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Induced seismicity related to geothermal projects versus natural tectonic earthquakes and other types of induced seismic events in Central Europe

Gottfried Grünthal

Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Section "Seismic Hazard and Stress Field", Telegrafenberg, D-14473 Potsdam

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ABSTRACT

Induced seismicity related to fluid injection in geothermal systems has gained an increased public awareness particularly in Central Europe. The paper discusses occurrence of induced seismic events at sites of geothermal projects in comparison to natural tectonic earthquakes and other types of induced or triggered seismicity in Central Europe (i.e. in Germany and adjacent areas). Other types of induced events are those in areas of mining or exploitation of coal, salt and potash, hydrocarbon and ores. Furthermore, induced seismicity in connection with water reservoirs and intense precipitation in areas of karst geology is also discussed. The subject of this study is the induced seismicity of a data set of moment magnitudes $M_w \geq 2.0$, while the distinct larger natural seismicity is displayed for $M_w \geq 2.5$. Parameters of the strongest seismic events of all studied sources of seismicity are listed, presented in epicentre maps, and discussed with respect to their maximum observed magnitudes and their frequency-magnitude distributions. Macroseismic intensities of strongest seismic events at geothermal project sites are compared to data of an intensity based probabilistic seismic hazard map for Germany. The general conclusion is that observed induced seismicity at geothermal sites is minor in comparison to other sources of seismicity.

1. Introduction

Perceptions of seismic shakings in connection with human underground activities, often largely distributed in news media, have recently gained great attention. These activities with a potential to generate induced seismicity encompass mining, exploitation of hydrocarbons and geothermal energy, subsurface injection of fluid, reservoir impoundments and carbon dioxide sequestration. Induced seismicity in connection with shale gas production is another controversially discussed subject, e.g. in the UK or in the US. Since this type of seismicity is so far not specified in Central Europe, it is not considered here.

This study does not differentiate between induced and triggered seismic events. The differentiation into induced and triggered events is only possible when the man-made contribution to the tectonic stress field can be quantified. According to *McGarr and Simpson* (1997) induced events are those, where man-made stress changes account for most of the stress perturbation and triggered events are those where the man-made stress changes are minor. Since it is rarely possible to reliably quantify the human-related stress changes, the classification into induced or triggered is not applied. In general the term induced is used here.

The public perception of induced seismicity compared with natural, tectonic earthquakes is accompanied with the primal fear of earthquakes, which cannot be predicted or forecasted like storms or floods. Induced seismicity in old existing mining areas of coal and salt belong to the accepted side effects of mining activities, with which the population is used to live with often for more than hundred years. A new phenomenon is induced seismicity in conjunction with projects of exploitation of geothermal resources. The macroseismic effects of these induced events, although very minor with respect to damage and of minor magnitude ($M < 3.5$) (in seismology, after Wiki/Richter-magnitude-scale, magnitudes in the range 2.0-3.9 are classified as minor), can be felt as many geothermal projects are located in close proximity to communities for the optimal use of geothermal energy for heating. Despite of these (in seismological terms) minor magnitudes they can be of economic concern as the example of the M_w 3.2 seismic event in 2006 in Basel (*Deichmann and Giardini*, 2009) or the M_w 2.6 event 2009 in Landau i. d. Pfalz (*Expert Team*, 2010). In the geothermal community such events, respectively those which are the largest at a geothermal site, are called in *Shapiro et al.* (2011) "large-magnitude events" (or large-magnitude earthquakes, LME for both). Originally, this term was introduced in the project proposal GEISER (http://www.geiser-fp7.eu/ReferenceDocuments/Pages/ReferenceDocuments.aspx). To avoid conflicts with the terms introduced in seismology to classify the strength of earthquakes the author suggests to replacing the term LME by "Seismic events of economic concern" (SEECo). Subject of recent geothermics research is to keep the SEECo occurrence rate due to man-made stress changes within acceptable limits.

Recently, several reviews on different types of man-induced seismicity have been published. A global overview on moderate-to-large seismicity induced by hydrocarbon production is given by *Suckale* (2010). Several cases of induced seismicity from geothermal projects around the world are discussed in *Majer et al.* (2007). A survey of induced seismic

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Tel.: +49 331 288 1120; fax: +49 331 288 1127.
E-mail address: ggrue@gfz-potsdam.de

events due to fluid injections in geothermal and CO_2 sequestration reservoirs in Europe has recently been published by *Evans et al.* (2012). *Grünthal and Minkley* (2005) provide an overview on non-tectonic seismic events in Germany in general, and focused on the maximum observed seismic effects of induced events in potash mining areas and the potential of future events. *Dahm et al.* (2010) discuss an epicentre map of selected significant induced or triggered events ($M > 3$, M unspecified) in Germany and immediate surroundings. Weak events with $M < 3$, as they are typical in areas of geothermal projects in France and in Germany, are therefore not considered in their study.

In contrast to previous studies this paper provides a comprehensive overview of all sources of seismicity; i.e. of induced seismic events of all relevant types, including those related to geothermal projects in comparison to natural tectonic earthquakes; i.e. it provides a review of observational facts. The study area covers western Central Europe; i.e. the area of Germany including Luxembourg and adjacent parts of Poland, Czech Republic, Austria, Switzerland, France, Belgium, and The Netherlands. The seven types of induced seismic events considered here are, apart from (1) geothermal related seismicity, induced events in areas of mining or exploitation of (2) coal, (3) rock salt and potash, (4) hydrocarbons and (5) ores. The comparisons between these types and tectonic earthquakes are discussed quantitatively in chronological order and with frequencies of the occurrences of the number of events within certain magnitude classes, henceforth called frequency-magnitude distributions. Induced seismicity related to (6) water reservoirs and (7) heavy rain fall in areas of karst geology is also considered but only discussed qualitatively; i.e. with their areal distribution in form of epicentre maps. Additionally, tables of the strongest events of all considered seismicity types are given here. Furthermore, a ranking of the maximum observed magnitudes of all seismicity types is presented as well as discussion of macroseismic intensities of the largest events related to geothermal projects and their comparison to intensity based probabilistic seismic hazard maps. Such comparative analysis may shed better light on the significance of different types of induced seismicity in relation to natural tectonic seismicity.

