction

Although awareness of earthquake risk has been increasing on the part of scientists and engineers, the scope and magnitude of the problem is not yet fully understood by local and regional public officials responsible for implementary land use policy. Estimating the likelihood of seismic hazard and the degree of damage is essential for damage mitigation planning as certain lifeline facilities such as oil, gas and water pipelines and electrical and telephone transmission lines can be equipped with means for limiting damage.

Investigations of groundstructure interactions form the necessary basis for the analysis and evaluation of the earthquake damage risk (Ahorner & Rosenhauer, 1993). Damage resulting from an earthquake varies spatially. Within the same zone of shock intensity, the damage may vary locally, being a function of both the type of structure and ground conditions, as for example of faults and fractures, lithology or ground water table. Seismic waves traveling in the subsurface will be refracted at sharply outlined discontinuities as for example faults, and, thus, arrive at a summation effect that might influence the damage intensity. Earthquake damage can be amplified by guided seismic waves along fault zones. Precise delineation of those faults can be a veritable input to seismic risk analysis.

The present study is an attempt to integrate various data sets (satellite radar data, seismotectonic data, geologic and geomorphologic field data) to obtain a general better understanding of the tectonic setting and to improve earthquake vulnerability maps. Aim of this study is to investigate the contribution of satellite lineament analysis for the detection of fault zones being of importance during an earthquake.

One purpose of this study is to research the possible relationships presented in Fig.1a and b:

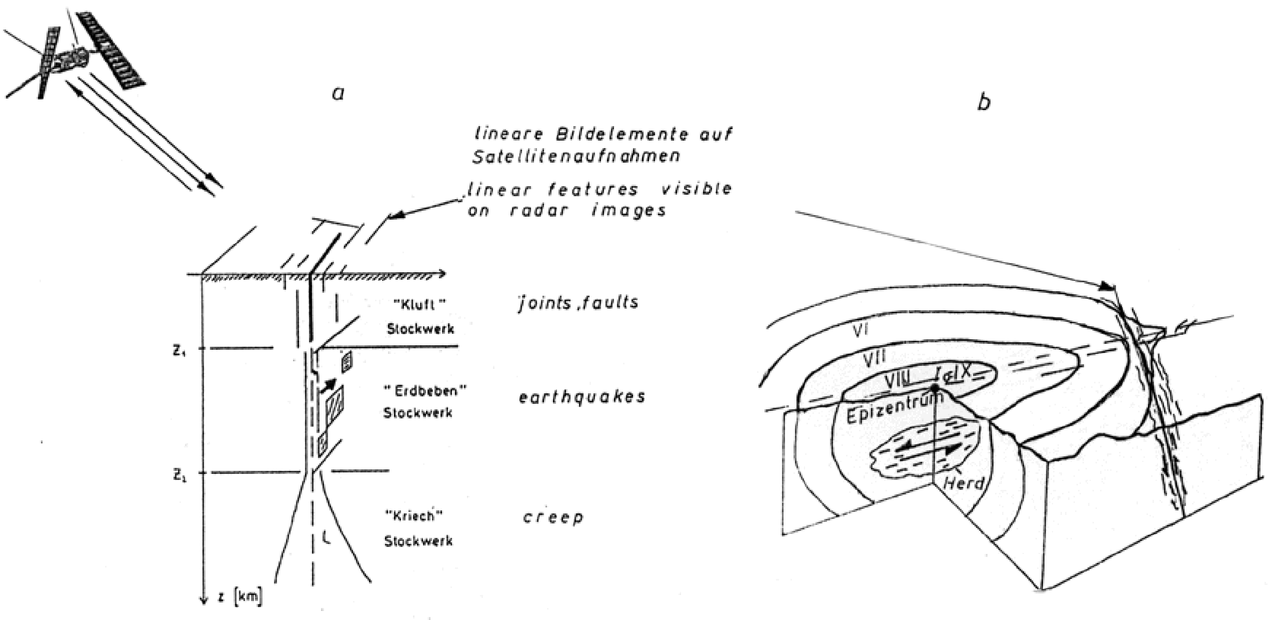

Figure 1a: Possible relations of linear features visible on radar-images to fault planes in the subsurface (according to Schneider, 1996, modified)

Figure 1b: Detectability of linear features on radar imagery tracing tectonic discontinuities as faults, fractures, etc. that might influence seismic wave propagation

Fig.1a illustrates a situation which would be optimal for radar image interpretation and evaluation of radar derived lineament analysis: The rupture pattern might be the result of a spatio-temporal evolution due to repeated earthquakes. It is reasonable to hypothesize that the fracture pattern occurs in response to stress from one or more seismotectonic significant events: The fault planes causing earthquakes are traced by fractures and faults and, thus, are visible as linear features on the radar images. This situation can be find especially in areas where earthquake related faults are visible at the surface as for example in California. In many areas the situation is not as clear as shown schematically in Fig.1a. It cannot be excluded, however, that repeated earthquake shock influences successively the fracture pattern of surficial rocks (Schneider, 1996).

