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FOCAL-DEPTH DISTRIBUTIONS IN THE AUSTRIAN EASTERN ALPS BASED ON MACROSEISMIC DATA

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KEYWORDS

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ABSTRACT

A single seismogenic layer-model is used for simulating focal depths-distributions for distinct regions of the Eastern Alps in Austria. Prior to this approach, macroseismic data are investigated in terms of slightly wrong intensity assignments, which might be the cause of secondary - hence artificial - peaks in those depth-distributions. This effect can cause a distortion - here referred to as a 'mirror-effect' - of the focal-depth distribution, leading to questionable average focal depths and standard deviations. Considering this effect and the practice of macroseismic data treatment and analysis during the past, it is possible in many cases to simulate focal distributions which match the observed distributions in a satisfactory manner by using a single seismogenic layer, which allows to estimate a maximum magnitude for that particular region.

Most earthquakes in the Eastern Alps seem to originate at a depth of 7 km. Two exemptions - a region in the province of Salzburg and an area around 'Pregarten' in Upper Austria - are noteworthy, however. The latter region was already known for very shallow earthquakes at around 3 km depth, whereas the 'Hagengebirge' region in Salzburg seems to be a region, where deeper earthquakes (10 km) tend to occur. Maximum magnitudes - using a scaling law based on the thickness of this seismic active layer - in the Eastern Alps are also estimated. In most regions below latitude of 47.5° and west of the Styrian Basin, an additional 1 km thin seismic active layer is necessary to explain the observed pattern of focal-depth distributions deduced from macroseismic data.

For further macroseismic investigations, the reader is encouraged to report earthquake experiences to www.zamg.ac./bebenmeldung to improve the assessment of local effects in Austria.

Mit Hilfe von makroseismischen Aufzeichnungen werden die Tiefenhorizonte, in denen sich die Erdbeben in den Ostalpen in Österreich ereignen, abgeschätzt. Dabei wir untersucht, zu welchem Maße leichte Abweichungen der Bewertungen der Intensitäten auf diese Tiefenbestimmungen sich auswirken. Solche erratischen Interpretationen bewirken sekundäre Spitzen in Häufigkeitsverteilungen der Herdtiefen, die hier als 'Spiegeleffekt' ('mirror effect') bezeichnet werden. Solche Effekte können eine Überschätzung der Mächtigkeit des seismisch aktiven Tiefenhorizonts bewirken, wobei das Ausmaß dieses Tiefenhorizonts auch als grobes Maß für die maximal zu erwartende Magnitude verstanden werden kann. Während im Durchschnitt die Herdtiefe in Österreich etwa 7 km beträgt, so zeichnet sich Pregarten durch seichte Beben (3 km) und das Hagengebirge durch relativ tiefe Erdbeben (10 km) aus. In den westlichen und südlichen Bereichen von Österreich südlichen des 47.5° Breitengrads erscheint es notwendig, noch einen zweiten seismisch aktiven Horizont - wenn auch geringer Mächtigkeit (1 km) - anzunehmen, um die dort beobachteten Häufigkeitsverteilungen zu erklären.

Um weitere makroseismische Untersuchungen zu ermöglichen, wollen wir auf die Internetseite www.zamg.ac./bebenmeldung hinweisen.

1. INTRODUCTION

On average every second year an earthquake happens causing at least minor damage to properties. Most of these events are ignored, since most of the population of Austria is not affected by it. In the following pages we try to elucidate of what can be learned from the past, and this concerns macroseismic data. Macroseismic data are data gathered from the community, evaluated and put into scientific perspective. Everyone is encouraged to describe the experiences made by reporting to www.zamg.ac./bebenmeldung to improve the assessment of local effects.

Macroseismic data can be extremely helpful to determine the local seismic potential if little or no instrumental data are available. This paper deals with aspects of determining focal depths from such data, and will later be used to derive focal depths and to conduct statistics, which should give an idea at which depth horizons earthquakes tend to occur in Austria.

A focal-depth distribution of earthquakes can be considered as one mean of constraining the seismic hazard and ultimately the maximum credible earthquake magnitude for a particular region. From the majority of earthquakes between 1900 and 1992 in Austria mainly descriptions of the effects are available. These effects are coined macroseismic data, which describe the effects - or intensity - of an earthquake to humans and to the built and natural environment. Nowadays, a comprehensive intensity or macroseismic scale "EMS-98" (Grünthal, 1998, see Appendix) is used, which constitutes an extended version of the Medvedev-Sponheuer-Karnik scale (MSK-64, 1981), being itself based on the Mercalli-Sieberg scale

“MS” according to which earthquake effects were assessed in Austria prior to the introduction of the EMS-98. Although some seismic instrumentation existed during the time span 1900 - 1992, the instrumental network was by far not sufficient to provide enough information on the location and depth of the earthquakes. Hence, local magnitudes from foreign agencies were used to complete the earthquake catalogue in order to estimate the focal depth of these earthquakes.

Relatively deep earthquakes were reported for the Eastern Alps in the past (Conrad, 1925; Conrad, 1928; Conrad, 1932; Mifka and Trapp, 1941), which placed hypocentres within what is known today as the lower crust. Later, this idea was mainly given up owing to better data and improved models of the earth’s crust, except for the following regions in Austria, which continued to be associated with focal depth’s exceeding 10 km: ‘Semmering’, ‘Tauern Window’ (corresponding best with the region ‘Katschberg’ covering the border region of Carinthia/Salzburg in this paper) and a region around the village of ‘Namlos’ in West-Tyrol (Drimmel, 1980). The earthquake of ‘Namlos’ was re-evaluated by Franke and Gutdeutsch (1973), leading to a focal depth near 9 km.

The idea of deeper earthquakes - that is more than 10 km in this context - was mainly substantiated by macroseismic data from a single earthquake on October 27, 1964 at the ‘Semmering’ (Region 2, see Fig. 4) - which involved the evaluation of two inner isoseismals - which are manually drawn lines which are separating areas of different intensity classes - with a resolution of ½° resulting in a focal depth of 18 km (Gangl, 1973/1974). Based on the macroseismic map of that earthquake, the isoseismals were re-evaluated by the authors using both extremes and averages of the radii of the respective isoseismals, finding a best fit at a focal depth of 9 km, when applying equation (3) (see below).

Gangl (1973/1974) reported an average focal depth of 9.9 km for earthquakes in the Eastern Alps, based on thirteen seismic events. This result was based on:

1. earthquakes selected from the ‘Vienna Basin’ and the ‘Semmering’, and not from the whole Eastern Alps complex, hence seismic events from the ‘Semmering’-region and the ‘Vienna Basin’ were treated as one data-set,
2. only stronger earthquakes were evaluated, and
3. the equation by Peterschmitt (1969) was used instead of equation (4) given below.

Meanwhile, numerous focal-depth distributions from various continental regions have been published and discussed (e.g. Sibson, 1982; Meissner and Strehlau, 1982; Marone and Scholz; 1988, Reinecker and Lenhardt, 1999). Since most investigations and data in Austria were still based on macroseismic information, this paper deals with the practice of evaluation and its inherent inaccuracy, and presents a method for judging whether subjective biases might have influenced the interpretation of these data spatially.

The first part of this paper tries to judge the influence of the determined non-integer epicentral intensity on estimating the focal depth. Later, a computer program is used to simulate the observed focal-depth distributions of several regions by assuming a single seismogenic layer with a distinct seismic behaviour while taking account a possible bias of intensity assignments as well. Once the vertical extent of such a layer within a particular region can be ascertained, a maximum magnitude for that region can be estimated, assuming a strike-slip mechanism along a vertical dipping fault plane. The latter appears to be the prevailing mechanism in the Central and Eastern Alps (Pavoni, 1991; Aric et al., 1992; Reinecker and Lenhardt, 1999). Deviations from the simulation based on a single seismogenic layer are finally discussed.