The terminology of this paper follows the nomenclature recommended by the International Association on Seismology and Physics of the Earth's Interior (IASPEI) and after *Bormann* (2002). This terminology differentiates between natural tectonic earthquakes and induced seismic events, which has also been adopted by the European Mediterranean Seismological Centre, EMSC (*Godey et al.*, 2009). The differentiation into these two classes might contribute to the increase of acceptance of underground man-made activities, which can cause induced seismicity. The human fear of earthquakes is caused by the facts that (1) they do not signalize their upcoming occurrence (apart of sometimes occurring as a precursory activity before large earthquakes, but hardly in the study area), that (2) they cannot be predicted and that (3) tectonic earthquakes have potential for causing severe damage. In contrast, induced seismic events can well be localized and the timing can be limited with high probability to human actions. The increasing knowledge of the physical processes will be used more and more to delimit their magnitudes.

Not included in this study are subsurface collapses and seismicity related to tunnel construction and underground civic works. Natural subsurface collapses and sink-holes, occasionally accompanied with seismic shakings, can occur within the study area. Historically, this category includes the collapses of huge underground cavities as a result of the extensive silver mining in the Erzgebirge (Ore Mountains) or collapses of dissolved cap rocks of salt domes. Such cap rock collapses have substantially enlarged the lake Arendsee in northern Germany in AD 811. The largest of these two types of collapse events are compiled in *Grünthal* (1988). The seismic events recorded near Faido (Tessin, Switzerland) in connection with the construction of the new St. Gotthard railway tunnel in 2006 (*Baer et al.*, 2007; *Hagedorn et al.*, 2008; *Deichmann*, 2011; *Husen et al.*, 2012) are very isolated phenomena with a maximum recorded $M_L = 2.4$ and not considered in this study.

This paper describes the data sources and the discrimination principles to differentiate between tectonic and induced seismicity in Section 2. Section 3 follows with a brief description of all types of seismicity compared in this study with respect to their areal and temporal occurrence. A further comparison is performed with respect to frequency-magnitude relations and maximum observed magnitudes of seismicity types (Section 4). Finally, the macroseismic intensities of the largest seismic events at geothermal project sites are discussed and related to the seismic zones of the German seismic building code (Section 5).

2. Data sources and discrimination of induced seismic events and natural tectonic earthquakes

The data set of induced events, which is subject of this study, is basically a by-product of the central, northern and north-western European earthquake catalogue CENEC (*Grünthal et al.*, 2009a) and its temporal and areal extension; i.e. the European-Mediterranean earthquake catalogue EMEC (*Grünthal and Wahlström*, 2012). In the framework of these catalogues the measure of strength of tectonic earthquakes and induced seismic events in the underlying database are calibrated in terms of harmonized moment magnitudes M_w. Both catalogues describe the procedures to derive these harmonized M_w in great detail. Consequently, the induced seismic events as part of the database behind these earthquake catalogues are given in M_w as well. Most of the induced seismic events of this study are originally provided with their local magnitude M_L. The conversion to M_w was performed with the well-established conversion relation derived for the study area according to 221 data points (*Grünthal et al.*, 2009a):

$$M_w = 0.0376M_L^2 + 0.646M_L + 0.53 \qquad \sigma = 0.2 \ldots 0.34, \qquad (1)$$

where σ denotes the magnitude dependent standard deviation. This 68% confidence interval for calculated M_w depends on the standard regression error and the corresponding regression covariances. It reaches minimum values at about M 2-4 (for more details of the error equation see Annex 4 in *Grünthal et al.* (2009a)). It is assumed that this relation is applicable to induced seismicity as well. The coda magnitudes of the Soultz-sous-Forêts events are, although according to *Dorbath et al.* (2009) calibrated in a way that they should correspond to moment magnitudes M_w, are used with lower priority than M_L, which are available for the here mentioned Soultz-sous-Forêts events by other sources as well (cf. Table 1).

Most domestic catalogues, which are the basis of the seismicity database used here, generally denote non-tectonic events as such, but usually do not specify the type of event. Mining areas which produce induced seismic events are generally known in the seismological community. For the discrimination of natural tectonic earthquakes and induced seismic events the mining areas were delineated with polygon traces. Numerous compilations exist which describe the areal extend of mining districts; among these is *Pasternak* (2009) or a summary by the Lower Saxonian State Office for Mining, Ener-

Table 1
The strongest induced seismic events at sites of geothermal projects with $M_w \geq 2.3$ in the study area.