Fig.1b shows schematically a situation where lineament analysis might contribute to the detection of faults influencing the contour and degree of seismic shock.

Reducing damage in areas subject to one or more **earthquake-induced processes** (landslides, displacements, etc) involves **hazard zonation** or mapping. These hazard maps form a necessary base for seismic safety planning. The use of radar lineament mapping is investigated to detect zones of weakness (faults, fractures) controlling movements of slopes, especially signs of possible further instabilities.

2. GEOTECTONIC SETTING

Southern Germay as a tectonic and seismo-tectonic unit has a shape of a triangle, bordered by the following structures: the Upper Rhinegraben in the west, the Prealpine Molasse basin in the south and the Bohemian Massif in the northeast. Beginning with the Swabian Jura earthquake in 1911 the seismic activity in the Central Europe is concentrated to this area. As far as it can be seen from historic records from the time before 1800 a shock of the quality as those in 1911, 1943 and 1978 has not been observed in this area before (Schneider, 1979, 1980, 1996). As can be deduced from fault-plane solutions, the prominent type of seismotectonic motions consists of horizontal strike slip motiones along NNE or NW directions (Fig.2). From the distribution of epicenters and the orientations of fault planes it is possible to conclude that the axis of main principal stress is oriented about NNW (Schneider, 1980, Gruental & Stromeyer, 1995).

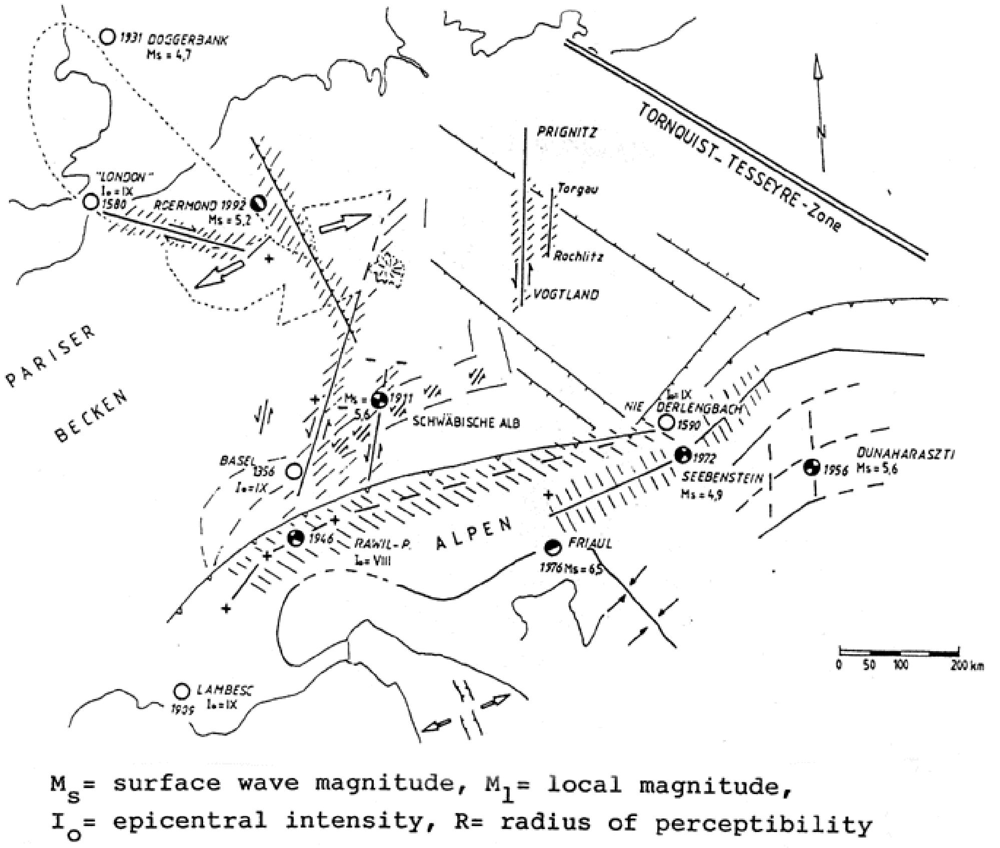

Figure 2: Directions of largest principal stresses in central Europe and earthquakes according to Schneider, 1996

