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A detailed rating scheme for seismic microzonation based on geological and geotechnical data and numerical modelling applied to the city of Basel

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Key words: Seismic microzonation, rating scheme, site effects, geological data, shear wave velocities, standard penetration tests, seismic ambient noise, Basel, Rhinegraben

ZUSAMMENFASSUNG

Um die Auswirkungen eines möglichen Erdbebens auf wichtige Infrastrukturbauten abschätzen zu können, wurde für den Kanton Basel-Stadt eine Erdbebenmikrozonierungskarte erstellt. Sie basiert auf den detaillierten Kenntnissen der geologischen und geotechnischen Verhältnisse, auf Messungen der natürlichen Bodenunruhe und ihrer Interpretation und Modellrechnungen der zu erwartenden Verstärkung der Bodenbewegung in Abhängigkeit vom lokalen Untergrund. Ein detailliertes Bewertungsschema der Auswirkungen der lokalen geologischen Verhältnisse auf die Verstärkung der Bodenbewegung wird entwickelt. Sieben charakteristische Parameter werden im Gebiet des Kantons Basel-Stadt auf einem 25 x 25 m Raster gewichtet. Hiervon bewerten vier Parameter den Einfluss der quartären Schotter: 1) Lagerungsdichte, 2) Typ (Korngrösse und Grad der Verkittung), 3) Mächtigkeit und 4) laterale Mächtigkeitsänderungen. Das Potential einer möglichen Bodenverflüssigung wird durch den Flurabstand des Grundwassers in die Bewertung einbezogen. Zwei weitere Parameter bewerten den Einfluss der präquartären Sedimente: 1) Änderungen in der Lithologie und 2) laterale Änderung am Rand des Rheingrabens. Die resultierende qualitative Mikrozonierungskarte des Stadtzentrums lässt sich mit den historischen Schäden des Bebens von 1356 vergleichen.

ABSTRACT

As a step towards mitigation of earthquake risk a microzonation map is established for the canton of Basel-Stadt. It is based on detailed knowlege of the geological and geotechnical conditions, measurement and interpretation of ambient noise data and numerical modelling of expected ground motion. To account for the effects of local geological and geotechnical conditions on the amplification of ground motion, a detailed rating scheme is developped. Seven characteristic parameters are mapped and rated on a 25 x 25 m grid within the area of the canton of Basel-Stadt. Four parameters account for the influence of the Quaternary sediments: 1) consolidation, 2) type (grainsize and lithification), 3) thickness and 4) lateral variations in thickness. The potential of liquefaction is expressed by the depth to the groundwater table. Two parameters account for the influence of the Prequaternary sediments: 1) differences in lithology and 2) lateral variation at the border of the Rhinegraben. The resulting qualitative microzonation map of the center of the town is discussed and compared to the historically reported damage of the 1356 earthquake.

1. Introduction

In 1356 a strong earthquake destroyed the city of Basel. The maximum epicentral MSK-intensity is estimated to be equal or greater IX (Mayer Rosa & Cadiot 1979). Although the present seismicity in the Basel area is low, another strong earthquake has to be expected due to the city's location close to the northern end of the African-European convergence zone at the southern end of the Rhinegraben. In 1993 a trinational workshop (France, Germany and Switzerland) was held in the Basel region in order to improve emergency preparedness in case of a large earthquake. Apart from the outcome on the questions of cooperation, communication and organization across the borders of the three countries and two cantons, one of the results was, that up to this date, possible failure of "critical facilities" was not taken seriously into account. "Critical facilities" include life lines such as major communication utilities and transport facilities, and their connections to emergency units such as police and fire stations, hospitals and communication centers. Within this context an earthquake microzonation map was established for the canton of Basel-Stadt. This map shows the expected geographical variations in shaking intensity based on the local geological conditions.

The intensity of ground motion at a given site depends on three factors: the characteristics of the seismic source (i.e. frequency and direction of the emitted energy), the crustal structure for the wave path between the source and the site and on the local geological conditions. The influence of local geologi-

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cal conditions has been recognized for a long time (for a summary and discussion see Rogers et al. 1985). Strong motion recordings e.g. of the Loma Prieta Earthquake 1989 (Borcherdt & Glassmoyer 1992, Borcherdt & Glassmoyer 1994) clearly confirmed the importance of local geological conditions on the ground motion at a site and the corresponding damage pattern. The described intensities varied by three units, from the highest for sites underlain by bay mud and Quaternary alluvium, to the lowest for sites underlain by the Franciscan Complex.

In order to describe the regional seismic hazard, probabilistic assessment is generally done on a national basis. On a local scale, microzonation studies can then be performed in order to identify sites where earthquake effects are most severe. The methods applied for microzonation studies depend mostly on the available geological and geotechnical data, as well as on the requested detail of the ground motion estimates. No standard microzonation scheme is so far accepted within the scientific community.

In Switzerland, a pilot project in the canton Obwalden (Swiss project within the international decade of natural disaster reduction (IDNDR); Schindler et al. 1996) focused on the geological correlation of observed intensity anomalies with local soil conditions, and the regional hazard assessment using a geographical information system. The project "Earthquake hazard and microzonation in Switzerland" (NFP31 "Climate Changes and Natural Hazards", Rüttener 1995, Beer 1996, Mayer-Rosa et al. 1997) focused on three test sites, including Basel and the Valais, with the purpose of assessing regional seismic hazard and seismic microzonation. In the canton of Basel-Stadt as well as in the Valais continuing applications could be initiated during the NFP31 project (Fäh et al. 1997a).

In the area of Basel, in 1992, four strong motion stations (Bettingen, Tropenhaus, Birsfelden and Schweizerhalle) have been operating (for exact location see Smit & Mayer-Rosa 1994). The Wutöschingen earthquake (30. Dec. 1992, ML 4.0) at an epicentral distance of about 60 km from Basel has been recorded at the stations Tropenhaus, Bettingen and Schweizerhalle. The seismograms show significant differences in amplitude, frequency and duration (Smit & Mayer-Rosa 1994) which can be attributed to differences in the response of the local soil conditions. The prediction of relative ground motion response can be roughly estimated by the correlation of a large number of strong motion recordings with local geological properties (e.g. Joyner & Fumal 1985, Rogers et al. 1985).

For the canton of Basel the strong motion recordings and macroseismic intensity observations are by far not dense enough for a reliable zonation. However, the geological dataset of the near-surface sediments is very dense. In the canton of Basel more than 2700 shallow wells for construction and ground water purposes have been drilled. A large number of lithologic logs describing the near surface sediments in terms of grain size, sand and clay content and lithification are contained in a geological database (Noack 1993, Noack 1997). This dataset gives a very detailed information on the alluvial gravels of the region. The density of the dataset allows to construct detailed and reliable maps of the thickness and the composition of the gravels. Therefore we establish in this study a qualitative rating scheme that relates geological data, such as variations of the thickness, the composition and the compaction of the unconsolidated Pleistocene and Quaternary sediments, to the attenuation or amplification of seismic waves (compare also Rogers et al. 1985). The most important soil parameter that governs the amplification of seismic waves is the shear-wave velocity of the near-surface sediments (Joyner & Fumal 1985). Therefore, special emphasis must be given to estimate the shear-wave (V_s) velocities for different geological units. As no reliable V_s measurements exist in the Basel-area, Standard Penetration Tests (SPT-measurements) and ambient noise techniques have been applied for this purpose.

In order to relate the geological and geotechnical parameters to ground motion amplification effects, numerical simulations of the expected ground motion have been carried out for different parameters such as variations in shear-wave velocities and thickness of the unconsolidated sediments (Fäh et al. 1996, Fäh et al. 1997b). The methods used are based on modal summation (Panza 1985, Florsch et al. 1991) and more advanced hybrid schemes (Fäh 1992). The results obtained from numerical modeling demonstrate the strong variability of amplification effects induced by variations of near-surface sediments. This is in good agreement with studies performed in other areas of the world (e.g. Fumal & Tinsley 1985, Joyner & Fumal 1985). The highest values of spectral amplifications are of the same order of magnitude for different site locations. However, depending on the thickness of the soils these highest values appear at different frequencies. In many cases, the maximum amplification occurs at the fundamental frequency of resonance of the soils. The determination of this frequency is therefore of paramount importance and it has been obtained from the ambient noise measurements for some test-sites in our area of interest. Two-dimensional modeling allowed to show examples of the expected amplification due to lateral variations (Fäh et al. 1997b).

The proposed qualitative microzonation scheme is a first important step to estimate local site effects and to identify sites where strong amplification effects have to be expected.