2. METHOD

2.1 HISTORICAL APPROACH IN AUSTRIA

Focal depths constitute an essential parameter for interpreting the recent movements and mechanism taking place in the Alps (Reiter et al., 2005) and are the least accurate standard information, which can be derived from kinematic seismic data. Although the use of travel-times of recorded seismic waves has become the standard for focal depth determinations during the past years, it requires a very dense seismic network. This information is limited in Austria, since the seismic network is still too sparse to assess the focal depth with sufficient accuracy. Hence, only limited information is at hand enabling focal depth studies based on seismic travel-time data

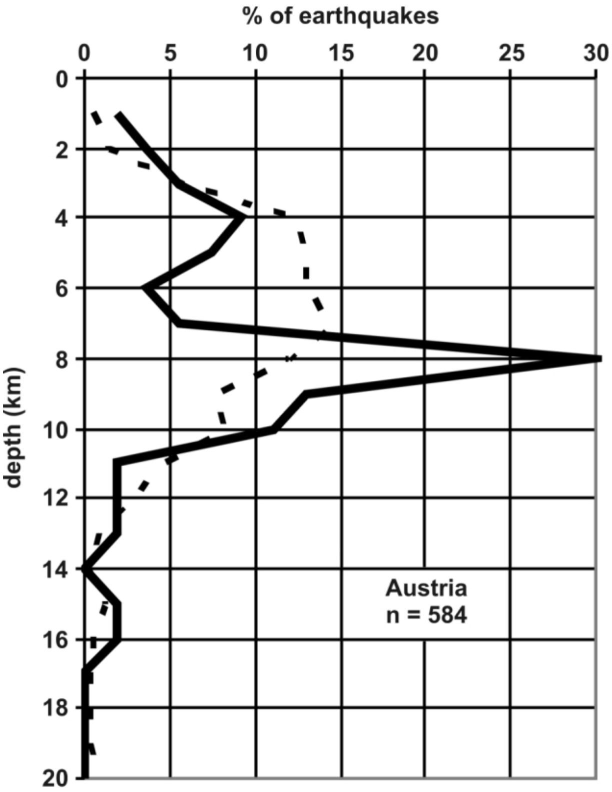

FIGURE 1: Focal distribution of Austria (1900-1992) based on 54 damaging earthquakes (intensity greater or equal degree 6, solid line). The dotted line indicates the focal depth distribution from the whole data set of 584 felt earthquakes.

alone, whereas a vast amount of consistent macroseismic data was gathered between 1900 and June 1992. Isoseismals were derived at that time by trying to encompass all sites from which reliable information was available to allocate a specific local intensity manually. After this time, focal depth were determined already with instrumental means with varying accuracy, which is still not enough to resolve focal depth down to 1 km until today. An accuracy around 1 km would call for a network with stations less than 30 km apart - similar to existing networks in Slovenia or Switzerland with comparable seismicity.

Only macroseismic data are dealt within this study. They were derived from the radii of isoseismals, whereby only isoseismals larger than intensity 3 were used. Intensities and 'macroseismic' magnitudes were calculated via a focal depth which was determined from the difference of isoseismal radii according to (Drimmel, 1980):

$$z_n = \frac{r_n}{\sqrt{10^{(I_0 - I_n)/2} - 1}} \tag{1}$$

with r_n being the average radius of the isoseismal of intensity I_n , whereby the epicentral intensity I_0 was adjusted simultaneously until a minimum in variation of I_0 and the focal depth z_n could be found. This approach resulted in non-integer intensities, which are later referred to as I_x. These were then grouped into four subgroups by Drimmel – quarter intensities (¼, ½, ¾) to preserve the information derived from the best fit to distance-dependent attenuation laws and instrumentally determined magnitudes. Finally, a 'macroseismic' magnitude

$$M = \frac{2}{3} I_0 + \frac{8}{3} \log(z) - 2.57 \tag{2}$$

was established (Drimmel, 1980) in order to match the magnitudes reported from abroad. This approach preserved the magnitudes of moderate earthquakes (3 < M < 5) pretty well within one decimal, when compared with published local magnitudes from abroad. However, the focal depths according to equation (1) turned out to be relatively deep, e.g. an earthquake associated with isoseismal-radii for I_5 = 16 km and I_4 = 39 km leads to an epicentral intensity I_0 of 6 and a magnitude M of 4.1 and a focal depth of 12 km. Using Sponheuer's (1960) relation in combination with Shebalin's (1958), Karnik's (1969) or Stromeyer et al.'s (2004) formulae, identical isoseismal radii result in a focal depth of 8 km only. Experience from deep mines has shown (Lenhardt, 1995), that Shebalin's relationship between magnitude and intensity matches observations from shallow events much better than Karnik's (1969) or Stromeyer et al.'s (2004) formulas (see Tab. 1), while magnitudes of earthquakes at a depth of 10 km are almost identical with those calculated with the formulas put forward by the other authors.

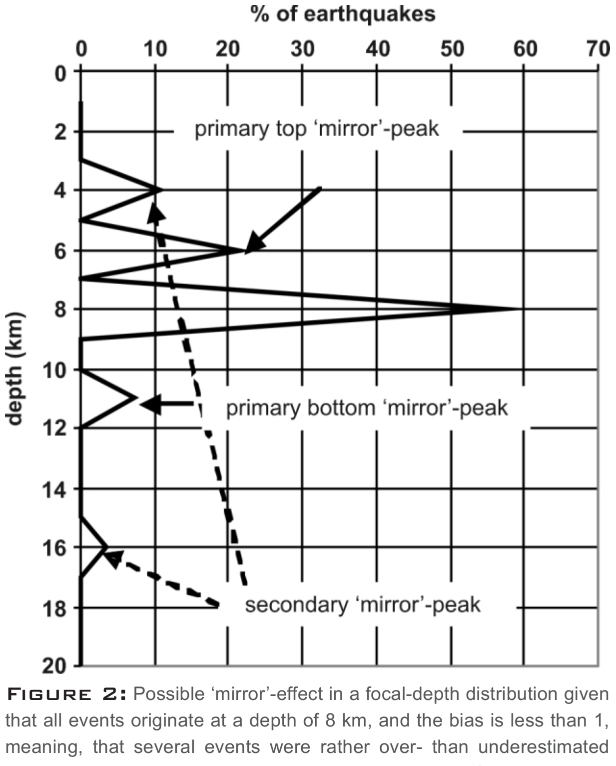

FIGURE 2: Possible 'mirror'-effect in a focal-depth distribution given that all events originate at a depth of 8 km, and the bias is less than 1, meaning, that several events were rather over- than underestimated in their epicentral intensity. The seismic activity ratio 'SAR' is ignored (SAR = 1.0, see text and Fig.3) in this context for clarity.

2.2 CURRENT APPROACH

Focal depths dealt within this paper are based on the relation between epicentral intensities according to EMS-98 and seismic event magnitudes *M* following Shebalin (1958)

$$M = \frac{2}{3} I_0 + \frac{7}{3} \log(z) - 2 \tag{3}$$

where z is the depth in km and I_0 is the epicentral intensity, derived from a best fit from Sponheuer's (1960) relation between epicentral and the intensity at a particular distance:

$$I_{local} = I_0 - 3 \log\left(\frac{R}{z}\right) - 1.3\alpha\,(R - z) \tag{4}$$

with α being the intensity attenuation factor usually ranging from 0.001 – 0.005, and R being the distance in km from the source. The average of α was determined by the authors and found to amount to 0.001 or even nil in Austria. Comparisons across a range of intensities from 4 to 8 and several focal depth assumptions show a good agreement between the magnitudes, the focal depth and epicentral intensities. Hence,

$M = a\, I_0 + b \log(z) + c$

Reference	a	b	c
Shebalin (1958)	0.66	2.33	-2.00
Karnik (1969)	0.50	1.00	0.35
Drimmel (1980)	0.66	2.67	-2.57
Stromeyer et a. (2004)	0.75	0.78	-0.87

TABLE 1: Some depth dependent magnitude-intensity relations. Depth 'z' in km.

only the epicentral intensities and magnitudes reported in the catalogue are used in this paper. The depths of earthquakes of the discussed regions in Austria are derived from formulae (3).