3. RADAR LINEAMENT ANALYSIS

ERS-1 data as well as SIR-C - L, C - and X-Band data from the Ueberlingen test site were used for lineament analysis. (The term lineament is a neutral term for all linear, rectilinear or slightly bended image elements.) Lineaments often represents the surface expression of faults, fractures, lithologic discontinuities, etc. .

3.1 Evaluation of ERS-1 DATA

The ERS-1 radar satellite has taken several complete SAR coverages from entire Germany. The processing of the data was done in the German Processing and Archiving Facility (D-PAF) at the German Remote Sensing Data Center (DFD) of the DLR/ Oberpfaffenhofen. The geocoded terrain corrected SAR images are the basic input data set for the generation of mosaics, the Radarmap Germany (Kosmann *et al.*, 1994). The precise gecoding procedure guarantees a geometic accurancy of 30 m.

The nature of the linear traces visible on ERS-1-image mosaics from SW-Germany varies along strike and is represented by some combinations of linear steep valleys, especially in the Black Forest Area, and depressions, linear hydrographic features and drainage segments, linear hills, ridges and abrupt ending straight scarp lines. Available geologic and geophysic data indicate correlations of the distinct expressed lineaments with fault zones in the subsurface. Comparisons of lineament maps with seismotectonic and aeromagnetic data suggest that some of most prominent lineament zones represent deep-seated structures as for example the Hegau-fault zone (Theilen-Willige, 1996). The pattern of linear features corresponds to the tensional stress field known in this area. Radar imageries from SW-Germany, thus, provide essential clues to the tectonic setting. The radar images allow an interpretation of lineaments and of structural trends that would have been impossible from field mapping alone. This is demonstrated by an ERS-1- image from Southwest-Germany (Fig.3) and ERS-1-derived lineament map (Fig.4). The lineament map is combined with the representation of known epicenters. Epicenters are concentrated predominantly in areas of crossing lineaments (Theilen-Willige, 1995). According to Schneider (1993) agglomerations of seismic activity are related to intersecting fault zones. There are agglomerations of sesmic foci near the intersectings between fault-zones striking with an angle of maximum shear stress considering the recent orientation of the tectonic stress field.

Until recently few attempts have been made to correlate seismic events to known surface faults and to study possible relationship between large seismic events and structural framework in this area. Comparisons of focal mechanisms with local neotectonic structures in the Lake Constance area and in northern Switzerland have shown in many cases a good correlation between the orientation of nodal planes of the fault plane solutions and the orientation of fault systems observed at the surface (Pavoni, 1987, Smit, 1989).