2. Geological and geotechnical data

2.1 Geological overview

The town of Basel is located at the eastern master fault of the southern Rhinegraben. Within the Rhinegraben the down thrown Mesozoic strata (Triassic to Jurassic limestones, marls and shales) are covered with 500–1000 m of Tertiary sediments (Fig. 1 and 2). They form an asymmetric syncline (Mulde von Tüllingen–St. Jakob) parallel to the border of the Rhinegraben. The "Meletta Schichten" are marine deposits of Oligocene age (lower marine Molasse). They consist of about 300 m of blue ("Blauer Letten") to gray argillaceous over-consolida-

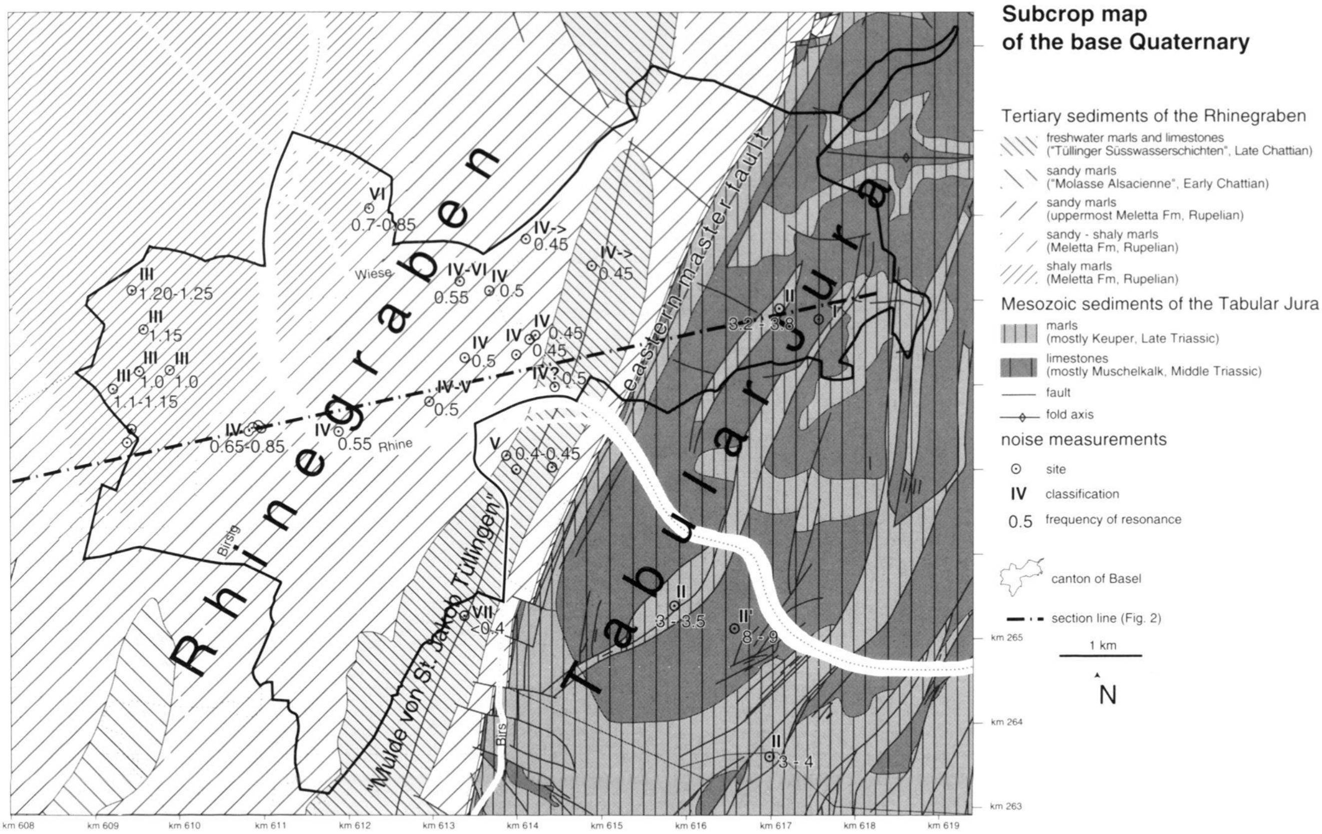


Fig. 1. Subcrop map of the base of the Quaternary sediments. The sites where ambient noise measurements have been carried out are indicated. These points are classified with roman numbers, according to the polarization spectrum observed (compare Fig. 5). The measured fundamental frequency of resonance is given in Hz. The type I spectrum corresponds to a bedrock site, and no fundamental frequency is given.

ted silt with very few fossils. The topmost 20–40 m are more sandy, in parts lithified to sandstones, and very hard at some places. The overlaying "Molasse Alsacienne" documents a facies change to terrestrial sands and marls. The youngest member are the "Tüllinger Schichten". In the North they are formed as freshwater limestones, towards the South they become more marly.

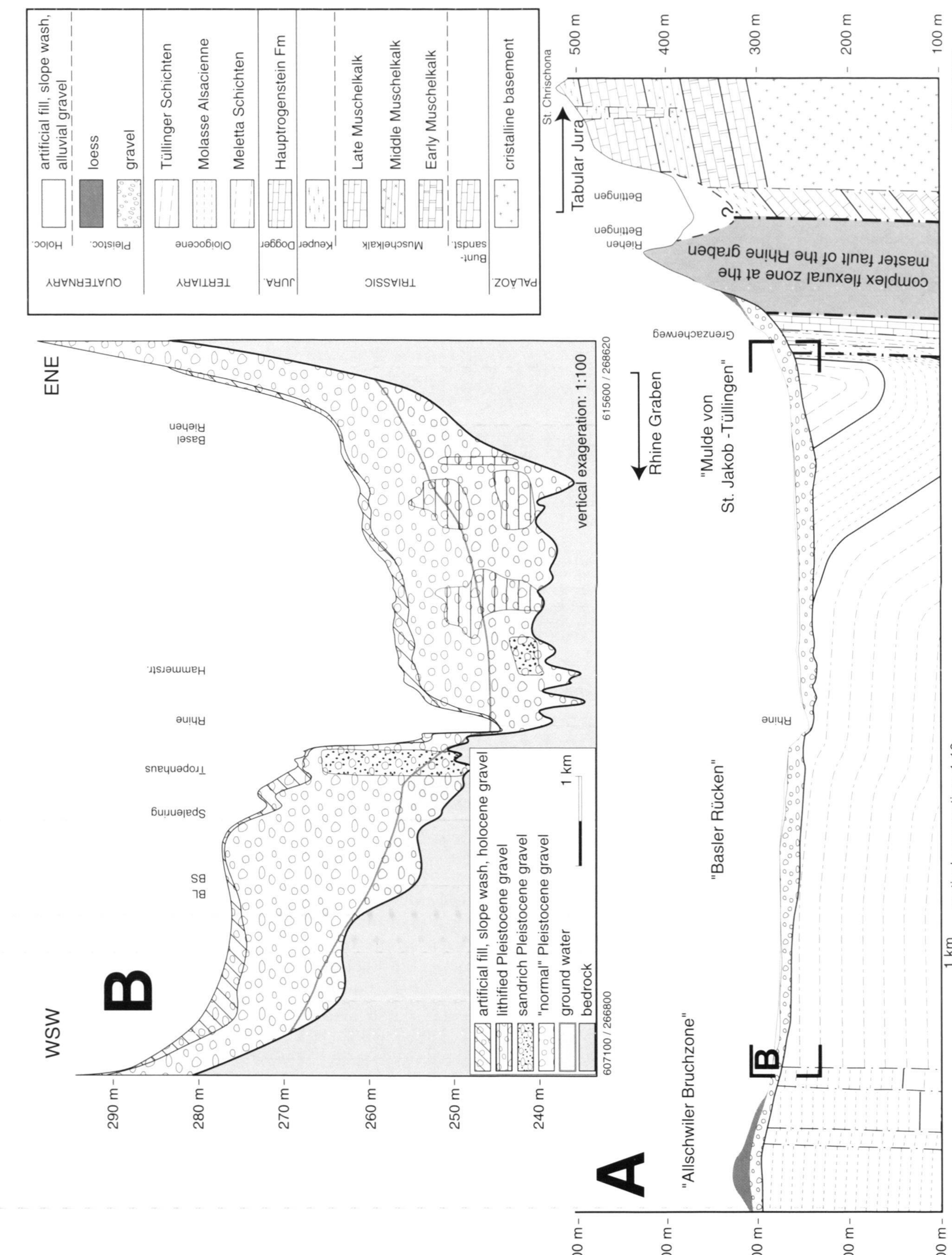
Many larger buildings of the town are grounded within the Tertiary layers. These also form the lower confining bed for the ground water circulating in the gravels. Most of the wells penetrated only the topmost few meters of the Tertiary layers. Only very few wells have been drilled through these layers (e.g. Brianza et al. 1983, Hauber 1991) so that our knowledge of the deeper layers beneath Basel is not very detailed.