Replacing I_0 by a non-integer parameter I_x, one may parameterise equation (4) by seeking a best fit of the observed local intensities at several hypocentral distances R by altering the parameters I_x and z. This was the approach by Drimmel (pers. communication, 2007), and applied to all events dealt with in this paper. The value of I_x was finally rounded to the nearest quarter. Hence, a best-fit value of intensity I_x of 6.6 would be rounded to 6 ½ or 6.5 and an intensity of 6.8 would be rounded to 6 ¾ or 6.75. The epicentral intensity I_0 for expressing a scenario would be the integer value of I_x if I_x falls within ± 0.25 of an integer, or e.g. 6-7, if I_x falls within ± 0.25 of Int(I_x) + 0.5.

These non-integer epicentral intensities I_x - meaningless in terms of macroseismic assignments (see scale according to Grünthal, 1998) on one hand but extremely useful in preserving a representative data set of isoseismals and their respective radii in a condensed form otherwise - were used from the Austrian Earthquake Catalogue (ZAMG, 2007) throughout this study. The inaccuracy of the determined focal depth due to a possible erroneous - that is an over- or under-estimated - I_x-parameter will be discussed in the following paragraph.

2.3 Assessing Inaccuracies

The main factor contributing to an incorrect assignment of intensities is certainly the lack of information on earthquake effects, which applies to areas of low population density such as the Alps. Thus, a low population density should be reflected in a consistent under-estimation of the epicentral intensity and I_x-parameter, whereas over-estimations are less likely - if intensity assignments are carried out correctly. To judge this influence, we may rewrite equation (3) while replacing I_0 with I_x (extracted from ZAMG, 2007) to arrive at

$$\log(z) = \frac{6}{7} + \frac{3}{7}M - \frac{2}{7}\mathrm{I}_X \qquad (5)$$

For the purpose to illustrate the effect of slightly wrong I_x-parameter assignments, which should daylight as region dependent biases, we keep the magnitude constant, since the magnitude constitutes an objective measure of the released energy at the source, whereas the intensity is a subjective measure of effects on surface. Once equation (5) is differentiated, we find

$$d\log(z) = -\frac{2}{7}dI_X \quad \text{or} \quad z_{estimated} = z\,10^{\frac{2}{7}\Delta I_X}, \qquad (6)$$

$$\text{with} \quad \Delta I_X = I_X - I_{X_{\text{estimated}}}$$

It should be noted here, that relationships other than (3) alter the factor 2/7 in equations (5) and (6) accordingly. Recognising that this effect is governed solely by ΔI_x, we may now infer the influence of erroneous intensity assignments on final depth estimates. An under-estimation of one degree of the I_x-parameter (ΔI_x = +1) leads to an apparent focal depth $z_{\text{estimated}}$ which is almost twice as deep as the true focal depth z.

Another aspect reflects the difference in regional population densities in Austria and its topography. Considering a radius R of 5 km from a potential epicentre as a conservative upper limit from where no macroseismic information may be available in the entire Eastern Alps, Sponheuer's relation (equation (4)) would lead to a numerical under-estimation of I_x of 0.3 assuming a focal depth of 7 km. Such an under-estimation corresponds to an over-estimation of the focal depth of 22 % at maximum. However, non-integer I_x-parameters could be utilised which involve apparent accuracies down to quarters of epicentral-intensity degree (actually the I_x-parameter) assignments in the earthquake catalogue. Hence, the involved apparent inaccuracy according to equation (5) is likely to be in the order of 10 % of the true depth - or less than 1 km, and thus effects of over- and under-assignments on a regional scale (biases of the I_x-parameter) should be clearly resolvable.

In addition it should be noted, that equations (3), (4) and (5) relate the intensity at the surface to the magnitude via the focal depth. Normally, this fact does not need to be considered since surface elevations are much smaller than the focal depth resolutions. However, in areas of extremely undulating topography, such as the Alps, this effect may introduce unnecessary errors of recognisable dimension, - or result in apparent deeper sources. Hence, in this paper all focal depths refer to 'below surface', and are rounded finally to the nearest integer.

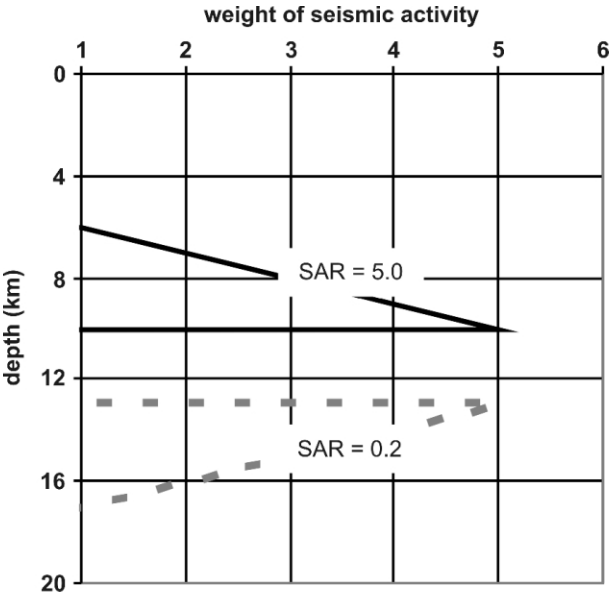

Figure 3: Definition of the Seismic Activity Ratio "SAR" for an enhanced model for a single seismic active layer ranging from 6 to 10 km and activity increasing with depth (SAR = 5.0), and for another layer extending from 13 to 17 km (SAR = 0.2) with activity decreasing with depth within the seismogenic layer.

2.4 SIMULATING APPARENT FOCAL-DEPTH DISTRIBUTIONS

As it can be seen in the focal distribution of whole Austria in Fig. 1, another peak appears alongside the most frequent focal depth of stronger events (solid line) that are equal or above an intensity degree of 6. Statistics over the whole data set, from which focal depths were determined, appear rather spread. This image raises the question, whether these other maxima (at higher intensities) and the spread (covering the whole data set) are genuine or artefacts. It will be shown later that the top peak in the focal-depth distribution of Austria is - to a large extent - indeed genuine due to locally concentrated shallower events, but is possibly enhanced by 'mirror'-effects from other regions.

As an example, we tried to simulate these peaks with a single seismogenic layer. Basically, we start with a model, and continue to alter the parameters until a best-fit to the observed data is achieved. The following paragraph describes this procedure in detail.

Macroseismic data with an over-estimation of 0.5 in the assigned I_x-parameter, especially at small epicentral intensities ranging from degree 3 to 4, lead to a focal depth, which is shallower by a factor of 1.4 according to equation (3) and introduce an apparent additional local maximum at a shallower depth in the focal-depth distribution. The opposite - an underestimation by 0.5 - results in an apparent focal depth which is 1.4 times deeper than the true focal depth. The same principle applies for wrong I_x-assignments of +1, -1 and so on. Hence, we may expect 'mirrored' images of focal-depth distributions at shallower and greater than the true depth, indicating systematic outliers due to slightly wrong intensity assignments and subsequent determined I_x-parameters. The example shown in Fig. 2 demonstrates this effect based on the assumption of a 1 km thick seismogenic layer at 8 km depth causing primary and secondary apparent peaks in the focal-depth distribution due to wrong intensity assignments. The two lower 'mirror-peaks' are smaller as a result of a bias of 1.5 introduced as follows: Each of the primary 'mirror'-peaks is initially given a weight of 0.125 (equalling 12.5 % of I_x-parameters are over- and 12.5 % are under-estimated by 0.5 units), secondary 'mirror'-peaks are given a weight of 0.0625. The amplitude of the top 'mirror'-peaks are multiplied by the bias-factor of 1.5, resulting in a contribution of 0.1875 for the primary top 'mirror'-peak, and 0.0938 for the secondary top 'mirror'-peak. The bottom 'mirror'-peaks have a weight of '2 - 1.5 = 0.5' leading to contributions due to primary and secondary bottom 'mirror'-peaks of 0.0625 and 0.0313, respectively. The value of '2' results from the following arbitrary definition:

- Bias = 0 = 1 - 1, means, the I_x-intensities are generally under-estimated, and all mirror peaks deeper than the actual true depth. This bias adds apparent deeper sources to the focal depth statistic.
- Bias = 1, means, that mirror peaks are equally weighted above an below the assumed true depth.
- Bias = 2 = 1 + 1, means, the I_x-intensities are generally over-estimated, and all mirror peaks are plotting above the actual true depth.