Date				**Location**					M_w	**Reference** as given in the EMEC database[a]
Year	Month	Day	Hour	Latitude	Longitude	Place, site, or district; country code		Depth		
2003	5	29	4	48.93	7.87	Soultz-sous-Forêts	F	4.7	2.3	*Horálek et al.* (2010)
2003	6	1	19	48.93	7.87	Soultz-sous-Forêts	F	4.7	2.3	*Horálek et al.* (2010)
2003	6	2	21	48.93	7.87	Soultz-sous-Forêts	F	4.9	2.4	*Horálek et al.* (2010)
2003	6	6	2	48.93	7.87	Soultz-sous-Forêts	F	4.2	2.3	*Horálek et al.* (2010)
2003	6	9	15	48.93	7.87	Soultz-sous-Forêts	F	5.2	2.3	*Horálek et al.* (2010)
2003	6	10	19	48.93	7.87	Soultz-sous-Forêts	F	4.4	2.3	*Horálek et al.* (2010)
2003	6	10	22	48.93	7.87	Soultz-sous-Forêts	F	4.4	2.7	*Horálek et al.* (2010)
2003	6	11	15	48.93	7.87	Soultz-sous-Forêts	F	4.6	2.6	*Horálek et al.* (2010)
2003	6	12	1	48.93	7.87	Soultz-sous-Forêts	F	4.2	2.6	*Horálek et al.* (2010)
2003	7	24	5	48.93	7.87	Soultz-sous-Forêts	F	5	2.4	SZGRF[b]
2005	2	10	2	48.93	7.87	Soultz-sous-Forêts	F	2	2.6	SZGRF[b]
2005	2	11	7	48.93	7.87	Soultz-sous-Forêts	F	2	2.3	SZGRF[b]
2005	2	15	12	48.93	7.87	Soultz-sous-Forêts	F	2	2.3	SZGRF[b]
2006	12	6	22	47.58	7.60	Basel	CH	5	2.3	ECOS-09[c]
2006	12	8	3	47.58	7.60	Basel	CH	5	2.6	ECOS-09[c]
2006	12	8	3	47.58	7.60	Basel	CH	5	2.4	ECOS-09[c]
2006	12	8	11	47.58	7.60	Basel	CH	5	2.3	ECOS-09[c]
2006	12	8	9	47.58	7.60	Basel	CH	5	2.3	ECOS-09[c]
2006	12	8	15	47.58	7.60	Basel	CH	5	2.6	ECOS-09[c]
2006	12	8	16	47.58	7.60	Basel	CH	5	3.2	ECOS-09[c]
2006	12	8	19	47.58	7.60	Basel	CH	5	2.4	ECOS-09[c]
2006	12	8	20	47.58	7.60	Basel	CH	5	2.5	ECOS-09[c]
2006	12	14	22	47.58	7.60	Basel	CH	5	2.5	ECOS-09[c]
2007	1	6	7	47.58	7.60	Basel	CH	5	2.9	ECOS-09[c]
2007	1	12	3	47.58	7.60	Basel	CH	5	2.3	ECOS-09[c]
2007	1	16	0	47.58	7.60	Basel	CH	5	3.0	ECOS-09[c]
2007	2	2	3	47.58	7.60	Basel	CH	5	3.0	ECOS-09[c]
2007	3	21	16	47.58	7.60	Basel	CH	4	2.7	ECOS-09[c]
2007	5	6	0	47.58	7.60	Basel	CH	4	2.4	ECOS-09[c]
2008	7	3	20	48.05	11.65	Unterhaching	D	5	2.4	*EDB* (2010)
2009	8	15	12	49.19	8.12	Landau i. d. Pfalz	D	2.8	2.6	*Expert Team* (2010)
2009	9	14	18	49.19	8.12	Landau i. d. Pfalz	D	5	2.3	*LBEG* (2010)
2010	4	9	10	49.15	8.15	Insheim	D	5	2.3	*LBEG* (2010)

[a] *Grünthal and Wahlström* (2012)
[b] SZGRF: *SZGRF* (2010)
[c] ECOS-09: *Fäh et al.* (2011)

gy and Geology (*LBEG)* (2010). Combining information on the start of mining activity and focal depths, the induced seismic events can be classified. The majority of the here studied induced seismic activity occurs in areas that are almost quiet with respect to natural seismicity, which strongly simplifies the discrimination. The applied approach follows the basic criteria to assess the probability that an earthquake was induced/triggered as introduced by *Davies et al.* (1995) (modified by *Dahm et al.*, 2010):

- The first known event of given character in the region.
- Occurrence of events only after human operation/mining had commenced.
- Correlation between operation/mining and seismicity.
- Epicentres within a specified distance from the mining area.

Further recommendations for the discrimination are given by *Dahm et al.* (2013).

References for the induced seismicity used in this study are given in Table 1. It summarises the parameters of the strongest seismic events of the different types of man-made activities (for details see Section 3).

However, discrepancies may exist in the interpretation whether a seismic event is natural or induced/triggered. For example, this was the case for the gas related M_w 4.4 Rotenburg event in northern Germany in 2004 (cf. Table 1e) with overwhelming proof that this event was not natural (*Dahm et al.*, 2007). Moreover, *Dahm et al.* (2007) concluded that the 1977 $M_w = 4$ Soltau event (northern Germany; cf. Table 2d) was also related to gas production. *Dahm et al.* (2007) refer to *Pasternak et al.* (2004) that in 1975 the testing phase of the gas production started close to the hypocentre of this event. After two years of production *Pasternak et al.* (2004) found a pore pressure drop of 1 MPa. If the amount of stress perturbation was not large enough to classify this events as induced, it might instead be classified as triggered. Additionally, the determined depth range between 4 and 13 km (*Leydecker et al.*, 1980) overlaps with the production horizon at 4.5-5 km depth (cf. *Dahm et al.*, 2007). Felt earthquakes prior to 1977 are, despite the well preserved comprehensive rich and long lasting historical records, not known from this area. Therefore, it is not unreasonable to consider a non-natural origin of the 1977 Soltau seismic event.

3. Induced and natural seismicity in space and time

3.1. Induced seismic events in areas of geothermal project sites

Induced seismic events with $M_w \geq 2.0$ in connection with geothermal projects have occurred in the study area at the sites Soultz-sous-Forêts (France), Basel (Switzerland), Unterhaching (Germany), Landau i. d. Pfalz and at the nearby site Insheim (Germany). These sites with their induced seismicity are shown in Fig. 1 together with the natural tectonic seismic activity for the same time span since this type of induced seis-

Table 2
The ten strongest tectonic earthquakes in Germany (incl. a 10–15 km margin) and the ten strongest induced/triggered seismic events in the study area according to different kinds of mining, hydrocarbon exploitation, and water reservoirs.