2.2 Lithologic characterization of the Pleistocene and Holocene sediments

Our knowledge of the 10 to 45 m thick Pleistocene and Holocene sediments is very detailed. More than 2700 wells and their thorough lithologic description render a detailed picture of the thickness and the composition of these gravels, mostly deposited by the Rhine but also by the Wiese and the Birs during the glacial events.

The Rhine gravels are braided river deposits and can be described as gray bimodal gravels consisting of well rounded mostly alpine material (metamorphic rocks and limestones) with a diameter of 1 to 40 cm with few larger boulders. At some places the content of sand is increased. Quite often some parts of the lithologic logs are described as lithified or as conglomerates. The Birs and Wiese gravels can be distinguished from each other, as the first consist of mostly yellowish Mesozoic limestones from the Jura mountains and the latter mainly of reddish crystalline cobbles from the Black Forest. In general these Pleistocene gravels are extremely well consolidated. This is reflected by unit weight values of up to 2.4 kg/m^3 and high values from SPT-measurements.

On top of the Pleistocene gravels we find at places some 2 to 5 m of Holocene gravels. They can only be distinguished from the older ones as they are less consolidated. Therefore the data from the observed well logs are not very reliable in terms of defining the separation between Pleistocene and


A
B
WSW
ENE
290 m
280 m
270 m
260 m
250 m
240 m
BL
BS
Spalenring
Tropenhaus
Rhine
Hammerstr.
Basel
Riehen
artificial fill, slope wash, holocene gravel
lithified Pleistocene gravel
sandrich Pleistocene gravel
"normal" Pleistocene gravel
ground water
bedrock
1 km
607100 / 266800
615600 / 268620
vertical exageration: 1:100
Rhine Graben
Tabular Jura
QUATERNARY
Holoc.
Pleistoc.
artificial fill, slope wash, alluvial gravel
loess
gravel
TERTIARY
Oligocene
Tüllinger Schichten
Molasse Alsacienne
Meletta Schichten
JURA.
Dogger
Hauptrogenstein Fm
TRIASSIC
Keuper
Muschelkalk
Late Muschelkalk
Middle Muschelkalk
Early Muschelkalk
Bunt-sandst.
PALÄOZ.
cristalline basement
500 m
400 m
300 m
200 m
100 m
"Allschwiler Bruchzone"
"Basler Rücken"
"Mulde von St. Jakob -Tüllingen"
complex flexural zone at the master fault of the Rhine graben
Grenzacherweg
Riehen
Bettingen
St. Chrischona
1 km
vertical exageration: 1:10
606000 / 266550
618300 / 269200

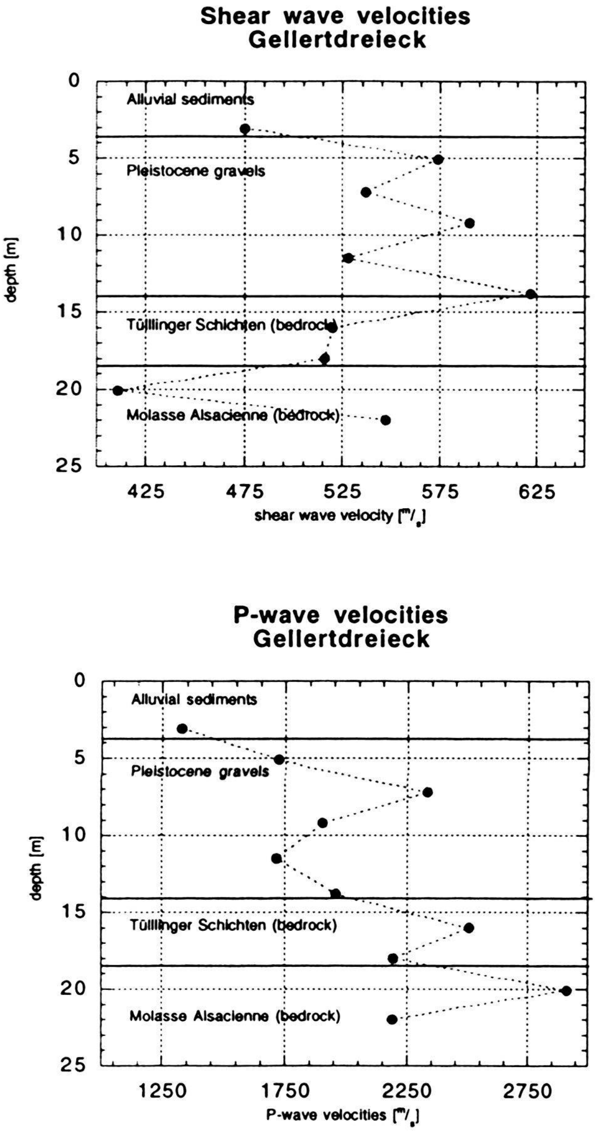


Fig. 3. S-wave and P-wave velocities from a cross hole measurement in the town of Basel (unpublished data from Kiefer & Studer 1972, internal report).

Holocene gravels. On the geologic map of Basel (Wittmann et al. 1970) the Holocene gravels are shown on the northern side of river Rhine. Hauber (1971) describes the finding of some trees in these layers with ages of 6000–2000 years.

Fig. 2. Cross sections along the section line indicated in figure 1. Section A has a vertical exaggeration 1:10, B: part of section A with a vertical exaggeration of 1:100. The different types of the Quaternary deposits (compare Fig. 7 and Tab. 2) could be worked out by classifying all the lithologic logs within 500 m of the section line.

On top of these gravels loess of different age is conserved at some places (Bruderholz and Riehen). Near the hills of St. Chrischona and Tüllingen and in parts of Kleinbasel the gravels are covered by slope wash.

2.3 Shear wave velocities of the Pleistocene and Tertiary sediments from SPT-measurements

According to different authors (e.g. Joyner & Fumal 1985) variation in the shear wave velocities of the near surface sediments is one of the most important factor for different local amplification of seismic waves. For the Basel region the knowledge of the shear wave velocities of the near surface gravels and the underlying Tertiary and Mesozoic sediments is very poor. To our knowledge only one in situ-measurement within the town of Basel exists. (Kiefer & Studer, 1972, unpublished internal report). The results of this cross-hole measurement are shown in figure 3. The shear wave velocities do not correlate well with the P-wave velocities and with the lithologic descriptions of the wells. However, the measured values give a reasonable order of magnitude.

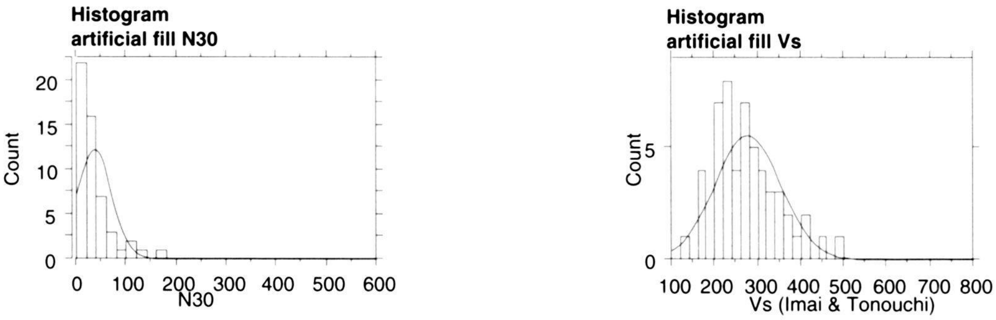
For near surface gravels similar to those in the Basel area, Imai & Tonouchi (1982) give an empirical correlation between SPT-measurements (Standard Penetration Test) and shear wave velocities:

$$V_s = 97 \cdot N_{30}^{0.314}$$

where V_s is the shear-wave velocity and N_{30} the number of blows from SPT measurements to penetrate 30 cm.