Finally, the frequency distribution in Fig. 2 is re-normalized to 100 %, thus trying to match the solid curve in Fig. 1. Although, the weighting appears to be arbitrary, the values serve only as

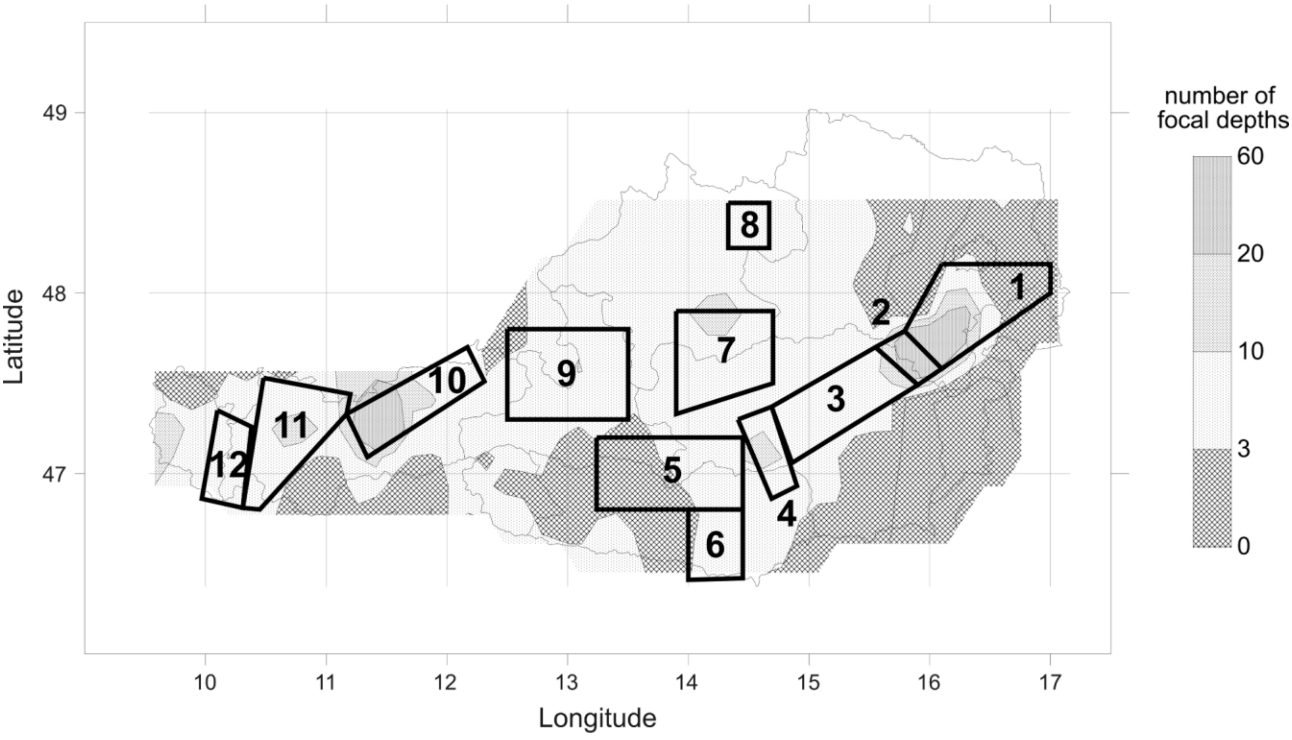

FIGURE 4: Data density - number of focal depths per bin - within discussed regions.

starting values for the following iteration process, which alters the weights according to biases (final weight = bias * original assigned weights; main peak = 0.625, two primary mirror peaks each 0.125 and two secondary mirror peaks each 0.0625, giving a sum of 1.0) and seismic activities in the proposed single layer in a loop, until the difference between the 'observed' focal depth distribution and the modelled distribution reaches a minimum.

As can be seen in Fig. 2, the mirror-effect not only causes a skewness in the focal-depth distribution, but might also lead to wrong estimates of the thickness of the seismogenic layer, which defines the depth-range within seismic events are assumed to originate (Scholz, 1990). Hence, areas with a tendency of more under-estimated than over-estimated I_x-parameters cause the mode of the focal distribution to be smaller than its average focal depth and the bias is less than 1.0. Over-estimations of I_x-parameters show the opposite effect: the mode is larger than the respective average focal depth and the bias exceeds 1.0.

To evaluate the influence of those mirrored foci on statistics of focal depths, a computer program was written to simulate various observed focal distributions. The program carries out an iteration process in which five parameters are continuously altered until a best fit with the observed focal distribution has been achieved. These parameters are:

1. the top of the seismogenic layer
2. contribution to the seismic activity of the top part of the layer
3. the bottom of the seismogenic layer
4. contribution to the seismic activity of the bottom part of the layer
5. a bias factor indicative for a region of systematic and spatially limited over- or under-estimations of the I_x-parameter

The following assumptions were made in the computer simulation:

All of the seismicity is assumed to originate within a single seismogenic layer. The seismic contribution may vary from the top to the bottom of the layer in a gradual way, however (Fig. 3). Each seismogenic layer is approximated by a subset of 1 km-thick layers with individual seismic activity contributions. This contribution may increase or decrease linearly from the top to the bottom of the seismogenic layer. A constant increasing number of events with depth within the seismogenic layer is indicated later by a 'seismic activity ratio'-value ('SAR') larger than 1.0, because we defined the SAR as the ratio of the number of seismic events originating at the bottom of the seismogenic layer divided by the number of those originating at the top of the seismogenic layer. This SAR -ratio is allowed to vary between 0.01 and 100 to simulate even extreme seismogenic layer properties.

In addition, the focal distributions were simulated, in which not only the 'mirror'-effect is accounted for, but also the bias - which is allowed to assume values between 0.0 and 2.0 - as a result of possibly incorrect data treatment typically for a single investigated region. The bias and the SAR may counteract each other, depending on the thickness of the modelled seismogenic layer defining the degrees of freedom for resolving the desired parameters and the scarcity of data. It will be tried to separate these two effects, however. It should be noted, that the 'SAR' does not reflect the released seismic energies but the frequency of events - as focal-depth distributions do. The weighting – as shown in Fig. 2 – is thus adjusted by the bias and the SAR in combination by matching observed and calculated distributions automatically.

After these influences have been judged, representative maximum magnitudes can be estimated from the available data for the discussed regions, too.

2.5 Estimating maximum magnitudes

Following Shebalin (1970) one may try to infer a maximum magnitude from the thickness of the seismogenic layer. The bottom of the seismogenic layer is also referred to as the transition from the schizosphere to the plastosphere where mylonitic fault material is altered to cataclastic material (Scholz, 1990). According to the above mentioned concepts, we may try to estimate the maximum magnitude from the thickness of the seismogenic layer which is somewhat less than the thickness of the schizosphere because fault material at the top of the schizosphere is filled with clay gauge which is unable to resist fault movement and hence incapable of storing strain energy and resisting shear movement. The thickness of the seismogenic layer, which can also be interpreted as the maximum down dip rupture width *w* in km along a vertical dipping strikeslip fault, has been found to correlate with the moment magnitude M_w (Wells and Coppersmith, 1994) according to:

$$M_w = 3.80 + 2.59\log(w) \qquad (7)$$

Equation (7) was derived from 87 pure and oblique strike slip events with moment magnitudes ranging from 4.8 to 8.1, predicting the magnitude ± 0.45 with a correlation coefficient of 0.84.