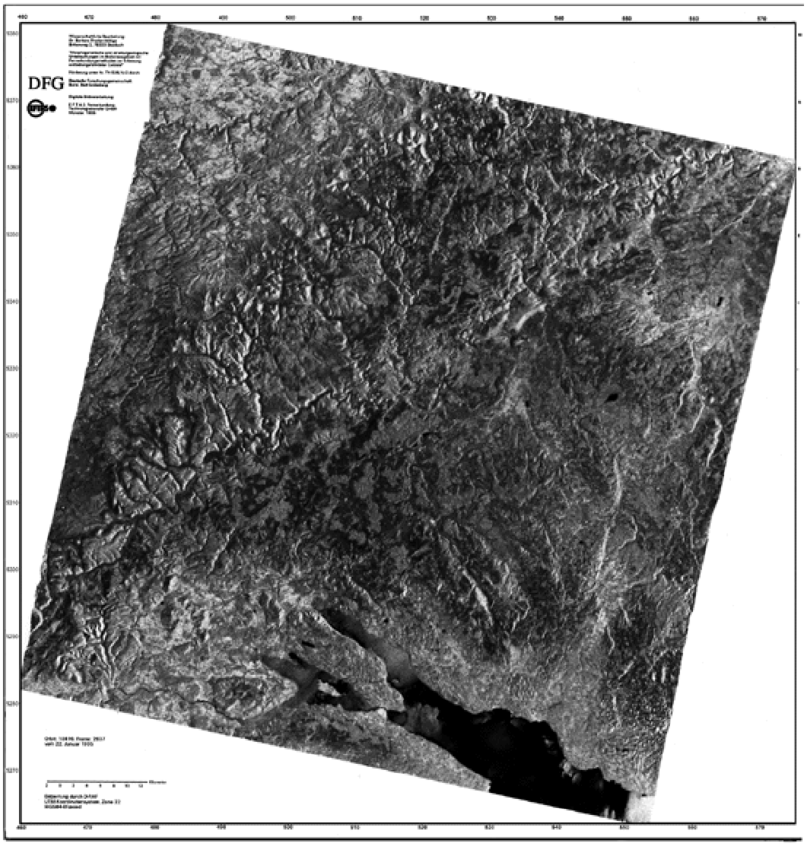

Figure 3: ERS-1 satellite radar image (22 Jan 1995) of southwest Germany (click for bigger view)

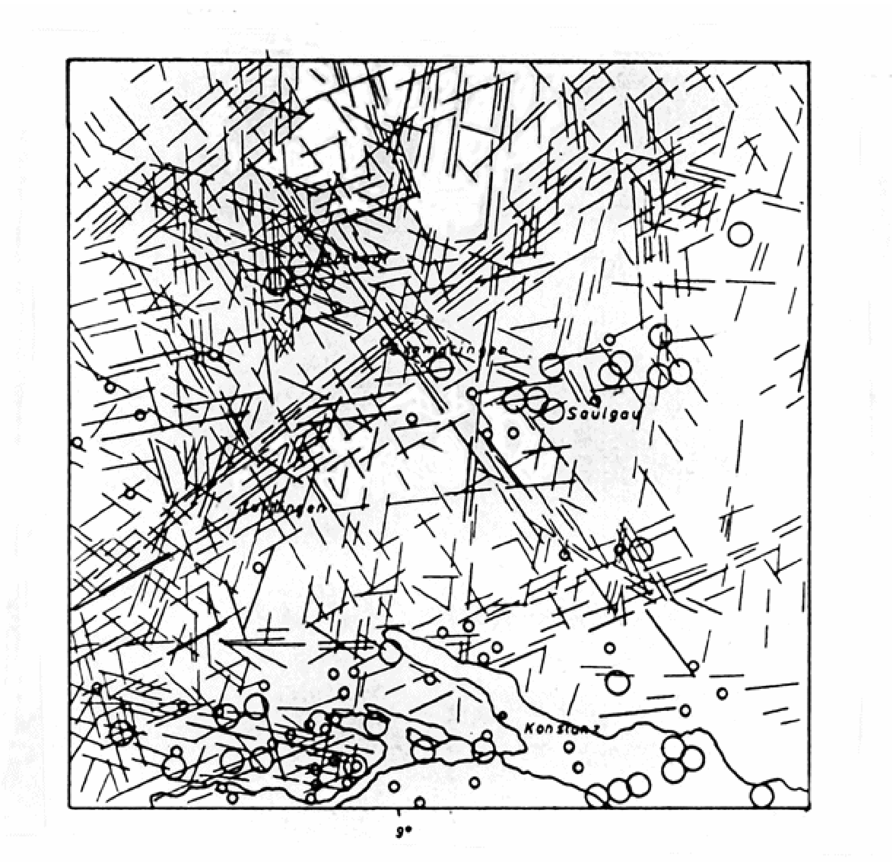

Figure 4: Comparison of earthquake epicenter distribution with ERS-1 image derived lineaments (Map of epicenters: Bundesanstalt fuer Geowissenschaften und Rohstoffe, Hannover, 1991, Deichmann, N., ETH Zuerich, 1996, person. commun.)

3.2 Evaluation of SIR-C-L and C-Band and X-SAR-Data

Shuttle Imaging Radar (SIR-C) data, L- and C-Band, have been provided by NASA's Jet Propulsion Laboratory (JPL), SIR-C Radar Data Center, Pasadena (USA) and SIR-C -X-Band data by DLR, DFD, Oberpfaffenhofen. Based on the SIR-C-data (L-and C-Band, HV, and X-Band, VV, Ueberlingen test site) from the northwestern Lake Constance area, Ueberlinger See, a lineament analysis had been carried out. Different amplifications of the radar imageries were interpreted to see the influence of scale on the manifestation of lineaments as 1 : 200.000, 1 : 100.000 and 1 : 50.000. Fig.5 shows the SIR-C-Band image at a scale of 1 : 200.000, Fig.6 the derived lineament map. To identify the mapped lineaments, the lineament maps were compared with topographic and geologic maps.