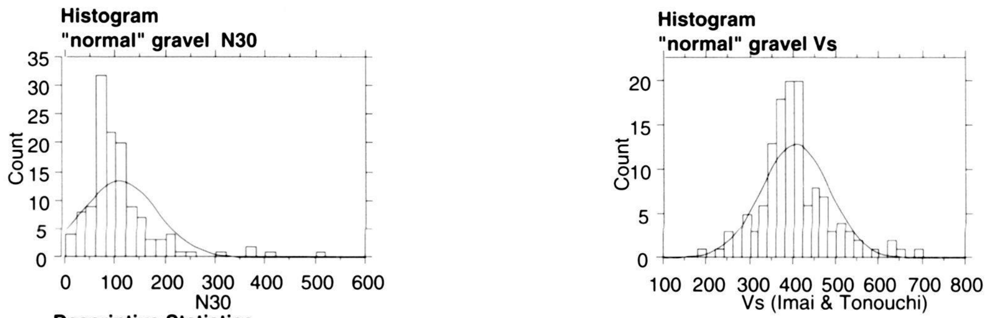
SPT measurements are performed as a cheap standard method in many boreholes to get information about the consolidation of a sedimentary unit. For SPT measurements the number of blows with a standardized weight to penetrate a standardized tip three times 15 cm into the ground is recorded. N_{30} is defined as the number of blows for the second and third 15 cm. If the number of blows for 15 cm is higher than 50, the effective penetration depth for 50 blows is recorded. To calculate N_{30} for these cases the number of blows is extrapolated for a penetration depth of 15 cm and 30 cm respectively. N_{30} in our figures and tables include these extrapolated values. We further eliminated values that did not penetrate the first 15 cm with less than 50 blows. This happens quite often in lithified gravels. From our database we evaluated some 350 SPT measurements distributed over the town. 254 gave reasonable values for N_{30}. As the SPT test is not designed to characterize lithified and highly consolidated gravels the resulting mean velocities from our selected data tend to be on the lower side. Imai & Tonouchi (1982) used the same definitions of N_{30}. They performed shear wave velocity measurements with downhole seismics and discriminated the resulting curves by the age of the penetrated sediments and their lithological characteristics. Despite all these restrictions and uncertainties, this method can be used to estimate mean shear wave velocities.

To determine characteristic velocities for different types of sediments and check for the possibility of a depth dependency,



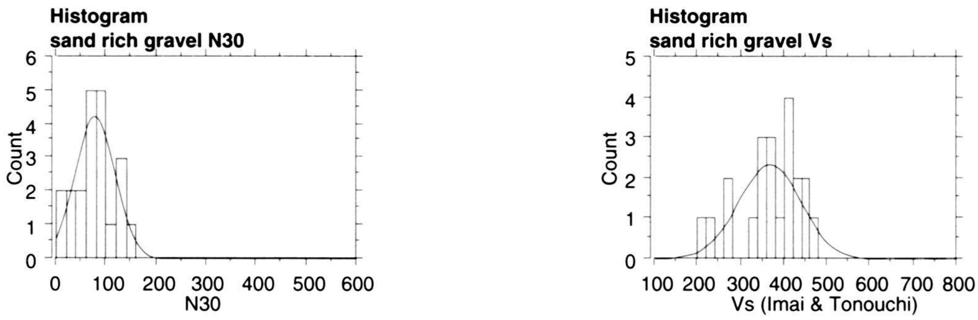
Descriptive Statistics

	Mean	Std. Dev.	Std. Error	Count	Minimum	Maximum	# Missing
N30	36	34	5	53	2	177	0
Vs (Imai & Tonouchi)	277	76	10	53	121	493	0



Descriptive Statistics

	Mean	Std. Dev.	Std. Error	Count	Minimum	Maximum	# Missing
N30	106	76	7	128	10	500	0
Vs (Imai & Tonouchi)	403	79	7	128	200	683	0



Descriptive Statistics

	Mean	Std. Dev.	Std. Error	Count	Minimum	Maximum	# Missing
N30	78	39	8	21	12	148	0
Vs (Imai & Tonouchi)	367	71	16	21	212	466	0

Fig. 4. Histograms for N_{30} of the different types of Quaternary gravels. The corresponding S-wave velocities are calculated after the empirical relation given by Imai & Tonouchi (1982).

Tab. 1. depth dependence of shear wave velocities within the "Meletta Schichten"

depth range	number of measurements	mean shear wave velocity	standard deviation
10–20 m	5 values	455 m/s	90 m/s
20–30 m	7 values	588 m/s	96 m/s
30–40 m	6 values	631 m/s	73 m/s

each SPT measurement was correlated with a classified lithologic description and its depth (Fig. 4). We distinguished 5 lithological types: 1) artificial fill, 2) "normal" gravel, i.e. gravel with little to no sand and silt, 3) sand-rich gravel and sand, 4) lithified gravel and 5) Prequaternary sediments. Although the variability within each type is high (Fig. 4) the mean values show significant differences. However no significant correlation with depth could be found, except for the "Meletta Schichten". The resulting velocities for artificial fill and sand-rich gravel are statistically significant. "Normal" gravel has values about 30 m/s higher than sand rich gravel. The values for lithified sediments are small in number and quite divergent. Here the limits of the method are reached.

For the different lithologies of Prequaternary sediments only few data exist. There seem to be different velocities for the "Meletta Schichten" and the "Molasse Alsacienne". For the "Meletta Schichten" an increase with depth can be observed (Tab. 1).

The resulting velocities for the different lithologies are probably to low, as SPT measurements are not designed to characterize highly consolidated gravels. Nevertheless, they can be used in absence of reliable measured data to assign mean velocities to the different types of sediments.

2.4 Shear wave velocities of the sediments from ambient noise measurements

One method that has the potential to characterize different sites is based on the analysis of the polarization of the micro tremor wavefield (e.g. Nakamura 1989). This method is very cheap and applicable for urban areas, as it uses the recordings of ambient noise measurements at different sites.

The polarization of the wavefield can be used to estimate the fundamental mode of resonance of the unconsolidated sediments and in case of known thickness, to estimate an average shear wave velocity.

In order to relate the measurements to characteristic geological features, the 25 sites for measurements were chosen in the vicinity of boreholes with a detailed and characteristic lithologic log. They were distributed over the area so that different characteristics of the gravels, e.g. thickness, sand content and lithification could be discerned. For a detailed description of the polarization analysis, see Fäh et al. (1997b).

The sites and the types of the spectra as well as the measured fundamental frequency of resonance are given in figure 1.

Three characteristic areas can be distinguished based on the ambient noise measurements (Type II, III and IV spectra (Fig. 5)). Careful correlation with the geologic data leads to the conclusion that the main factor for most areas are the different lithologies of the Prequaternary bedrock.

- Type II spectra (Fig. 5a) are observed outside the Rhinegraben. There we find Mesozoic sediments of the tabular Jura covered by a thin (20–50 m) layer of Quaternary gravels. Two types can be distinguished: Type II with a fundamental frequency of resonance between 3 and 4 Hz characterizes small grabens where Keupermarls and Opalinus-Shales lie under Quaternary gravels. Here the resonance frequency is predominantly influenced by two layers: the gravels and the marls. The average velocity of the "soft" sediments is in the order of 380–520 m/s depending on the thickness ratio of the two layers. In contrast to Type II, Type II' corresponds to areas where the Quaternary gravels are underlain by Muschelkalk limestones and dolomites. Only one site has been studied, where the resonance frequency (8–9 Hz) is only dominated by a single layer of gravel. Numerical simulations taking into account the borehole information at the studied site allow an estimation of the average velocity of the gravels which is in the order of 490 to 560 m/s – a velocity that compares well with the derived velocities from the SPT-measurements.
- Type III spectra (Fig. 5b) are found in the western part of Basel (Fig. 1). The fundamental frequency of resonance varies between 1 and 1.3 Hz and the maximum polarization value is exceptionally high. The shear-wave velocity is estimated to be of the order of 500 to 600 m/s. The low resonance frequency between 1 and 1.3 Hz can be attributed to the presence of the "Meletta Schichten" of Tertiary age underlying the Quaternary gravels. The "Meletta Schichten" are composed mostly of argillaceous marls ("Blauer Letten") and have a thickness of up to 300 m. Its topmost 50 to 100 m at the transition to the terrestrial "Molasse Alsacienne" are more sandy and partly formed as sandstones.
- Type IV spectra (Fig. 5c) are characteristic for the Mulde of St. Jakob Tüllingen. The thickness of the Tertiary sediments is increasing towards this asymmetric syncline. This is expressed as a decrease of the fundamental frequency of resonance. The amplitude of the average polarization curve at the fundamental frequency is smaller than those for Type-II and Type-III spectra. This indicates a larger average shear-wave velocity that corresponds geologically to the transition from marine argillaceous marls to sandstones and freshwater limestones that have higher shear wave velocities.