The distance '*w*' between the top and the bottom of the simulated layer of seismic activity can then be used for estima-

Bin-characteristics	Mean	Standard deviation	Minimum	Maximum
Number of focal depths per bin	9.02	9.48	3	61
Focal depth in km	6.86	2.10	1	15
Standard deviation of focal depth in km	2.65	1.30	0	7.4
Most frequent focal depth (mode) in km	5.56	2.40	1	11

Table 2: Bin-characteristics of focal depths in Austria (1900 - 1992) derived from 246 bins sized 10 km *10 km with at least three focal depth determinations per bin.

ting the maximum magnitude M_{max} from Eq. (7), assuming a vertical dipping strike-slip fault, such as in the Vienna Basin (Gangl, 73/74). Hence, a stated distance between the top and the bottom layer of a seismogenic layer in Tab. 3 of 4 km (+ 1 km for the inaccuracy due to the modelling-resolution in steps of 1 km) results in a maximum magnitude 'M_{max},' of 5.6 (e.g. region 11 – West Tyrol, Tab. 3). In oblique cases, a higher magnitude would be possible - even up to magnitude of + 0.4 more than stated in Tab. 3. No information about the dip of these discontinuities is currently available, however.

Using a relation between intensity and magnitude other than Shebalin (1958, see Tab. 1) leads to a widening of the respective seismogenic layer and thus to larger maximum magnitudes, again. However, we used Shebalin's formula in this paper for the reason given above.

3. Focal-depth distributions

3.1 General

Only seismic events, which were evaluated by macroseismic means, were used from the data set (ZAMG, 2007), covering a period from 1900 until June 1992, consisting of 1371 earthquakes in Austria, of which magnitudes were assigned to 585 events. Just one event (April 22, 1972, 'Tauern Window') of this data set was found in the catalogue with an apparent macroseismic focal depth of 21 km. This one weak event of intensity degree 4 was excluded from further investigations, since its depth was based on only two isoseismals. Because the epicentral area is very poorly populated, a proper I_x-parameter assignment with enough information for arriving at a focal depth could not be carried out.

The statistic of the remaining 584 earthquakes leads us to an average focal depth of 7.2 km below surface (Fig. 1). The standard deviation amounts to 3.1 km and the mode of the distribution at 7 km coincides almost with the mean focal depth, indicating a minor bias for the whole data set. However, selecting earthquakes with an of I_x-parameter larger than 6 from this data set - such as damaging events (see Grünthal, 1998) - we find a dominant peak at 8 km depth (see also Fig. 1). This peak could identify the average bottom of the seismogenic layer, where stronger earthquakes are suspected to originate (e.g. Sibson, 1982, Ohnaka, 1992, Mikumo, 1992). However, these results are averages which are dominated by data from several active seismic areas and do not permit further interpretations regarding typical regional differences.

When studying spatial differences of focal depths, the uneven spread of seismicity due to the varying tectonic setting within the Austrian territory must be considered. Scattered erratic information, which are not deemed to be representative, must be treated with care. Such data are excluded from further interpretations if less than three focal depths could be determined within a radius of 10 km from data points which are separated by 10 km, thus permitting an overlap of 10 km per bin (Tab. 2). These restrictions are necessary to allow for a compromise: gaining representative values on one side, thus permitting an insight into regional differences, and providing a relatively large coverage of focal depth information for the Eastern Alps in Austria.

When treating the characteristics of each bin on its own, the most frequent focal depth appears shallower than the average focal depth of the respective bin. The distribution also tends to be slightly skew in the sense, that the average depth is more than 1 km deeper than their respective mode. Hence, focal distributions from the Eastern Alps are slightly asymmetric and skewed towards greater depths.

3.2 Spatial differences between regions of pronounced seismic activity

The spatial extent of the selected regions have been chosen according to seismicity patterns – in spite of the fact that only little or no information on focal depths were available from some parts of Austria. Discussing the selected regions, we start in the East with the Vienna Basin, and proceed towards the Arlberg mountain range in the West of Austria, thus the numbering in Fig. 4 follows an E-W direction. All discussed regional focal-depth distributions are shown in Fig. 5.

In the Vienna Basin (region 1, Tab. 3, Fig. 4), the focal-depth distribution (Fig.5) is relatively symmetrical, hence the mode of the distribution almost equals the average focal depth. The first peak in the depth-distribution appears at 4 km. This shallow peak is deemed to be an effect of frequent over-estimations on the order of 0.5 of the I_x-parameter at the occasion of minor earthquakes resulting in too high I_x-parameters, for the mode appears at a depth which amounts to 1.4-times the depth of 4 km - at 7 km. It could very well be, that equation (3) may not be suited for the region of the Vienna Basin, since this area is dominated by 2-4 km of overlying tertiary sediments, which are capable of altering ground motions. This effect could apparently lead to shallower or deeper than true hypocentres when applying equation (3), and indeed the bias of 1.9 in this region (Tab. 3) indicates that many earthquakes have been assigned slightly elevated I_x-parameters. However, this phenomenon is also encountered in many other evaluated regions too, indicating the geology of the Vienna Basin is not as dominating regarding macroseismic effects as one might expect. An aftershock monitoring after the 'Ebreichsdorf'-earthquake from July 11, 2000 (s.a. Meurers et al., 2004) has shown, that all aftershocks recorded in the epicentral area by the On-Site Investigation Group of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) in Vienna were confined to depths between 6 and 10 km (Anonymus, 2002), - a depth-range which is also indicated in Fig. 5 - region 'Vienna Basin'. All aftershocks recorded within 2 km of the epicentre of the main shock showed distinct P- and S-wave onsets, the latter arriving between 2 - 2.2 seconds after the P ones. Hence, the presented focal depth estimates do not seem to be affected by the presence of the tertiary sediments of the Vienna Basin, and equations (3) and (4) seem to remain valid even within such a geological environment. In addition, four earthquakes were recorded with strong-motion instruments in Schwadorf near Vienna and Wiener Neustadt. All of these events showed almost vertical incidence of the P-wave at the recording stations and time differences (ts - tp) between S- and P-wave arrivals of 2 – 2.2 seconds (Tab. 4) again, almost identical to the aftershocks of the Ebreichsdorf earthquake, which occurred between Schwadorf and Wiener Neustadt. Thus, the focal depth of these events are likely to range from 6 to 10 km. This is the only region in Austria where such data are available from for reasons of comparison.

Irrespective of their frequency, the majority of earthquakes in the Vienna Basin tend to originate at depths similar to other regions as well, possibly due to the water saturated crust (Sibson, 1982). The top level of the seismogenic layer could be slightly more active than the bottom of the layer as indicated by the seismic activity ratio-value 'SAR' of less than 1.0 (Tab. 3) due to the abundant small seismic activity when compared with the few larger events, such as the 'Ebreichsdorf'-earthquake of July 11, 2000 in the Vienna Basin.

Progressing to the southwest and entering the region of 'Semmering' (region 2) no major differences in focal depths - when compared to the Vienna Basin - can be observed except for the fact, that the seismic activity concentrates at a depth of 7 km - which can be explained by the bottom of the presumed seismogenic layer. Simulating the distribution by introducing a single seismogenic layer ranging from 5 to 7 km depth and letting most seismic activity originate at the bottom level of this assumed layer at 7 km (SAR = 1.8, see Tab. 3) leads to an excellent fit and even matches secondary deeper peaks which may be attributed to the 'mirror'-effect.