Although the area is covered by vegetation radar return is more influenced be the local topography and SAR viewing geometry. Most of the linear features visible in the SIR-C-radar imageries, especially C- and X-Band, correspond to linear morphologic units as linear valleys, linear scarps or hills.

For the structural inventory radar illumination is a limiting factor, as for example in this case N-S striking geologic features are suppressed and therefore the lineament inventory based on SIR-C data alone must be incomplete. To get a complete inventory of the structural setting an additional analysis of other data sets is neccessary as for example geologic maps and of structural field data. Comparing the SIR-C-C-Band-lineament map with geologic maps it is clearly detectable, that some faults identified in the field are expressed as lineaments on the radar image. This is confirmed by field check of features seen on the radar imageries. Correlations of tectonic inventories in the field with mapped lineaments show a clear coincidence between the strike and position of prominent lineaments on the radar imageries and the strike of faults or principal strike directions of the fracture system. This seems to justify the assumption that many of these linear features correspond to geologic features as fractures and faults.

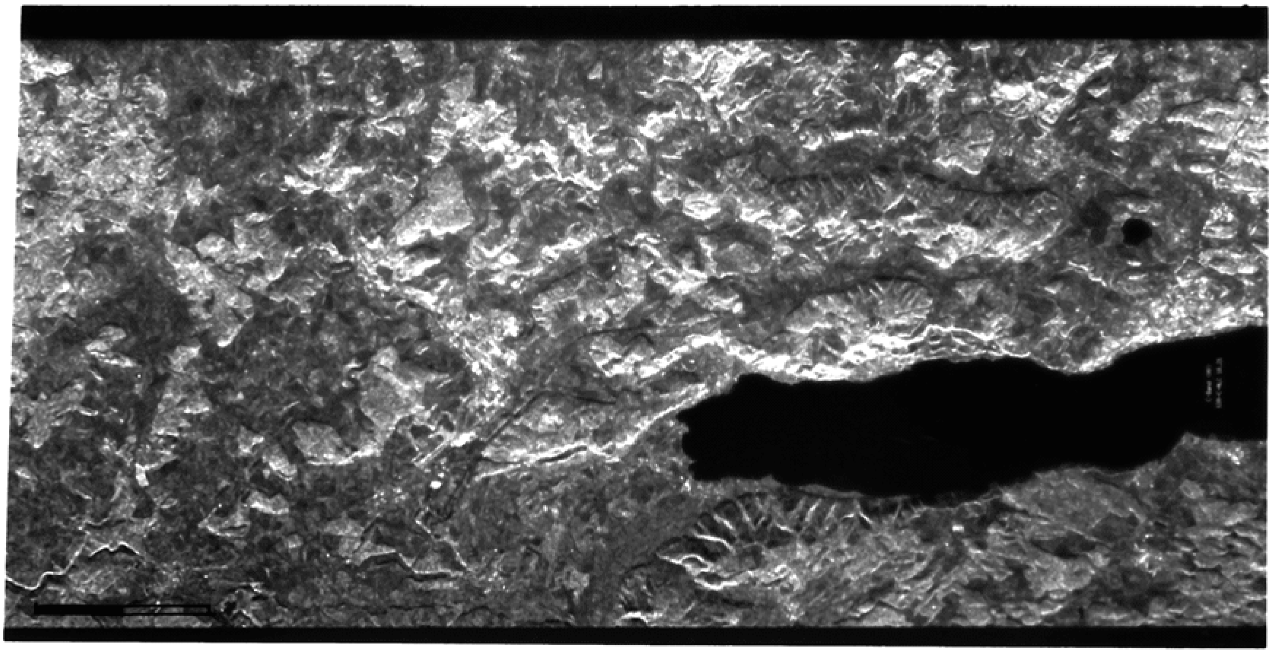

Figure 5: SIR-C C-band (HV) imagery from the Ueberlingen test site (NASA/JPL, Radar Outreach Program, USA, April 1994, digital image enhancement by Ch. Koenig, BVBK, Diessen, 1996; click for bigger view)

Figure 6: Lineament maps based on SIR-C data of the Ueberlingen test site - SIR-C C-band (HV) derived lineament analysis

4. COMPARISON OF ISOSEISMAL MAPS WITH LINEAMENT MAPS

Lineament maps derived from interpretation of ERS-1-data and SIR-C-data were compared with available macroseismic observations of stronger earthquakes (intensities of 7 to 8 on the MEDVEDEV-SPONHEUER-KARNIK-Scale). As an example is shown the isoseismal map of the 3. September 1978 event (Fig.7). The correlation and combination of the 3. September 1978-isoseismal map with the ERS-1 derived lineament map clearly indicates that **areas of high damage intensities are related to surface traces of larger faults and to areas with a dense lineament pattern** . The more affected areas are concentrated where larger lineaments are crossing.