Date				**Location**					M_w	**Reference** as given in the EMEC database[a]
Year	Month	Day	Hour	Latitude	Longitude	Place, site, or district; country code		Depth		
a. Strongest tectonic earthquakes in Germany including a margin of about 10-15 km										
1356	10	18	21	47.47	7.60	Basel	CH		6.6	ECOS-09[b]
1650	9	21	3	47.55	7.53	Basel	CH		5.3	ECOS-09[b]
1756	2	18	8	50.80	6.47	Düren	D	14	5.9	*Meidow* (1995)
1846	7	29	21	50.15	7.68	St. Goar	D	10	5.2	*Meidow* (1995)
1878	8	26	9	50.93	6.55	Tollhausen	D	9	5.7	*Meidow* (1995)
1911	11	16	21	48.22	9.00	Albstadt	D	10	5.7	*Kunze* (1986)
1935	6	27	17	48.04	9.51	Saulgau	D	14	5.4	*Stange and Brüstle* (2003)
1943	5	28	1	48.27	8.98	Albstadt	D	9	5.3	*Kunze* (1986)
1951	3	14	9	50.63	6.78	Euskirchen	D		5.6	ORB10[c]
1978	9	3	5	48.28	9.03	Albstadt	D	7	5.2	*Stange and Brüstle* (2003)
b. Strongest induced seismic events in areas of coal mining										
1876	10	17	2	51.53	7.45	Ruhr	D		3.4	*Leydecker* (1986)
1888	3	18	0	51.53	7.45	Ruhr	D	1	3.7	*Leydecker* (1986)
1936	11	3		51.55	7.3	Ruhr	D	1	4.1	*Leydecker* (1986)
1962	11	29	4	47.8	11.1	Peissenberg	D	1	3.7	*Leydecker* (1986)
1967	9	16	6	47.83	11.1	Peissenberg	D		3.8	*Leydecker* (1986)
1981	7	13	8	52.26	7.71	Ibbenbühren	D	2	3.8	*Leydecker* (1986)
1986	5	1	13	49.18	6.72	Saar/Lorraine	D/F	1	3.6	*Leydecker* (1996)
1991	5	16	2	52.28	7.76	Ibbenbühren	D		4.0	*Leydecker* (1996)
2003	1	6	21	52.33	7.76	Ibbenbühren	D	1	3.9	SZGRF[d]
2008	2	23	15	49.38	6.84	Saar/Lorraine	D/F	1	3.7	SZGRF[d]
c. Strongest induced seismic events in areas of salt and potash mining										
1940	5	24	19	51.48	11.79	Saale, Teutschenthal	D	1	4.6	*Grünthal* (1988)
1943	3	5	23	51.75	11.52	Saale	D	1	4.1	*Grünthal* (1988)
1953	2	22	20	50.92	10.00	Werra	D	1	4.7	*Grünthal* (1988)
1958	7	8	5	50.82	10.11	Werra	D	1	4.5	*Grünthal* (1988)
1961	6	29	11	50.82	10.11	Werra	D	1	3.7	*Grünthal* (1988)
1971	4	4	5	51.75	11.52	Saale	D	1	4.1	*Grünthal* (1988)
1975	6	23	13	50.79	10.00	Werra, Sünna	D	1	4.8	*Grünthal* (1988)
1983	7	2	3	51.42	10.66	S-Harz	D	1	3.1	*Grünthal* (1988)
1989	3	13	13	50.8	10.05	Werra, Völkershausen	D	1	5.4	*G&M* (2005)[e]
1996	9	11	3	51.45	11.85	Saale	D	0.7	4.6	*Tittel et al.* (2001)
d. Strongest induced seismic events in areas of hydrocarbon exploitation										
1977	6	2	13	52.94	9.94	Soltau/Munster, Niedersachsen	D	6	3.7	*Dahm et al.* (2007)
1997	2	19	21	52.83	7.04	Roswinkel, Drenthe	NL	2	3.2	*Dost and Haak* (2007)
1998	7	14	12	52.83	7.05	Roswinkel, Drenthe	NL	2	3.1	*Dost and Haak* (2007)
2000	10	25	18	52.83	7.05	Roswinkel, Drenthe	NL	2	3.0	*Dost and Haak* (2007)
2001	9	9	6	52.65	4.71	Alkmar, Noord Holland	NL	2	3.5	*Dost et al.* (2012)
2001	9	10	4	52.65	4.71	Alkmar, Noord Holland	NL	2	3.1	*Dost et al.* (2012)
2004	10	20	6	53.04	9.54	Rotenburg (Wümme)	D	6	4.3	*Dahm et al.* (2007)
2005	7	15	15	52.89	8.75	Bassum, Niedersachsen	D	4.7	3.7	SZGRF[d]
2006	8	8	5	53.35	6.69	Groningen	NL	3	3.4	*Dost et al.* (2012)
2008	10	30	5	53.34	6.72	Groningen	NL	3	3.1	*Dost et al.* (2012)
e. Strongest induced seismic events in areas of ore mining (copper mining since 2005, and iron mining)										
1973	4	20	12	49.36	6.04	Lorraine	F		4.0	*KNMI* (2009)
1974	7	1	1	49.29	5.96	Lorraine	F		4.0	*KNMI* (2009)
2005	7	19	3	51.53	16.26	Legnica/Głogów	PL	1	4.1	SZGRF[d]
2006	5	21	10	51.52	16.2	Legnica/Głogów	PL	1	4.5	SZGRF[d]
2007	8	15	8	51.49	16.1	Legnica/Głogów	PL	1	4.0	SZGRF[d]
2007	12	13	14	51.47	16.15	Legnica/Głogów	PL	1	4.0	SZGRF[d]
2008	7	23	16	51.52	16.16	Legnica/Głogów	PL	1	4.0	SZGRF[d]
2008	8	6	12	51.6	16.11	Legnica/Głogów	PL	1	4.0	SZGRF[d]
2010	4	3	1	51.49	16.12	Legnica/Głogów	PL	1	4.1	SZGRF[d]
2010	12	30	8	51.51	16.14	Legnica/Głogów	PL	1	4.2	SZGRF[d]
f. Strongest induced seismic events in connection with artificial water reservoirs										
1953	10	17		46.18	6.83	Salanfe	CH		3.5	ECOS-09[b]
1953	11	7	14	46.18	6.85	Salanfe	CH		3.5	ECOS-09[b]
1953	12	1	18	46.18	6.87	Salanfe	CH		3.5	ECOS-09[b]
1953	12	2	5	46.18	6.88	Salanfe	CH		3.5	ECOS-09[b]
1953	12	16	5	46.18	6.90	Salanfe	CH		3.5	ECOS-09[b]
1953	12	31	0	46.18	6.93	Salanfe	CH		3.5	ECOS-09[b]
1954	2	4	22	46.22	6.92	Salanfe	CH		3.5	ECOS-09[b]