The 'Mur-Mürztal' (region 3) shows a similar distribution, which can be simulated by a seismic activity originating mainly at the top of the layer between a depth from 7 to 10 km. The maximum magnitude derived from this width of a single seismogenic layer matches estimates from historical earthquakes as expressed in the earthquake catalogue (ZAMG, 2007). These focal depth characteristics can be followed right into the 'Obdacher Sattel' area (region 4), except for the fact, that the average focal depth seems to be 10% deeper than in the 'Vienna Basin', 'Semmering-' and 'Mur-Mürztal'. Secondary peaks are observed at 5 and 12 km's, which can possibly be attributed to the 'mirror'-effect due to few over- and under-estimations of the respective I_x-parameters.

Continuing westward, region 5 ('Katschberg') covers an area with very diffuse and presumably major historical seismicity (Hammerl, 1995). Not surprising, this region also exhibits the second largest standard deviation of all investigated areas (Tab. 3). Still, the mode of focal depth points to rather shallow events with depths around 5 km. The best match of simulating this distribution was found when using a very wide seismogenic layer extending from 4 down to 16 km. However, as it can be seen in Fig. 5, the match could be better. Only an additional deeper seismogenic layer would help to explain this special pattern of the focal depth distribution.

A similar pattern is encountered further to the south - in the 'Glan-Rosental' (region 6), which is orientated almost N-S (Fig. 4) - although most foci tend to concentrate at a rather shallow depth of 4 km. Here again, we may infer to observe the 'mirror-effect' at 6 km, but the pronounced peak at 13 km cannot be modelled successfully. A second thin layer - or seismic active horizon - would be necessary to match this pattern.

Nr.	Region	Number	Average (km)	Stand. dev.	Mode (km)	Top (km)	Bottom (km)	SAR	Bias	Bias* SAR	M_{max}[4]	M_{hist}
1	Vienna Basin	82	6.9	2.3	7	6	11	0.32	1.9	0.61	5.8	5.3
2	Semmering	61	6.8	2.2	7	5	7	1.80	1.0	1.80	5.0	5.3
3	Mur-Mürztal	33	7.2	3.0	7	7	10	0.04	1.3	0.05	5.4	5.4
4	Obdacher Sattel	20	7.7	2.3	7	5	9	1.81	0.5	0.91	5.6	5.1
5	Katschberg	32	7.8	3.5	5	4	16	0.45	2.0	0.90	(6.7)[2]	6[?]
6	Glan-Rosental	19	7.1	2.9	4	4	11	0.45	2.0	0.90	(6.1)[2]	4.6
7	Ennstal	28	7.9	3.3	6	7	14	0.16	1.5	0.24	(6.1)[2]	4.6[?]
8	Pregarten	12	2.3	1.1	2	1	3	1.13	0.5	0.57	(5.0)[1]	3.6
9	Hagengebirge	27	8.3	2.8	10	9[?]	10	3.62	2.0	7.24	(4.6)[1,2]	4.1
10	Inntal	95	7.1	2.9	6	5	12	0.08	1.3	0.10	6.1	5.2
11	W-Tyrol	47	7.7	3.2	8	5	9	0.90	0.7	0.63	(5.6)[2]	5.3
12	Arlberg	21	8.9[3]	4.1	7[3]	7[3]	12[3]	0.23	1.7	0.39	(5.8)[2]	4.3

[?] questionable

[1] extrapolated with equation (5)

[2] needs an additional second thin layer to match the focal depth distribution better

[3] subtract 1 km to take average surface elevation into account

[4] In case of an inclined strike slip fault – the resulting magnitude could be larger by approximately 0.4 magnitude units

Table 3: Focal depth characteristics of each region. The number in the first column refers to Fig. 4. The 'top' and 'bottom' refer to the depth of the best-fitting single seismogenic layer with an individual SAR (seismic activity ratio, see text). 'M_{max}' refers to the maximum magnitude derived from the vertical extent of the rupture zone according to Wells and Coppersmith (1994).

This would ultimately result in a much smaller maximum magnitude - 5.6 - than magnitude of 6.1, which is based on a single seismogenic layer with slightly decreasing seismic activity towards greater depth (SAR = 0.45).

Further north, near the provincial borders of Styria and Upper Austria, the 'Ennstal' (region 7) shows similar diffuse seismicity like the 'Katschberg'-region, but the difference between the mode and the average of its focal depth pattern is less pronounced. In addition, all three peaks can only be partially approximated by interpreting individual peaks as mirror-effects of seismic sources at the top of the seismogenic layer. The maximum magnitude could amount to 6.1 in this region. Up to now, there is no evidence of an earthquake of such magnitude ever striking this area. However, it could very well be, that such events tend to occur in geological rather than historical time. The evidence for an additional seismogenic layer at 16 km depth is weak, since only two events from the catalogue indicate this so far. Still, this part of Austria is also exposed to slightly deeper than general earthquakes, in particular near Gröbming in the 'Ennstal'.

Even further north, the region 8 ('Pregarten') - part of the Bohemian Massif - is known for the shallowest events in Austria. Focal depths vary between 1 and 4 km, peaking at 3 km. The maximum magnitude is therefore small, probably in the order of 5.0 according to equation (5). However, the latter equation was not derived from such shallow and weak events. Hence, the validity of the derived maximum magnitude is questionable in this case. A study on earthquakes in the Bohemian Massif has revealed so far (Lenhardt, 2004), that such events cannot even be substantiated by earthquake catalogues from the neighbouring countries.

The region with the deepest earthquakes appears to be a area starting at the 'Hagengebirge' (region 9), which borders to 'Berchtesgaden' in Germany, stretching across the 'Salzach'-river into the 'Tennengebirge' in Salzburg/ Austria. The seismic activity clearly concentrates at a depth of 10 km. Because the deep seismogenic layer is relatively thin, the magnitude 'M_{max}' would be relatively small. A second shallower peak at 5 km of depth cannot be explained as a mirror peak, however. This peak necessitates an even larger simulated local maximum at 7 km depth, which is not present in the data, indicating that the peak at 5 km depth might be genuine, and a second thin and shallow seismogenic layer would improve this match.

The 'Inntal' and its surrounding (region 10) is known for many historical earthquakes and represents one of the most seismic active regions - together with the 'Vienna Basin' and the 'Mur-Mürztal' - in Austria. Within this region, the most common focal depth lies around 6 km. The distribution is evenly spread and no secondary peaks are apparent. The shape of the distribution can be modelled best by a rather thick seismogenic layer ranging from 5 to 12 km of depth, with the majority of events (small magnitude-earthquakes) originating at the top of this layer. The region of the 'Inntal' shows the best match of all investigated regions between observed and simulated focal-depth distributions using a single seismogenic layer.

In the western part of Tyrol (region 11), the focal distribution shows two peaks again - one at 5 km and one at 8 km below surface. These two peaks cannot be attributed to a specific geological feature such as the 'Engadiner'-fault system alone, but appear throughout Western Tyrol and may be an indication, that the region was chosen to large. Subdividing this region into two or three smaller areas would have resulted into too small data sets for carrying out these statistics, however.

In region 12 ('Arlberg'), a very similar pattern emerges, with peaks - at 5 and 7 km below surface. The shallower peak lends itself to be interpreted again as a 'mirror'-effect, although it can be much better modelled using two layers again. The discrepancy between the largest known magnitude and the simulated ones between W-Tyrol and Arlberg (Tab. 3) indicates, that the largest potential earthquake in the Arlberg region is either not known or did not happen since the 13th century - the time, the earthquake catalogue covers - or Eq.(7) should not be applied to earthquakes in the Eastern Alps in general.

When interpreting geomechanically the slightly deeper hypocentres at 7 km depth, the average elevation of villages in the region of 'Arlberg' between 1000 and 1500 m above sea level should be considered, since all stated focal depths refer always to the average elevation above sea level of the particular region, where the effects of the earthquakes were reported from. In the other discussed regions of Austria, this effect does not need to be considered. Hence, the statistic in the "Arlberg"-region should actually refer to depths of 1 km less than stated in Tab. 3. Hence the seismogenic layer would range from a depth of 6 to 11 km below sea-level.