Lineament evaluations based on the different SIR-C-data of the Ueberlingen test site at the northwestern border of the Lake Constance were compared as well with isoseismal maps of earthquakes occuring during the last decades of the Lake Constance area. These maps have been provided by the Geophysical Survey of Baden-Wuerttemberg / Freiburg. It is obvious that stronger affected areas correspond to areas on the lineament maps with distinct expressed lineaments crossing each other (Fig.8). The contours of areas with higher damage intensities on the isoseismal maps seem to be influenced by structural patterns in the subsurface.

Figure 7: Combination of the Swabian Jura - earthquake (3 Sep 1978) macroseismic map for main shock in southwest Germany (MSK-scale, Schneider, 1992) and the ERS-1 mosaic (radarmap) derived lineament map

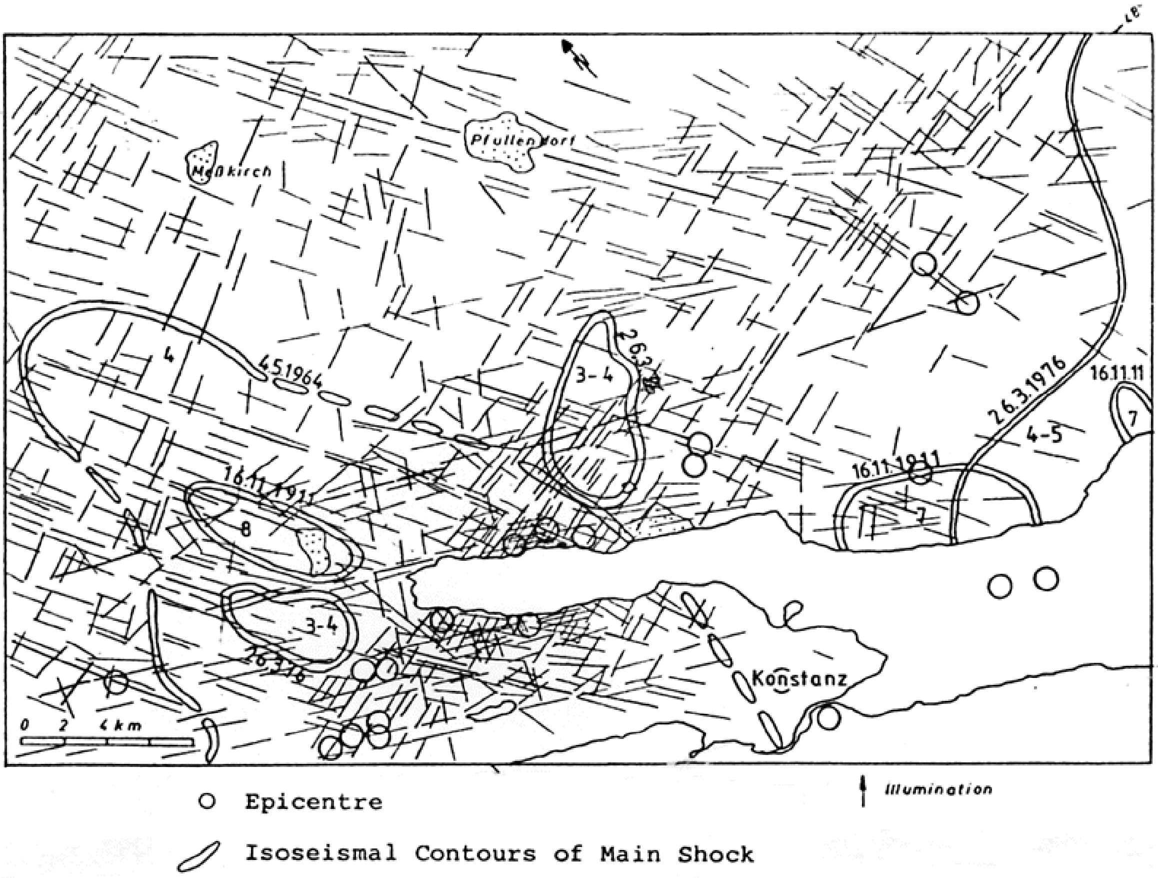

Figure 8: Comparison of isoseismal maps of the Lake Constance area with SIR-C / X-SAR imagery derived lineament maps; areas of main shock during seismic events clearly correspond to areas with distinct expressed lineaments.