In addition to these three main types, other spectra can be distinguished. To the north of the zone with Type IV spectra the Tertiary sediments are stiffer (Type IV ->). To the south of the Mulde of St. Jakob Tüllingen the stiffness is decreasing (Type V) due to the predominant marly facies of the Tertiary layers.

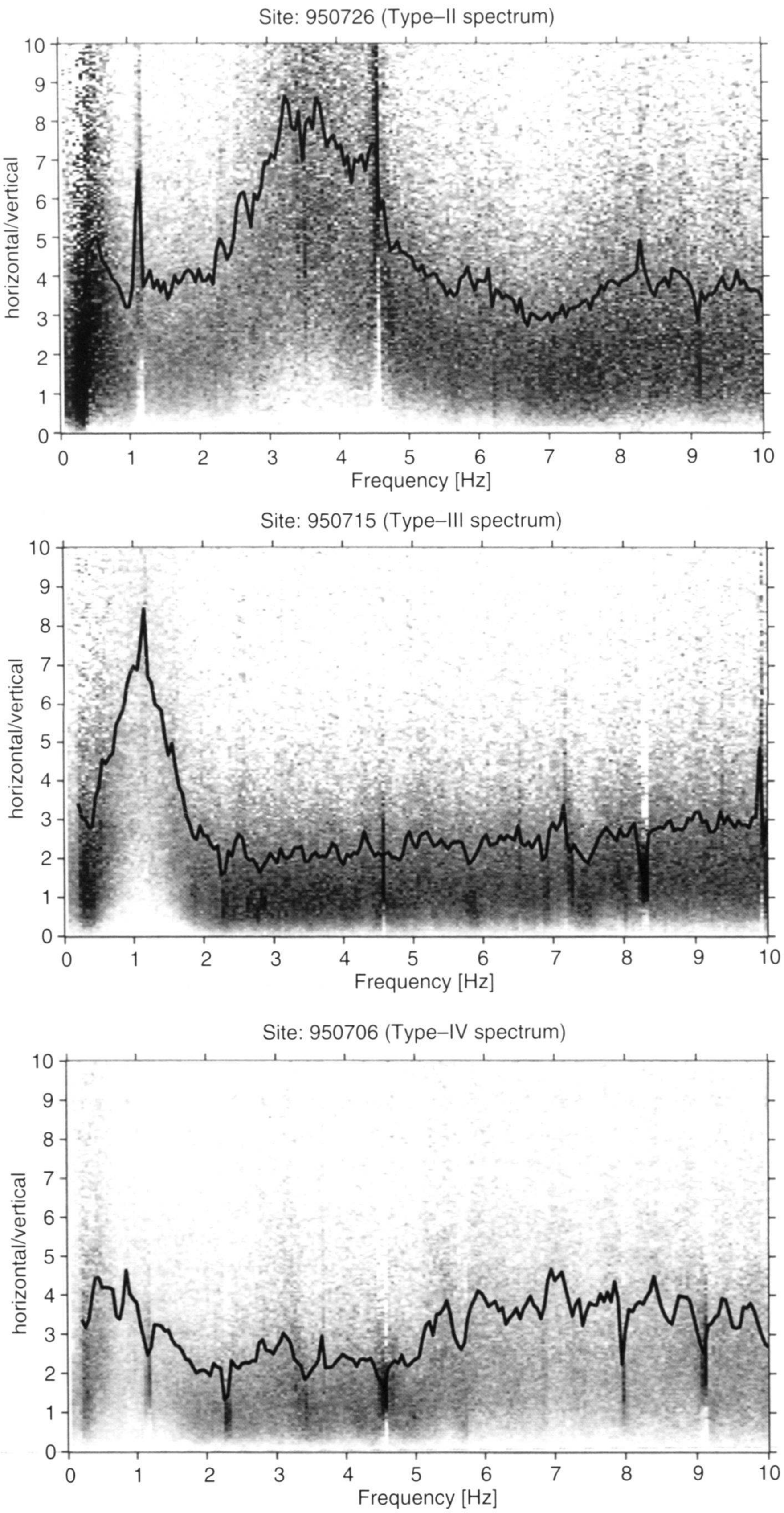


Fig. 5. Observed ambient-noise polarization spectra of types II, III and IV. Polarization is defined as the ratio between the Fourier spectrum of the horizontal components and the one of the vertical component. The solid lines correspond to the average polarization for all noise samples.

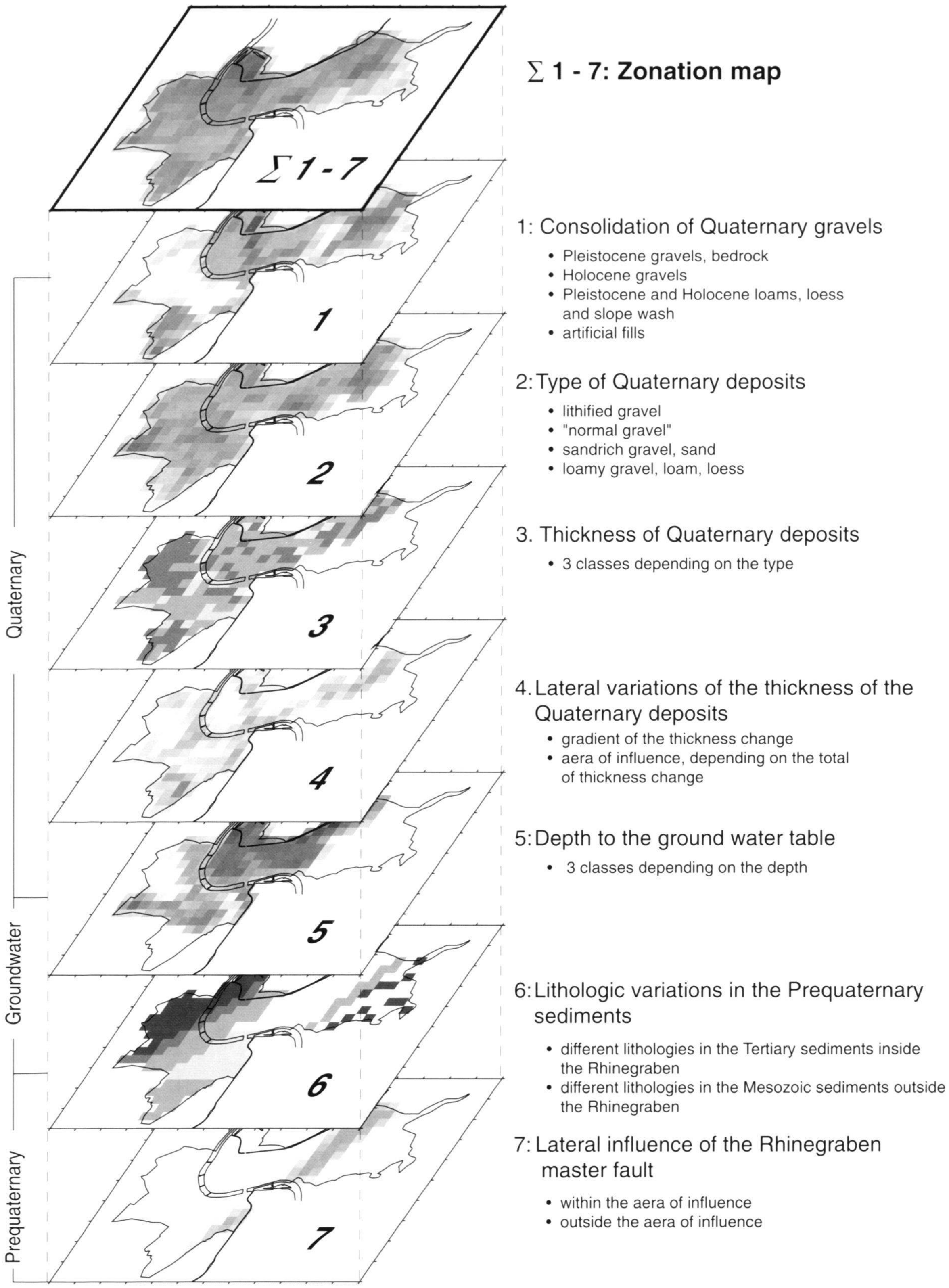


Fig. 6. Schematic representation of the application of the rating scheme (cf. Tab. 2). The local contributions of each characteristic parameter are mapped on a 25 x 25 m grid (e.g. Fig. 7 & 8). The zonation map is the sum of all the different contributions at each grid cell.

The interpretation of the ambient noise measurements lead to the important result, that for the Basel region the Prequaternary marls and clays usually denoted as bedrock are to be treated similar to unconsolidated gravels, although they are old and therefore described mostly as over-consolidated. Further research, eg. comparing measurements of ambient noise with other techniques, will help to better constrain shear-wave velocities to different soil types.