Table 2 (Continued)

Date				**Location**					$\mathbf{M_w}$	**Reference** as given in the EMEC database[a]
Year	Month	Day	Hour	Latitude	Longitude	Place, site, or district; country code		Depth		
1954	1	1	20	46.18	6.95	Salanfe	CH		3.5	ECOS-09[b]
1954	4	14	18	46.18	6.97	Dents du Midi	CH		3.5	ECOS-09[b]
1971	6	21	7	46.35	5.70	Vouglans	F		4.5	*G&H* (1984)[f]

[a] *Grünthal and Wahlström* (2012)
[b] ECOS-09: *Fäh et al.* (2011)
[c] ORB10: *ORB* (2010)
[d] SZGRF: *SZGRF* (2010)
[e] *Grünthal and Minkley* (2005)
[f] *Goldsmith and Hildyard* (1984)

micity occurred; i.e. since June 2000 until March 2011, when the current version of the database (cf. Section 2) terminates. The natural seismicity is described in the next sub-section.

Information on injection activities and maximum observed magnitudes of induced events at most of these sites are given in *Evans et al.* (2012). More details with respect to the Basel project and associated seismicity are provided by *Deichmann and Giardini* (2009). General information on induced seismicity as a result of stimulations at the site Soultz-sous-Forêts is given in *Cornet et al.* (1997), *Dorbath et al.* (2009), *Cuenot et al.* (2008, 2011). Seismic events at Soultz-sous-Forêts with $M_w \geq 2.0$ were generated in connection with stimulations at the following boreholes (named GPK): June/July 2000 at GPK2, May/June 2003 at GPK3, September 2004 at GPK4, and February 2005 at GPK5. The respective bursts of seismicity as a function of time for this site are shown in Fig. 2a. The largest events caused by the fluid stimulation at GPK1 in September 1993 were two events with magnitude 1.9 on September 15, when the flow rate had reached its maximum value, and another event also with magnitude 1.9 on September 26; i.e. ten days after injection flow had stopped (Cornet, pers. communication, 2011). These two seismic events are included in Fig. 2a.

The series of induced events at the geothermal project sites Basel, Unterhaching and Landau i. d. Pfalz and Insheim with time are shown in Fig. 2a but in different colours. Table 1 contains the parameters of seismic events with $M_w \geq 2.3$. Data in Table 1 show that the maximum induced seismic events at the geothermal project sites vary between $M_w = 3.2$ (Basel) and $M_w = 2.3$ (Insheim).

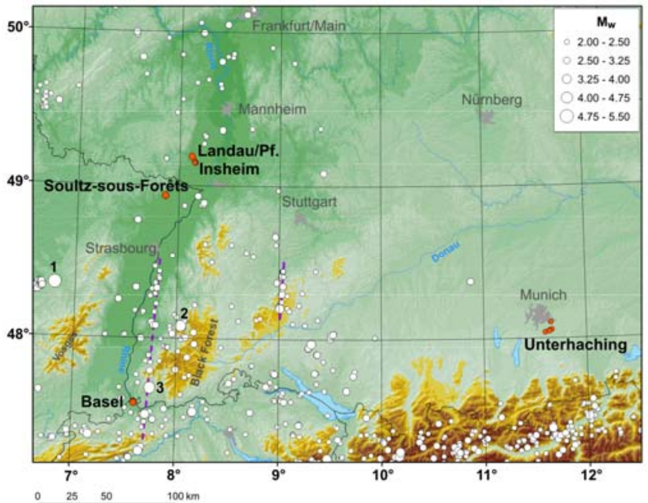

Fig. 1. Induced seismicity at sites of geothermal projects Soultz-sous-Forêts, Landau i. d. Pf. resp. Insheim, Unterhaching and Basel (red circles) in comparison with natural tectonic earthquakes (white circles) from June 2000 to March 2011. The first induced seismic event of geothermal projects with $M_w = 2.0$ occurred in the study area in June 2000. An almost N-S trending tectonic feature in direction N 9°E, where significant earthquakes occurred in 1911, 1913, 1943 and 1978 (cf. text and Table 1b), is marked by micro-earthquakes. Tentatively a tectonic feature is indicated east of Basel and west of the Black Forest. The three strongest earthquakes within the depicted time frame are marked: (1) the $M_w = 4.8$ 2003 Rambervillers earthquakes, (2) the $M_w = 4.6$ 2004 Waldkirch (Kandel) earthquake, and (3) the $M_w = 4.2$ 2009 Schopfheim earthquake.

3.2 Natural seismicity

The known catalogued natural seismicity of the study area since AD 1000 is shown in Fig. 3. The seismicity in the study area is largest in the Western and Central Alps and in the area of Friuli/Carinthia (i.e. in the most SE part of Fig. 3). North of the Alps pronounced seismicity extends along the NNE-SSW striking Upper Rhine graben north of Basel up to the area of Frankfurt/Main, and continues with a NW-SE trend, dominated by extensional faulting along the Middle Rhine zone and the Lower Rhine embayment. The years of occurrence of selected significant earthquakes or those with civil engineering relevance are indicated on the map. Other concentrations of seismic activity occur west and east of the southern part of the Upper Rhine graben, along the river Danube, and further NE in the Saxothuringian seismic province between 12° and 13° E and 49.5° and 51.5° N. So far, the magnitudes within this seismic province have not exceeded $M_w = 5.0$. The ten strongest tectonic earthquakes are given in Table 2a.