5. LANDSLIDES

In the northwestern part of the Lake Constance area landslides cover a wide variety of landforms as rockfall, rockslide (translational and rotational slide), debris slide and even earth flow. Landslides occur after nearly every wet season of the year, often activated when the water table is high. However, casualty and damage statistics pertaining to landslides are very fragmentary.

Landslides have been triggered by seismic shock in this area: **Slope-instabilities developed in the superficial quaternary deposits and tertiary Molasse sediments during the 16 Nov 1911-event demonstated the existence of potentially hazardous secondary effects of earthquakes in this area** as rockfalls and rockslides (Sieberg & Lais, 1925).

The movements of slopes in this area are structurally controlled by surfaces or planes of weaknes, such as faults, joints and bedding planes. The steep slopes bordering the northwestern Lake Constance / Lake Ueberlingen consist of tertiary Molasse sandstones containing many prominent open fractures and faults. A careful search to locate areas with close spacing of faults and joints, especially where they cross, helps to look for evidence of possible continued movement. The most significant sign of possible futher instability is the presence of cracks on the crown of slopes. SIR-C- imageries have been investigated to detect lineaments or curvilinear features in the areas of the headwall scarps in order to find traces of possible failure surface-traces. The lineament map based on the SIR-C-C-Band (HV)- imagery is represented in Fig.6.

Fig.9 shows an aerial oblique view photograph from the area of Sipplingen at the northern border of the Ueberlinger Lake where block movements of tertiary sandstones towards the lake are controlled by faults clearly detectable on the radar images. The presence of former landslides had to be considered for such evidence of past instability is frequently the best guide to future behaviour in the locality. This is of fundamental value for planning purposes. Smaller landslides still happen regularly in this area. It cannot be excluded that in case of a stronger earthquake during a wet season larger movements could be initiated by seismic shock.

Fig.10 shows a combination of a SIR-C-C and L-Band- lineament analysis and a slope gradient map. This combined representation provides important clues for delineating landslides. Movements can be detected in the field exactly in those areas where prominent lineaments cross steep slope areas.

Environmental pollution as a consequence of broken pipes after a strong earthquake is one of greatest problems in a densely populated and industrialized area. Surveying of piplines that might be affected by earthquakes or earthquake induced effects as for example landslides, liquefaction or displacements is important for the maintainance of supply. Water of the Lake Constance is needed for the supply of more than 3,5 million people.

Updating and digitalization of all available piping documentations, integrating the data into existing digital topographic map and at least comparing them with ERS-1/2- and SIR-C satellite-radar derived lineament maps is an important step toward seismic hazard prevention measurements.

Figure 9: Aerial photograph - oblique view (to NW) from the northwestern Lake Constance area showing block movements of tertiary sandstones towards the lake near Sipplingen (Theilen-Willige, 31 May 1996)

Figure 10: Slope gradient map of the northwestern Lake Constance area combined with the SIR-C C-band lineament map to delineate areas objected to slope failures

linear features visible on the radar image

areas objected to land slides

Conclusions

Lineament analysis based on satellite radar data contributes essentially to the tectonic inventory.

In comparison with the available ERS-1-data from the Lake Constance area SIR-C-data provide a more accurate representation of lineaments mainly because its higher resolution and viewing geometry, whereas ERS-1-data provide a valuable overview about the tectonic setting. Lineament analysis based on SAR imageries can help to delineate local fracture systems and, thus, provide informations about types of seismic wave motion associated with earthquakes. When lineament maps based on ERS-1- and SIR-C-data are merged with isoseimal maps, the correlation of sub-surface structural information with the damage intensity occuring after earthquake shock contributes to a better delineation of hazard prone areas.

The combined interpretation of satellite radar data and isoseismal maps improves the understanding of the influence of local soil and structural conditions on seismic wave radiational propagation and on ground motions .

Lineament analysis provides important clues for delineating slope failures as probable secondary effects of stronger earth- quakes.