3. Rating scheme for local soil conditions

By considering the important characteristics of different soil types with respect to their capabilities to amplify seismic waves, we developed a rating scheme that takes into account the influence of seven characteristic parameters of the local soil. For each of these parameters, that gives a contribution to the amplification of ground motion, local values are assigned to a 25 x 25 m grid. The zonation map is the sum of all the different contributions at each grid cell (Fig. 6).

Four parameters take into account the influence of the Quaternary gravels (Tab. 2):

- The consolidation of the Quaternary gravels expressed by their age.
- The type (grain size and lithification) of the Quaternary sediments.
- The thickness of the Quaternary sediments weighted by their type.
- Lateral variations in the thickness of the Quaternary sediments to account for the excitation of local surface waves and resonances.

A fifth parameter considers the potential of liquefaction. Liquefaction is considered for the Basel region as of minor importance, as we find water saturated sands only at very few places. It is expressed by the depth to the water table (compare Brebbia 1996).

Finally two parameters account for the influence of the Prequaternary sediments:

- The different lithologies of the Prequaternary sediments
- The lateral variation at the border of the Rhinegraben master fault.

The different layers and their compilation from the geological data is described in the following. Some of the layers were compiled from geologic maps. The areas with the same content were subsequently rasterized onto a 25 x 25 m grid. Other data sets were interpolated from irregular point data onto a 25 x 25 m grid. The logical operations combining the different grids were done using the raster oriented GIS software MAP II.

3.1 Consolidation of the Quaternary deposits

Compact materials have higher S-wave velocities and the expected amplification is lower than at places where the sediments are not so well consolidated. The consolidation can be expressed by the age of the sediments. The oldest gravels, the Pleistocene deposits are assumed to have the highest compaction. The least consolidated layers are artificial fills. This layer is compiled from the geologic map of Basel (Wittmann et al. 1970) complemented by observations available in the "Baugrundarchiv" at the Geological Institute of Basel University.

The Pleistocene gravels are generally highly consolidated. Their unit weight goes up to 2.4 kg/m^3. In some parts of the town they are overlain by a few meters of less consolidated Holocene alluvium of the same content. They can only be distinguished by their degree of compaction (e.g. by SPT measurements). On the geologic map of Basel (Wittmann et al. 1970) the area of the town north of the Rhine is mapped as Holocene gravels. Their thickness is not well defined. At the hill slopes of the St. Chrischona and the Tüllinger Hügel as well at the Allschwiler Bach we find slope wash – a highly loamy sediment. Here again the exact thickness is not known. On the southern hills (Bruderholz) and in parts of Riehen in the north west the Pleistocene gravels are covered by up to 50 m of Pleistocene loess. In the Bruderholz region the thickness of the loess is well known as quite a number of wells have fully penetrated these sediments.

The youngest and least consolidated sediments are the artificial fills. Artificial fill has low S-wave velocity and the risk of settlements is increased. During the middle ages the town of Basel had two moats that have been filled during the last centuries. There also exist a number of gravel pits, that have been filled with building dump and other waste. The artificial fills were compiled from the maps of hazardous waste sites. All the artificial fills with a depth of more than 5 meters were taken into account.

3.2 Type of Quaternary deposits (grain size and lithification)

Sand and sand rich gravels have lower S-wave velocities and consequently the amplification of ground motion is larger than for gravels without or with little sand and for lithified gravels. The lithological content of the gravels could be classified into three categories: gravel with little or no sand, sand rich gravel and lithified or conglomerate gravel. As it is impossible to correlate structures between different wells (drilling technique, poor description, lacking lateral continuity of the layers) we generalized the lithological descriptions of the gravels for each well in the database. In a first step each described layer is classified as one out of 8 types. These are: 1) open framework gravel, 2) gravel with little sand and loam, 3) sand-rich gravel, 4) sand, 5) loam-rich gravel, 6) loam and loess, 7) lithified gravel and 8) conglomerate. The thickness of each class is calculated and expressed as the percentage of the total thickness of the gravels in this well. To get a summarizing map with different clusters, the percentages of the classes 1 and 2, 3 and 4, 5 and 6, 7 and 8 were combined according to the scheme in table 3. In order to rate the dynamic effect of sand, loam, loess and conglomerate, the percentages for these classes were multiplied by two.

Tab. 2. Rating scheme used for the quantitative seismic microzonation of Basel. Different geological and geotechnical properties are rated according to their influence on strong ground motions.

PARAMETER	WEIGHT	REMARKS
1. Consolidation of the Quaternary sediments (as a function of age)		
• Pleistocene alluvium (highly consolidated)	0	• No contribution from Prequaternary lithified sedimentary rocks
• Holocene alluvium (medium consolidated)	2	
• Pleistocene and Holocene slopewash and Pleistocene loess (low consolidation)	3	• Map is compiled from geologic maps, well data, map of hazardous waste and outcrops at building sites
• artificial fill (very low consolidation)	4	
2. Type of Quaternary sediments (grain size and cementation)		
• lithified gravel: Gc	1	
• gravel with little sand, "normal" gravel: Gn	2	• map is compiled from lithologic descriptions of well logs
• sand rich gravel, sand: Gs	3	
• loamy gravel, loam, loess: Gl	3	
3. Thickness of Quaternary sediments (dependant on the type of the sediment)		
• Gn: 0-10 m; Gs, Gl: 0- 7 m; Gc: 0-12 m	1	• Weights are dependant on the type of the Quaternary deposit
• Gn: 10-20 m; Gs, Gl: 7-15 m; Gc: 12-25 m	2	• Map is calculated from well data, a digital terrain model and the map of paramter 2
• Gn: 20-45 m; Gs,Gl:15-45m; Gc: 25-45 m	3	
4. Lateral variations of the thickness of the Quaternary sediments		
• Gradient: 0.05 - 0.10	1	• For areas with a gradient ≥ 0.15 an extended zone is defined where local surface waves are expected
0.10 - 0.15	2	
≥ 0.15	4	• Map is calculated from the map of the thickness of the Quaternary sediments
• Extended zone: 12*Δh>d	2	
24*Δh>d>12*Δh	1	
(d=distance from lateral heterogeneity, Δh=thickness-change at the lateral heterogeneity)		
5. Depth to ground water table		
• 10 - 20 m	2	• Map is calculated from the map of the mean groundwater table and the digital elevation model
• 3 - 10 m	3	
• 1 - 3 m	4	
6. Lithologic variations in the lithified Prequaternary sediments		
Tertiary sediments		
• "Meletta Schichten" (lithified clay and marl)	4	
• transition zone from clay rich to sandy marl	3	
• uppermost "Meletta Schichten" (lithified sand, marl)	2	
• "Tüllinger Schichten", "Molasse Alsacienne"		• Weights for the "Tüllinger Schichten" and the "Molasse Alsacienne" correspond to a facies change from calcareous in the north to more sandy in the south
northern part	0	
eastern part	1	• Map is compiled from geologic maps, well data, outcrops at building sites and ambient noise measurements
southern part	2	
Mesozoic sediments outside the Rhinegaben		
• Middle Triassic limestones	0	
• Middle to Late Triassic Marls and Shales	4	
• strongly weathered sediments	4	
• Liassic limestones tectonically fractured near the master fault	2	
7. Lateral influence of the Rhinegraben master fault		
• within the area of influence (1000 m inside the Rhinegraben)	2	• Map is compiled from geologic maps and well data
• outside the area of influence	0	