A more detailed pattern of natural tectonic seismicity in the southern part of the study area is reproduced in Fig. 1. A diffuse seismicity pattern occurs along the river valleys of the Inn in Austria, in SW Germany and in northern Switzerland. A remarkable alignment of microseismicity is shown at 9° E SW of Stuttgart. This rather short N 2° E striking tectonic feature has produced a series of fairly strong earthquakes during about the last 100 years, i.e. (from S to N) the $M_L = 6.1$, $M_w = 5.7$ 1911 earthquake, in 1913 with $M_L = 5.6$, $M_w = 5.0$, in 1943 with $M_L = 5.6$ and $M_w = 5.3$, and in 1978 with $M_L = 5.7$ and $M_w = 5.2$. This fault can be detected with remote sensing radar data (*Wetzel and Franzke*, 2001, 2003) but cannot be traced by classical geological methods (cf. Fig. 5 of *Burkhard and Grünthal*, 2009).

The Upper Rhine graben between Basel in the south and Frankfurt/Main in the north does not exhibit any remarkable seismicity along the western and eastern border faults in Fig. 1. But there seems to be an alignment of seismicity striking N 4° E; i.e. steeper than the strike of the graben itself, which cuts through the eastern border fault of the graben. Such a tectonic feature, here tentatively postulated, is so far not constrained by other data.

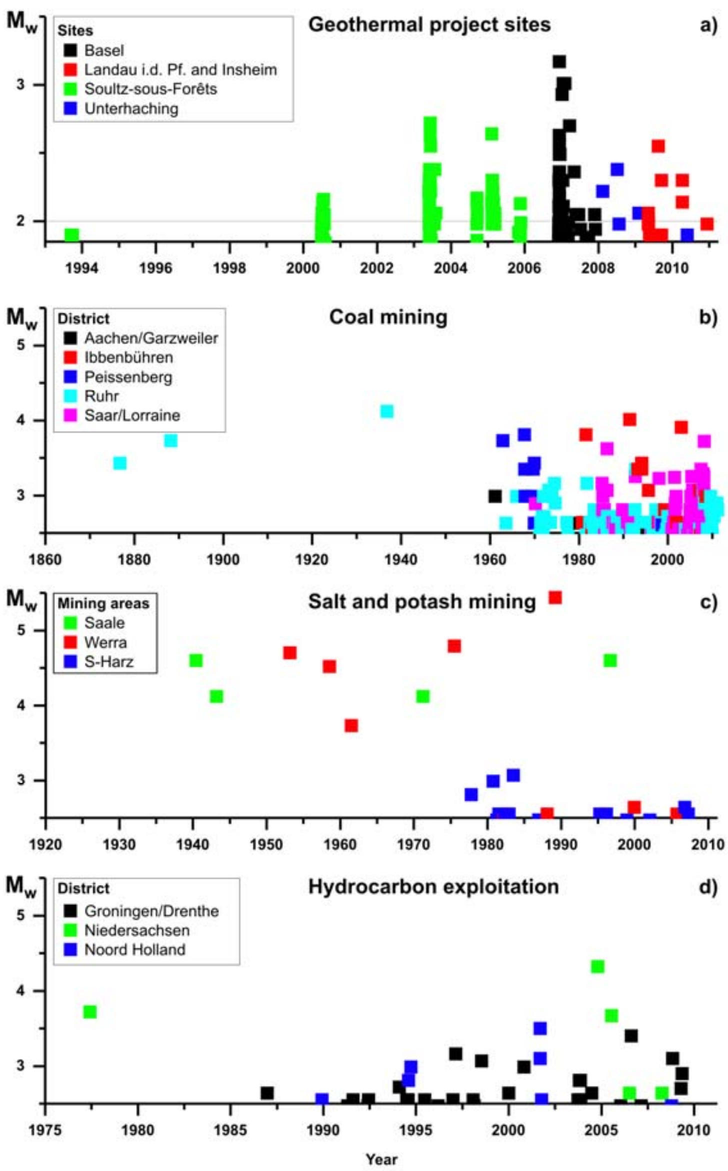

Figure 2. Temporal occurrence of induced/triggered seismic events in the study area at (a) sites of geothermal projects for $M_w \geq 1.9$, (b) coal mining, (c) salt and potash mining, and (d) hydrocarbon exploitation for $M_w \geq 2.5$. Note, the time and magnitude axes are different in the four graphs.

3.3 Induced seismicity in coal mining districts

Several of the coal mining areas are known for their pronounced induced seismicity. These areas include the Ruhr black coal mining district with first known events in 1876 ($M_w = 3.4$) and the strongest one in 1936 with $M_w = 4.1$. Starting in 1961 the seismic networks became sufficiently sensitive to record the seismic activity with adequate completeness (Fig. 2b). Apart from the Ruhr coal mining district there are six other which generate seismicity with $M_w \geq 2.0$; i.e. the districts of Ibbenbühren (D), Saar/Lorraine (D/F), Aachen (D), of Peissenberg (D), and the brown coal or lignite mining areas of the Rhenish district (D) and the Northern Bohemian basin (CZ) (Fig. 4). In the last 30 years the strongest induced events of this type have occurred in the anthracite coal mining district Ibbenbühren.

The black coal district of the Saar region extends westward to the Lorraine in France. An $M_w = 3.7$ seismic event in 2008 in the Saar mining area, which caused significant damage to houses and churches, was one aspect to stop mining operations.

Another local spot where induced events occurred is the Peissenberg coal mining area in southern Germany, W of Munich. The coal mining has ended also in this area as well. The occurrence of the recorded events was restricted to the time of mining activities. All these events at Peissenberg occurred at depths of about 1-1.5 km below ground surface. Their epicentres were localized in the periphery of the mining area (Wassermann, personal communication).

The fairly deep open pit brown coal mines in the Rhenish district have caused seismic events with a moment magnitude of $M_w = 2.6$. Seismic events in the Northern Bohemia district are smaller with a maximum $M_w = 2.0$ in the Tušimice opencut mine (*Mittag et al.*, 2002).