3.3 SEISMIC ACTIVITY RATIO VERSUS BIAS

In Tab. 3 biases other than 1.0 are given. Extreme biases with values = 1.5 were found in the regions of the 'Vienna Basin', 'Katschberg', 'Glan-Rosental', 'Hagengebirge' and 'Arlberg'. All other regions exhibited almost no bias. Highest SAR-values were found, however, in the regions 'Semmering', 'Obdacher Sattel' and the 'Hagengebirge'. All these regions are poorly populated. Looking at Tab. 3, one notices - with one exemption (the 'Hagengebirge', where the seismogenic layer seems to be only 1-2 km thick) - whenever the bias is larger than 1.0, the SAR is lower than 1.0 and vice versa, possibly indicating that the determined biases cannot be separated from the SAR-values and consequently, the depth-dependent contribution from within a seismogenic layers cannot be determined and both parameters tend to compensate each other. Still, the assumption of a single seismogenic layer - including a minor 'mirror'-effect – serves the purpose to model the observed focal-depth distributions in many cases. In six out of twelve regions, the focal-depth distributions could be successfully modelled with a single layer. The other six regions require an additional thin seismogenic layer to match the observed focal-depth distributions. The authors refrained from modelling this second layer, because the second layer appears to be always very thin, and it is obvious, that an

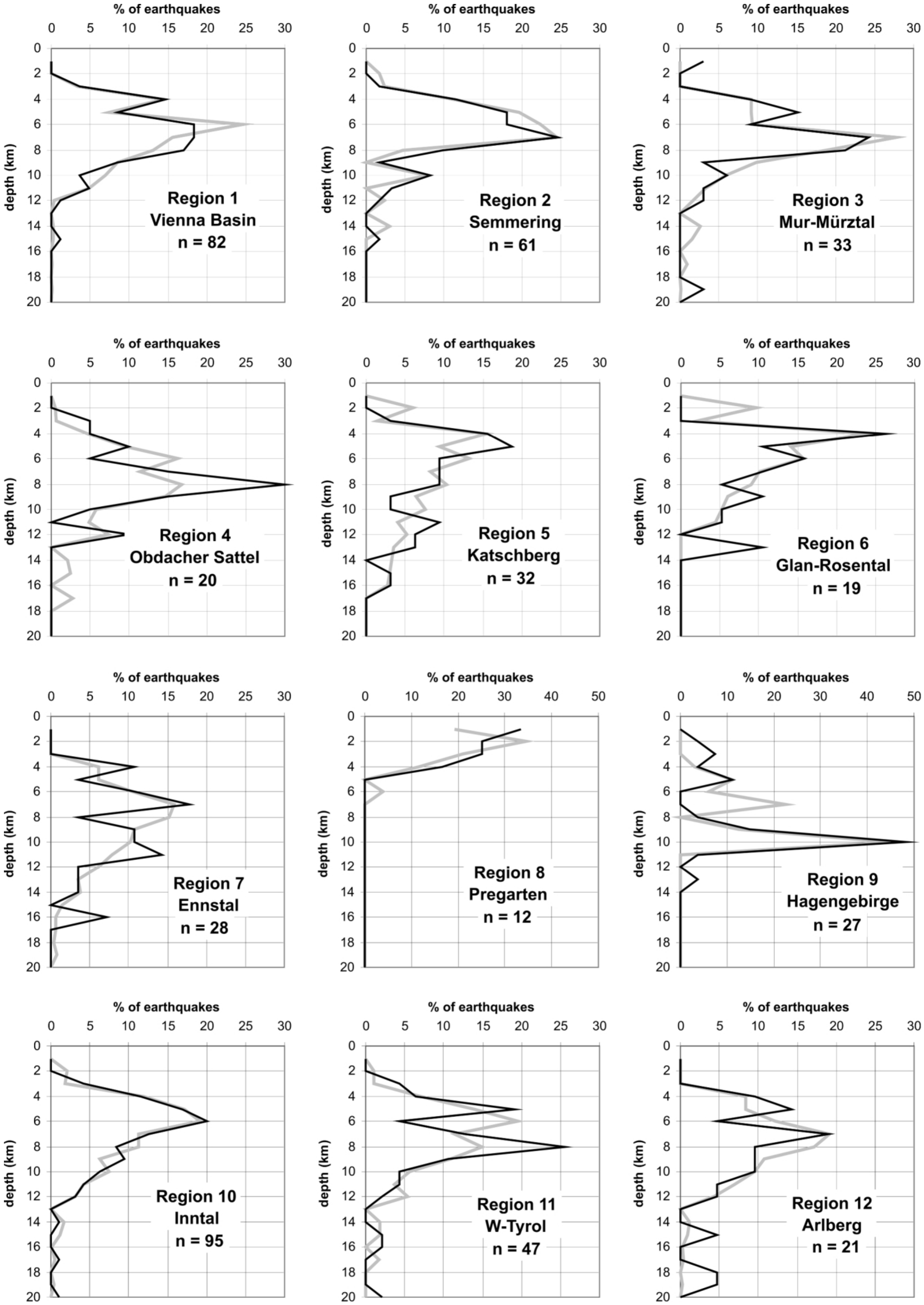

Figure 5: Regional focal depths distributions (percentages of earthquakes per 1 km depth-interval, black = from catalogue, grey = simulated with single seismogenic layer and 'mirror'-effects).

Date	Time (UTC)	M	Io (EMS-98)	ts - tp (s)	Epicentre
10.05.1997	19:29	3.4	5	2.0	Schwadorf
11.03.1997	21:44	2.6	4	2.2	Wiener Neustadt
11.03.1997	23:17	2.6	4	2.2	Wiener Neustadt
24.11.1997	08:48	2.6	4	2.1	Wiener Neustadt

Table 4: Minor earthquakes in the Vienna Basin with almost vertical P-wave incidence and similar 'ts-tp' time difference as recorded with strong-motion stations. Epicentral distance < 2 km.

improvement of the match can be achieved without gaining more information. The two additional parameters of bias and SAR resulting from the modelling of this second thin layer would be of no significance, especially if one considers, that the product of the two parameters appear to counteract each other and the useable data set is always rather small.

4. Discussion

4.1 The mirror-effect

While calculating the statistics, it became apparent that some focal-depth distributions showed distinct secondary peaks. These distributions were investigated of being artificial effects of few over- or under-estimated epicentral intensities and subsequent I_x-parameters resulting in 'mirror'-images. These are additional peaks that show up below and above the seismogenic layer in the respective focal-depth distribution.

What has been coined here as the 'mirror-effect' is subjected to a general bias symptomatic for poorly populated areas (leading to apparent shallower hypocentres due to over-estimated 'reconstructed' intensities), and to the seismic behaviour of the supposed 'single' seismogenic layer (leading to both, too deep and too shallow hypocentres) with inherent seismic activity properties ('SAR'). Both these effects alter the weight by means of the bias-factor of the primary and secondary artificial peaks in the simulated focal-depth distributions. Separating these two parameters suggests, that they counteract each other. In most cases, the product of the bias and the SAR (Tab. 3) appears to vary only little, suggesting the two parameters cannot be resolved. Nevertheless, the concept of the 'mirror'-effect allows to reduce the scatter of focal distributions, thus determining the thickness of the seismogenic layer in a specific region. The only dramatic exemption appears to be the region of the 'Hagengebirge' with a bias*SAR value of 7.2, indicating a complete different behaviour, and possibly asking for a distinct separation of two thin seismogenic layers. The most active layer appears at a depth of 10 km and a bias indicates an underestimation of epicentral intensities due to a poor macroseismic coverage, possibly substantiated by lack of information from the Bavarian side. In contrast, low values (< 0.3) were found in valleys: 'Mur-Mürztal' (0.05), 'Ennstal' (0.24) ,'Inntal' (0.10). Hence, dense populated areas - mainly in valleys - exhibit rather low bias*SAR values, whereas poor populated areas show up with rather high values, respectively. This effect could be explained by seismic activity concentrated pretty deep at the bottom of their respective seismogenic layers.