Acknowledgements The author is indebted to the German Research Association (DFG)/Bonn for financial support and a grant. Prof. Dr. G. Schneider, Institute of Geophysics, University of Stuttgart is kindly acknowledged for supplying literature and base maps and for helpfull discussions. Dr. W, Bruestle, Geophysical Survey, Freiburg and Dr. N. Deichmann, ETH Zuerich are acknowledged for delivering geophysical data as isoseismal maps and epicentre maps. The author thanks H. Runge and D. Kosmann, DLR, Oberpfaffenhofen, E.O. Leary, JPL, California for providing ERS-1- and SIR-C-/ X-SAR-data and SIR-C- L- and C-band - data. Dr. Ch. Koenig, Bildverarbeitungs-Buero Koenig, Diessen, is acknowledged for the digital image enhancement.

References

Ahorner, L., Rosenhauer, W., 1993
Seismische Risikoanalyse. *Deutsche Forschungsgemeinschaft (Hrsg.): Naturkatastrophen und Katastrophenvorbeugung - Bericht zur IDNDR* VCH-Verlag, Weinheim, pp. 177-190.

Gruental, G., Stromeyer, D., 1995
Rezente Spannungsfelder und Seismizitaet des baltischen Raumes und angrenzende Gebiete - ein Ausdruck aktueller geodynamischer Prozesse. *Brandenburgische Geowiss. Beitr.,* **2**, No. 2, Berlin, pp. 69-76.

Kosmann, D., Winter, R., Sties, M., Wiggenhagen, M., 1994
Mosaicing and Classification for the Radarmap Germany. *Proceed. Second ERS-1 Symposium - Space at the Service of our Environment, Hamburg,* 11-14.10.1993, ESA SP-361, Noordwijk, pp. 629-633.

Pavoni, N., 1987
Zur Seismotektonik der Nordschweiz. *Eclogae geol. Helv.*, **80**, No. 2, Basel, pp.461-472.

Schneider, G., 1979
The Earthquake in the Swabian Jura of 16 Nov 1911 and Recent Concepts of Seismotectonics. *Tectonophysics*, **53**, Amsterdam, pp. 279-288.

Schneider, G., 1980
Seismic Stresses in Southern Germany. *Rock Mechanics Suppl.* **9**, pp 69-73.

Schneider, G., 1992
Erdbebengefaehrdung. *Wissenschaftliche Buchgesellschaft* , Darmstadt, 167 pages.

Schneider, G., 1993
Beziehungen zwischen Erdbeben und Strukturen der Sueddeutschen Gross-Scholle. *N.Jb. Geol. Palaeont. Abh.*, **189**, Nos. 1-3, Stuttgart, pp. 275-288.

Schneider, G., 1996
Erdbebengefaehrdung in Mitteleuropa - Hinweise aus Geodaesie und Gravimetrie auf Scherzonen mit seismischem Bewegungscharakter. *Deutscher Verein fuer Vermessungswesen*, **43**, No. 1, Maerz 1996, Stuttart, pp. 47-56.

Sieberg, A., Lais, R., 1925
Das mitteleuropaeische Erdbeben vom 16.11.1911, Bearbeitung der makroseismischen Beobachtungen. *Veroeffentl. Reichsanstalt fuer Erdbebenforschung Jena*, H.4, Jena.

Smit, P., 1989
Seismotektonische und aeromagnetische Untersuchungen in der Region Ramsen (Kanton Schaffhausen). *Diplomarbeit an der Abt. fuer Naturwiss.*, ETH Institut fuer Geophysik, Zuerich.

Theilen-Willige, B., 1995
Erdbebengefaehrdung im Bodenseegebiet. *Geowissenschaften*, **13**, No. 2, Berlin, pp. 40-46.

Theilen-Willige, B., 1996a
Satellitenaufnahmen Suedwestdeutschlands und der Bodenseeregion als Hilfsmittel bei der Erfassung erdbebengefaehrdeter Bereiche. *Publ. der Deutschen Gesellschaft fuer Photogrammetrie und Fernerkundung (DGPF)*, **4**, Vortraege 15. Wissenschaftl. Techn. Jahrestagung, 4-6.10.1995, Universitaet Hannover, Hannover, pp. 63-74.

Theilen-Willige, B., 1996b
Seismic Risc Analysis in Southwest Germany - Based on Satellite Radar Data. *Intern. Archives of Photogr. and Remote Sensing*, **XXXI**, Part B7, Vienna 1996, pp. 705-708.