All seven clusters of induced seismicity in coal mining areas are shown in Fig. 4. Table 2b summarizes the ten strongest events of this type of seismicity.

3.4 Induced seismicity in salt and potash mining areas

The by far strongest induced seismic event occurred in Central Europe due to potash mining, namely the world-wide recorded $M_w = 5.4$ ($M_L = 5.6$) Völkershausen event in 1989

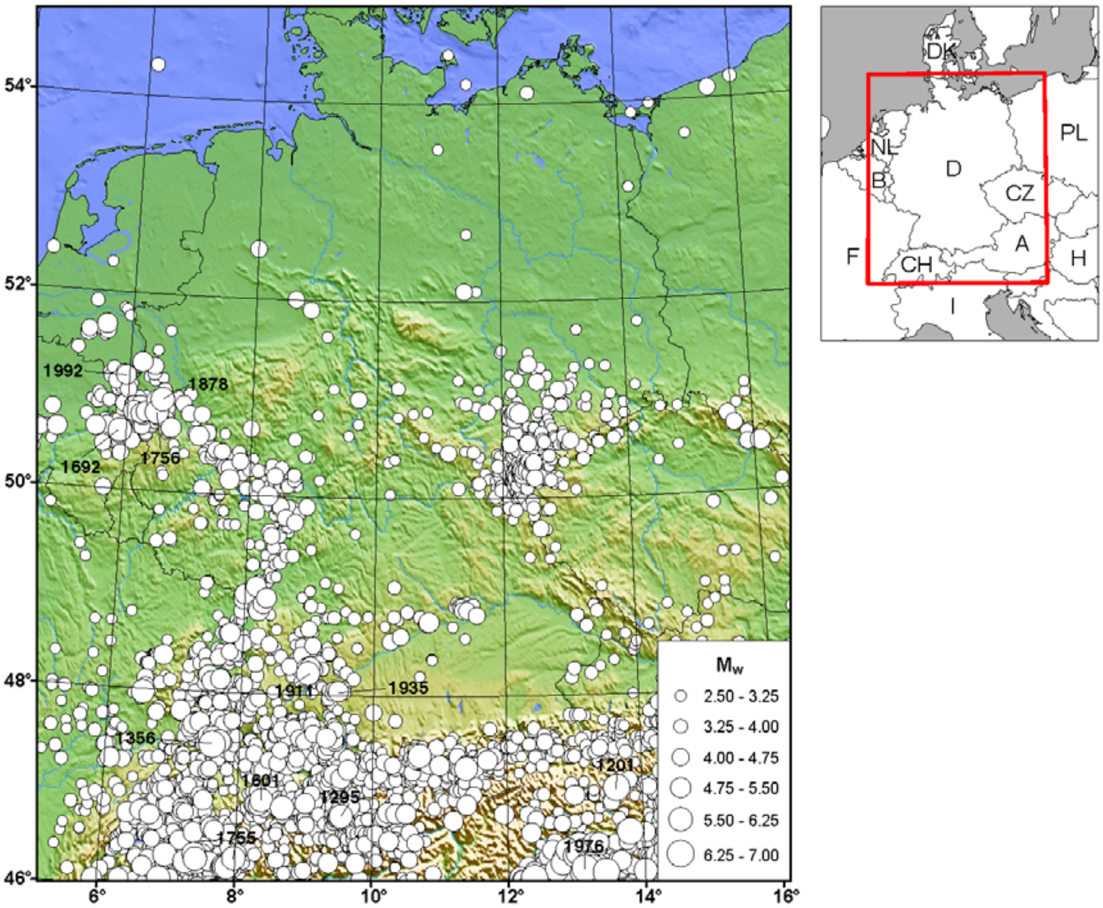

Fig. 3. Natural tectonic earthquakes, as catalogued from 1000 AD to 2011. Data are from the database related to the earthquake catalogue EMEC (*Grünthal & Wahlström*, 2012). The years of strongest earthquakes are provided.

(cf. Table 2c). It is probably the strongest mining-induced seismic event observed so far. The seismic event occurred at a depth of about 900 m within the Zechstein formation where carnallite was mined in room-and-pillar mining system (*Minkley*, 1991, 1998). The carnallite, embedded in ductile reacting rock salt layers, behaves extremely brittle. The seismic event was initiated by blasting and caused subsequently the failure of a large number of pillars (*Ahorner*, 1998; *Minkley*, 1991, 1998).

Induced seismic events in salt and potash mining areas are known since 1894. Fairly strong induced seismic events in areas of rock salt and potash mining are basically observed in three mining districts: the Werra district, the S-Harz district, and the Saale district E of the Harz mountains (Fig. 4). The temporal occurrence of this activity is depicted in Fig. 2c. It shows that smaller events in the range of $M_w = 2.5$-3.0 are mainly catalogued after the $M_w = 4.8$ Sünna seismic event in the Werra district. The stronger seismic events of this type in the range of $3.7 \leq M_w \leq 5.4$ seem to occur in another seismicity regime than the events with $M_w \leq 3.0$ (in this respect cf. Section 4).

3.5 Induced seismicity in hydrocarbon exploitation areas

Induced seismicity as a result of hydrocarbon exploitation, which in this study includes natural gas only, is mainly known from the area in the northern and north-eastern part of The Netherlands (*Dost and Haak*, 2007; *Dost et al.*, 2012) and from NW Germany; i.e. from an almost E-W trending belt in Lower Saxony (Fig. 4). Except for the probably triggered event in 1977 (cf. the discussion in Section 2), the induced seismicity with $M_w \geq 2.5$ can be traced back to 1987. The temporal occurrence of this type of seismicity is shown in Fig. 2d. The ten strongest events are given in Table 2d. The Rotenburg/Wümme $M_w = 4.3$ event in 2004 was the strongest (*Dahm et al.*, 2007).

3.6 Induced seismicity due to ore mining

Induced seismicity as a result of ore mining in the study is known from three mining areas: (1) the Legnica/Głogów copper district in Lower Silesia in SW Poland, (2) the iron ore mining district in the northern Lorrain in France and at the border region to Luxembourg, and (3) the Uranium mining area which was concentrated in Saxony (Germany) (Fig. 4). The strongest seismic events of this type are given in Table 2e.