4.2 Interpretation

In general, focal-depth distributions of half of the twelve discussed regions could successfully be modelled with a single seismic layer, within which the seismic activity varies only little, although some regional differences are apparent. Most focal depths concentrate between 6 and 8 km, thus placing most hypocentres at the top or within the crystalline basement. 'Deeper' hypocentres – around 10 km - seem to occur mainly in the western and southern parts of Austria. In addition, the depth range at which most earthquakes tend to occur in the Eastern Alps can be explained by concepts put forward by e.g. Sibson (1982) or Meissner and Strehlau (1982) considering a strain rate of 10^{-14} s^{-1} and a geothermal gradient of 30°C/km in saturated crust. The match between calculated maximum magnitudes based on the width of a single seismogenic layer and estimates from historical records are similar in many regions discussed, suggests that some regions - like the 'Vienna Basin', 'Mur-Mürztal' and 'Semmering'-region - were already exposed to their 'maximum' earthquake in historical times, assuming a vertical dipping strike-slip fault. The largest discrepancy between estimated and calculated magnitudes can be found in the 'Inntal', where a magnitude of 5.2 was estimated from historical earthquakes and a magnitude of 6.1 is found when modelling the pattern of the focal-depth distribution.

The match of simulated and observed data sets in the regions of 'Katschberg', 'Glan-Rosental', 'Ennstal', 'West-Tyrol' and 'Arlberg' and the 'Hagengebirge' can be improved by adding a second thin (1 km) seismogenic layer. Thermomechanical considerations of the earth's crust can explain this phenomenon of two layers of seismic activity (e.g. Cloetingh and Burov, 1996). Especially in regions with elevated heat flow in excess of 80 mW/m^2, one finds two strength-peaks matching the observed frequency-peaks of the focal-depth distribution in the region of 'Glan-Rosental' (Nemes et al., 1997) when assuming a dry crust environment. Following this idea, one notices that almost all regions with focal-depth distributions, which can only partly be explained by a single layer and inherent 'mirror'-effects, were found in Austria in areas of elevated heat flow (see also Haenel and Zoth, 1973). This area encompasses all regions west of the 'Mürztal'. Two exemptions prevail: the 'Inntal' and the 'Hagengebirge'. The latter region, where earthquakes seem to originate rather deep (10 km), shows no density contrast (Granser, et al., 1989) when compared with the rest of Austria, - but interestingly enough, coincides with the magnetic anomaly of 'Berchtesgaden' (Bleil and Pohl, 1976, Blaumoser, 1992). Future focal mechanisms - derived from an increasingly dense seismic network in collaboration with neighbouring countries - of seismic events in this region will certainly shed more light on the mechanism involved. The focal-depth distribution of the 'Inntal' to the east of Innsbruck, however, can perfectly be modelled again with a single layer, but this time a 'wet crust' environment in terms of a corresponding thermomechanical model in an area of slightly elevated heat flow (Nemes et al., 1997) is needed.

As to whether thermomechanical models are the key to explain the focal depth patterns in the Alps remains open for discussion. On the other hand, when comparing those parts of the Alps, where the seismogenic layer either extends deeper than average into the crust - or a second seismogenic layer improves the match of depth-patterns - leads to an anticorrelation with heat flow maps. According to the data, those parts with highest heat flows exhibit the deepest seismogenic layers and not the shallowest, as thermomechanical models would suggest, because the depth at which brittle failure turns into ductile deformation should be less deep. In addition, it has been suggested (Ohnaka, 1992) that earthquakes in crustal regimes of moderate heat flow are mainly stress-driven down to a critical depth of say 10 km, and below their failure mechanism is dominated by the prevailing temperature. It could well be that both criteria apply, one explaining the shallower stress driven seismogenic layer, and one explaining the deeper temperature-driven seismogenic horizon, as in the case of central and western part of the Eastern Alps with the exemption of the Inntal-Valley.

5. CONCLUSIONS

The evaluation of macroseismic data from the period between 1900 and mid-1992 initiated the development of a method which allowed to estimate the extent of seismogenic layers from several regions in Austria. The seismic network existing during this time-span cannot be considered a network as we know it today, but rather as an indicator that an earthquake has happened. In conjunction with abundant macroseismic data it was possible to determine the epicentre more accurate than the evaluation of seismograms of seismic stations could do, since there were too few seismic stations available. Making use of these macroseismic data is the only mean to gain more information about focal depths from this data set even now. Though, the station density has improved a lot since then, a resolution of focal depth down to 1 km with an average spacing of stations of 50 km is and remains not realistic, unless more stations are installed in Austria. Only at one occasion additional instruments and personnel were available, when the CTBTO (Comprehensive Test Ban Treaty Organization) deployed instruments and personnel for monitoring aftershocks of the Ebreichsdorf-earthquake in 2000 (Anonymus, 2000) under the guidance of the ZAMG. This occasion helped to proof instrumentally the focal depth of aftershocks of the July 11, 2000 earthquake in Austria near Ebreichsdorf.

Being well aware on how inaccurate macroseismic data can be, we tried to separate the following influences:

1. biases introduced by the interpreter, due to spatial erratic deviations from actual depths, because the analyst tried to adjust the macroseismic pattern according to surplus or lack of population density
2. a possible contribution of a seismogenic layer in terms of increasing or decreasing seismic activity with depth and its upper and lower bounds.

Both factors were inverted in the same process. The data revealed, that such a separation is somewhat cumbersome, indicating erratic small wrong intensity assignments. Including these deviations, matches between simulated and observed focal depth distributions were generally pretty good, being an indication, that erratic deviations from true macroseismic intensities can be treated in a proper manner by introducing - what was coined here as - the 'mirror-effect' concept, meaning that a certain part of observations were subject of erratically slightly over- or underestimations.

Spatial differences in focal depth distributions became evident when applying this approach on data spanning more than 90 years. Mainly areas in the southern and western part of the Eastern Alps in Austria appear to be subjected to earthquakes which originate either slightly deeper than the rest in Austria, or indicate the existence of two seismogenic layers in the upper crust. The latter earthquakes could be a result of the high compression of the Alpine body leading to subductions from the North and the South and to a complex stress regime, favouring sometimes horizontal or inclined discontinuities still belonging to the brittle crust. These events take place mainly at a depth between 6 and 8 km. Exemptions are to be found in the Bohemian Massif, where the seismic activity concentrates much shallower - at 3 km, and in the 'Hagengebirge' in Salzburg with depths reaching 10 km. In general, it appears, that most of the seismic activity is concentrated at a depth of 7 km, and larger earthquakes have a tendency to originate rather at the bottom of a seismogenic layer - that is 8 - 10 km - than at their top.

Today, this problem is persistent, despite the installation of additional seismic stations. An exact determination of the focal depth - enabling a clear association with geological units and discontinuities detected by geophysical means - requires stations placed at distances less than 20 km from each other, - hence much more stations are required in Austria. Slovenia and Switzerland have already established a network meeting these requirements. One way to mitigate this problem in Austria is the introduction of a 3D-crustal model into the location algorithm, which is currently being developed. Nevertheless, more seismic stations must be installed in Austria to enable locations down to an accuracy of less than 1 km which are not only of geological but of national interest to ascertain a proper knowledge of the seismic hazard and potential economic loss in Austria in case of an earthquake.

We would like to encourage everyone to report observations made during an earthquake to www.zamg.ac.at/bebenmeldung (in German only) to help us to improve the assessment of local effects and facilitate prompt evaluations.

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