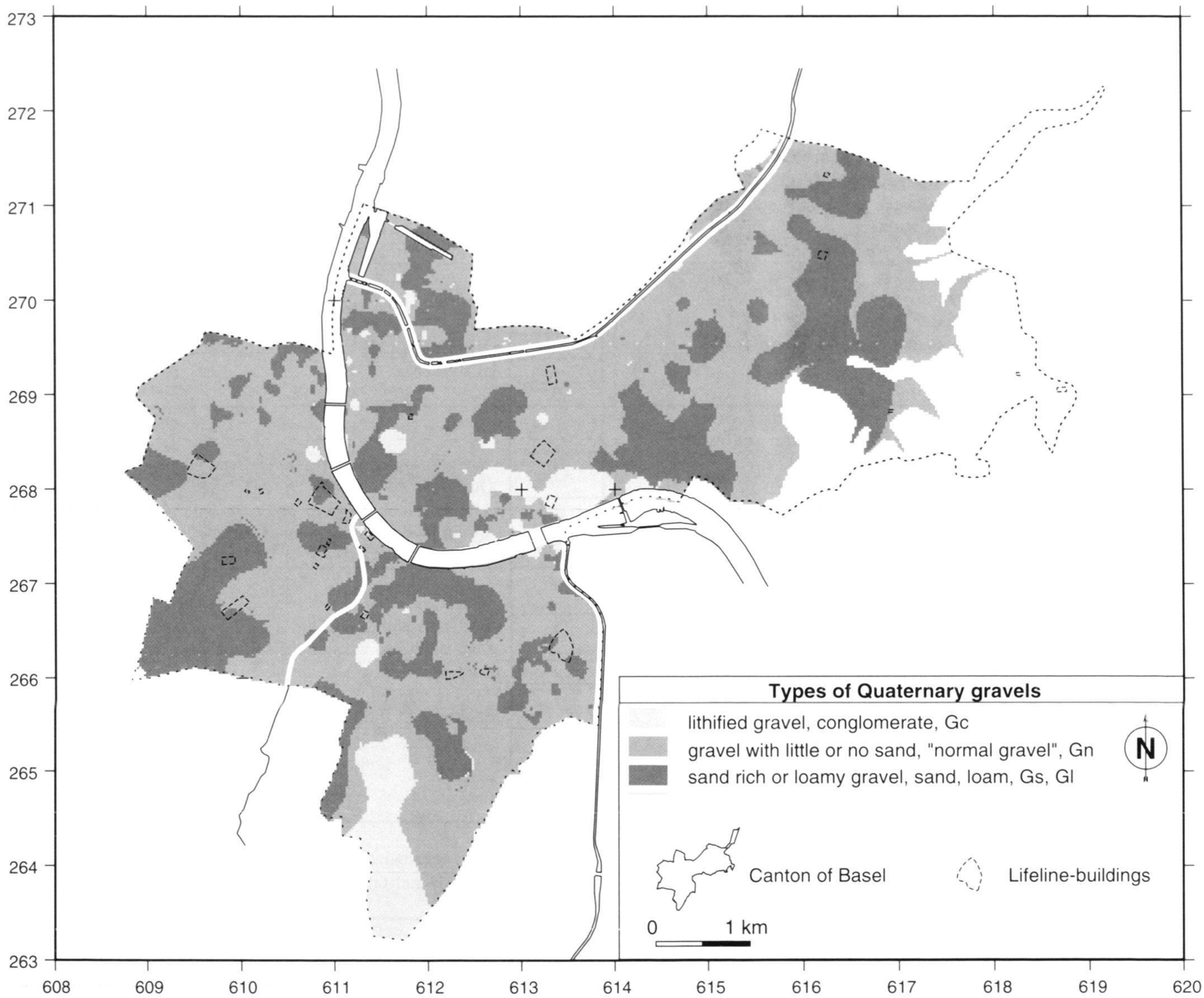


Fig. 7. Map showing the contributions according to the type of the Quaternary deposits.

Tab. 3. Types of Quaternary gravels and their weight used to establish the map (Fig. 7)

Gc: Cemented gravel, conglomerate	perc. of lithified gravel + 2 * perc. of conglomerate
Gn: "normal" gravel, gravel with little or no sand	perc. of open framework gravel + perc. of gravel with little or no sand
Gs: sand-rich gravel	perc. of sand-rich gravel + 2 * perc. of sand
Gl: loam-rich gravel	perc. of loam-rich gravel + 2 * perc. of loam

On the resulting map of the types of the gravels (Fig. 7) patches of some 100 meters of sand rich gravels can be distinguished from patches with an increased percentage of conglomerates and from areas with "normal gravel".

3.3 Thickness of the Quaternary deposits dependant on the type of the deposit

The thicker a layer of unconsolidated sediments, the broader the frequency range for which amplification of seismic waves is expected. Most of the wells were drilled one or two meters into

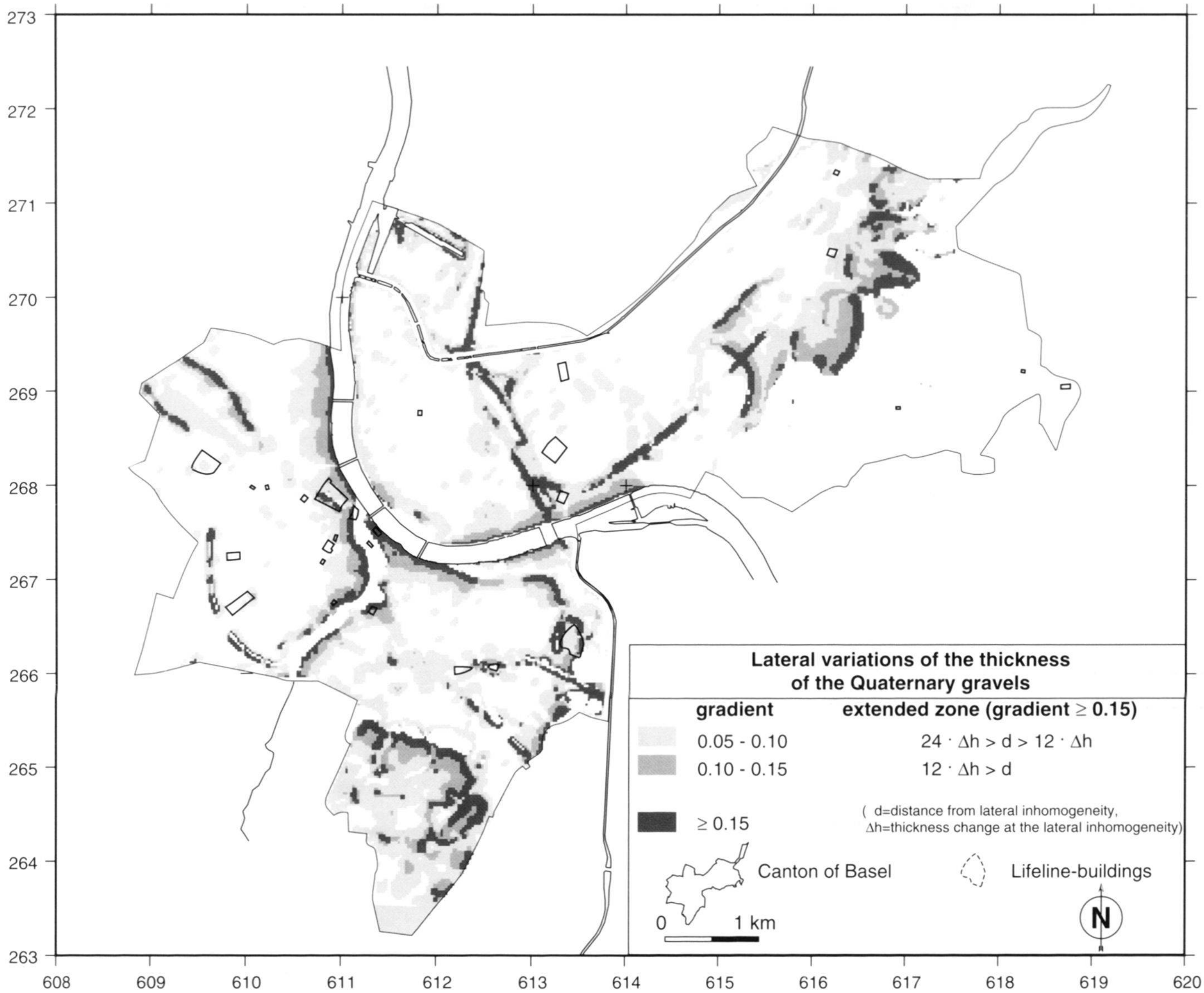


Fig. 8. Map showing the contribution of the influence of lateral variations in thickness of the Quaternary gravels.

Prequaternary sediments (bedrock). The z-coordinate of the top of the Prequaternary is noted in the database. With this dataset a contour map of the top Prequaternary is calculated. By subtraction from a detailed digital elevation model the thickness of the Quaternary deposits is obtained. In areas with a high density of wells these values are very reliable. In other areas, where there are less wells and at the hill slopes of St. Chrischona and the Tüllinger Hügel, these data are interpolated over some distance. The grid of the thickness and the type of the Quaternary gravels were combined and classified by using GIS software.

3.4 Lateral variations of the thickness of the Quaternary deposits

It is well known, that lateral inhomogeneities may be responsible for the excitation of local surface waves, resonances or focusing effects during earthquakes. It is therefore important to take into account not only the one-dimensional structure just underneath the site of interest, but also the surrounding geometries of the sedimentary deposits. A method to map the lateral heterogeneities (Fig. 8) is the calculation by means of thickness gradients. Three classes of gradients were mapped

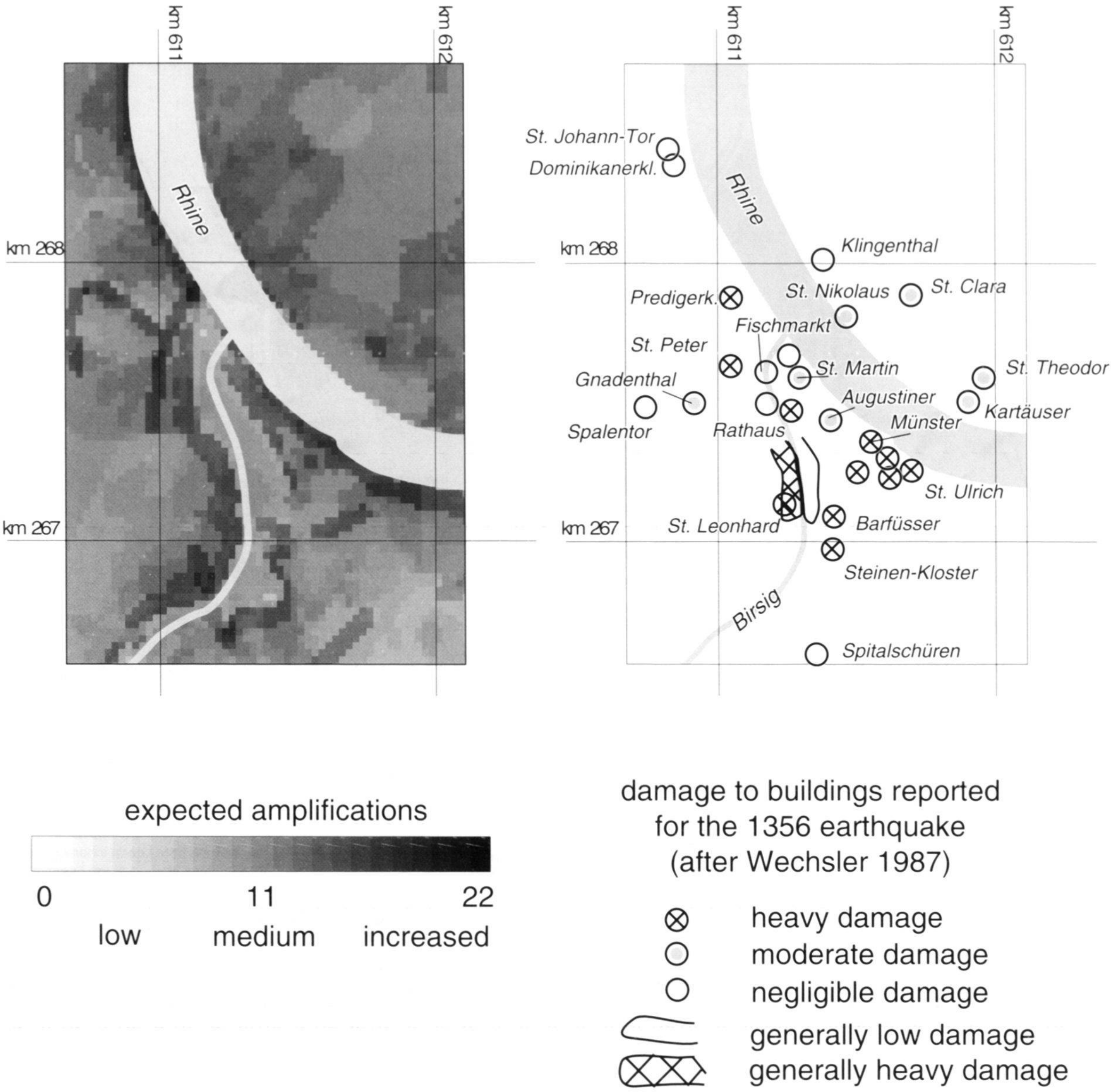


Fig. 9. Comparison between the qualitative microzonation map of the centre of Basel and the damage reported for the 1356 earthquake.

for gravel thicknesses exceeding 7.5 m: areas with a gradient of 0.05 to 0.10, areas with a gradient of 0.10 to 0.15 and areas with a gradient higher than 0.15. These gradients correspond to a slope angle of 3°, 6° and 9° respectively. The ranges where propagating local surface waves have to be expected depend on the total thickness change of the gravels. The ranges were calculated only for gradients higher then 0.15 after the following scheme:

$$d_1 < 12 * \Delta h$$
$$\text{and } 12 * \Delta h < d_2 < 24 * \Delta h,$$

where d is the distance from the lateral variation and Δh is the difference in thickness at the lateral variation.

3.5 Depth to the ground water table

Groundwater has a twofold influence on local amplification of ground motion. One is the increased potential of ground failure due to liquefaction in watersaturated sands, the other is a reduction in S-wave velocity leading to an increased amplification. Important for the shaking potential are the depth to the ground water table, the sand content and the lithification of the gravels below the ground water table. The map of the different gravel types (Fig. 8) refers to the total gravel thickness without any depth dependence. This means, that we are not able to determine whether the different lithologies are above or below the groundwater table. Therefore only the depth to ground water table considered as a contributing parameter (Tab. 3) is considered. The values for mean water level across the town were taken from a finite element model (Kiefer & Studer 1988, unpublished report) and subtracted from the digital elevation model.

3.6 Lithologic variations in the lithified Prequaternary sediments

The map shown in figure 1 is a compilation of descriptions of the Prequaternary sediments from the wells of our database, descriptions of outcrops and of older compilations (e.g. Bitterli-Brunner et al. 1977). There remain uncertainties as to the exact location of the transition from the topmost sandy "Meletta Schichten" to the more argillaceous "Blauer Letten" as well as from the "Meletta Schichten" to the overlying Molasse Alsacienne. The exact location of the facies change within the "Tüllinger Schichten" from North to South is not well documented by well data. However it can be narrowed down by comparing ambient noise measurements.

3.7 Lateral influence of the Rhinegraben master fault

This major fault zone ("Rheingrabenflexur") can be mapped from surface data and well data (e.g. Wittmann et al. 1970, Hauber 1991). Resonance effects may be expected at very low frequency due to the basin structure of the area within the Rhinegraben nearby the flexure. The extent of the influence has been fixed at 1000 m inside the Rhinegraben.

4. Preliminary microzonation map and comparison to damages reported for the 1356 earthquake

The preliminary microzonation map for the center of Basel (Fig. 9) gives a very differentiated picture of dark areas where an increased amplification has to be expected and light areas with a decreased expected amplification with respect to a regional value. A variability of plus and minus one intensity degree compared to an average regional intensity can be expected (Fäh et al. 1997b).

As there are no recent observations of intensity anomalies in the canton of Basel-Stadt, the only possibility to check the map is to look at the descriptions of damages reported for the 1356 intensity IX to X event. This earthquake, one of the largest known in Northern Europe destroyed most of the fortified medieval castles within a 30 km radius from the epicenter (Mayer Rosa & Cadiot 1979). For the town of Basel the "Rotes Buch" from that time describes the earthquake as devastating. But there are no historical documents that describe exactly which houses have been destroyed. A careful investigation of historic documents on expenditures for the repair of damaged buildings (Wechsler 1987) renders a picture of damage distribution that can be compared to the microzonation map (for details see Fäh et al. 1996). Although there is quite an amount of uncertainty as to how the buildings were constructed and the degree of damage due to the earthquake itself and to subsequent fires, the comparison of the damage distribution and the microzonation map shows acceptable agreement. Mainly the St. Leonhard church and the Birsig left-bank nearby, described as totally destroyed, are in good agreement with the expected amplifications. The same is true for the Münster and St. Ulrich church (significant destruction, high amplification) and the Birsig right-bank (little destruction, low amplification). Some other sites are in disagreement. This is partly due to changes in local soil conditions because of human activities. For example some of the moats of the city, which have been filled during the last century and can be well identified on the map did not exist in 1356. Some other buildings may have suffered damage due to the low quality of construction.

The results from this qualitative microzonation demonstrate that sites can be recognized in the Basel area where ground-motion amplification must be expected. This study is based on detailed geological and geotechnical observations, the interpretation of ambient-noise measurements and the interpretation of numerical simulations. The map is a practical tool for recognizing areas where amplification effects have to be expected. In order to describe the ground motion by means of physical quantities, more research work is needed. It is envisaged to apply measurements of shear-wave velocities, numerical simulations and the calibration to future strong-motion recordings.

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