The copper mining in the Legnica/Głogów district was reactivated after World War II in 1968 (*Gibowicz et al.*, 1979, *Orlecka-Sikora et al.*, 2009). Within this year the first seismic station was placed in operation and a local seismic network was systematically extended since 1970 (*Gibowicz et al.*, 1979). Several $M_L = 3.0$-3.5 seismic events were recorded between 1972 and 1977. The seismicity pattern drastically changed since the $M_L = 4.5$ ($M_w = 4.1$) event on March 24, 1977, i.e. the magnitude level of the local seismicity became distinctly larger than in the previous years. A source study of this remarkable seismic event and a description of the related mining works is provided by *Gibowicz et al.* (1979). Several thousand seismic events in the magnitude range of 0.5 to 4.5 are recorded annually by the local seismological network (*Orlecka-Sikora et al.*, 2009). Hundreds of events from this district are observed by other European seismological networks each year. The strongest of these events are connected to distinct fault slip in the surrounding rock masses. These events caused ten accidents with two casualties between

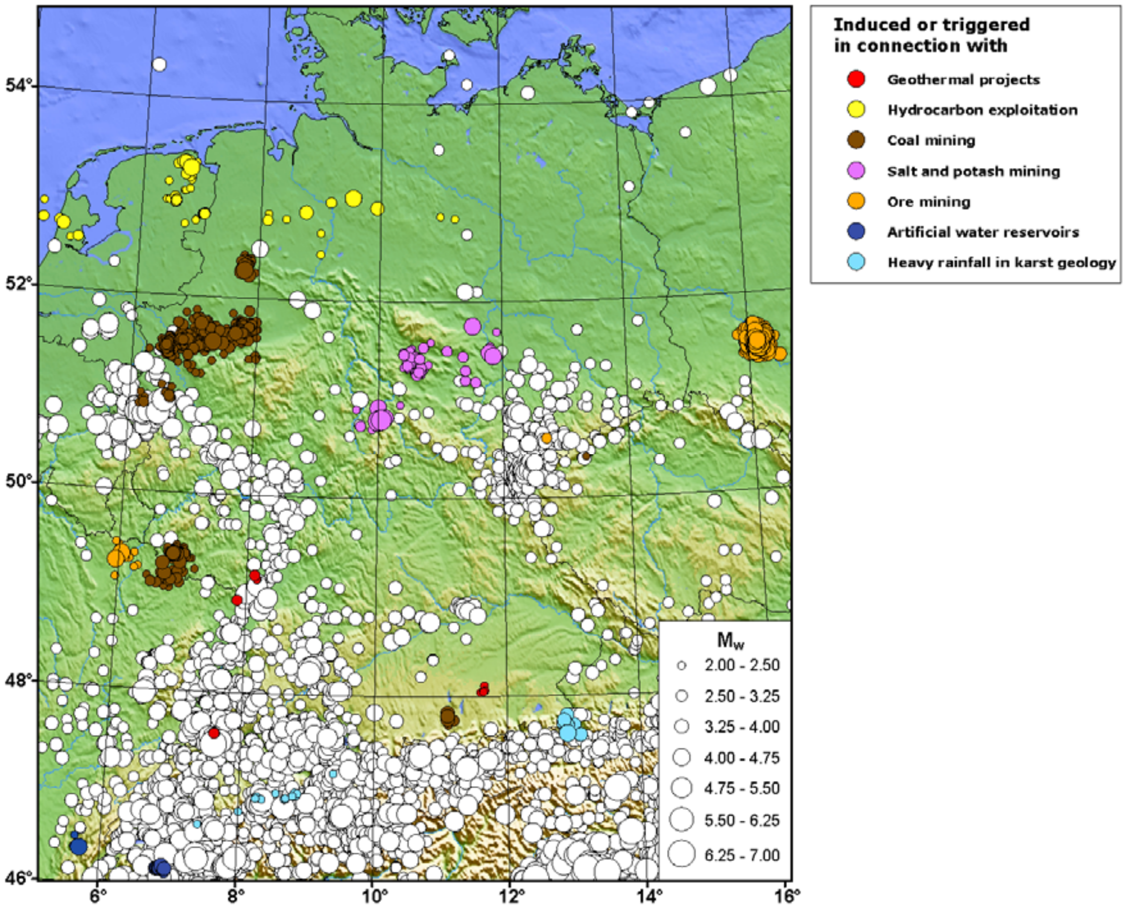

Fig. 4. Varying sources of induced seismicity ($M_w \geq 2.0$, see insert box) superimposed on epicentres of natural tectonic earthquakes ($M_w \geq 2.5$, white circles). Strongest tectonic earthquakes and induced seismic events are given in Table 1.

1985 and 2006 (*Kłeczek*, 2007 in *Orlecka-Sikora et al.*, 2009). Effects of these rockbursts at or near the surface lead to damage to bridges, roads, railway lines, pipelines, and cables as mentioned in *Ciesielski* (1988). The copper schist deposit extends further to the west and becomes exploitable in Germany in the Lausitz (Brandenburg) in the area of the towns Spremberg and Schleife. The exploitation in the Lausitz is expected to commence in the coming years.

The iron ore mining activity in the Lorrain and the geological situation is described e.g. in *Bornuat* (2006a, b) and *André-Mayer et al.* (2008). Systematic studies on induced seismic events in this mining district are not known to the author. Remarkable are two $M_w = 4.0$ seismic events reported by the Royal Netherlands Meteorological Institute (*KNMI*, 2009).

The investigation of induced seismic events in connection with the intense uranium mining in Saxony (Germany) from 1946 to 1990, which was the third largest operation worldwide, is difficult due to being strictly classified at that time. The largest induced seismic event in the active exploitation phase occurred on 25 September 1979 in the area of the Aue-Alberoda mine (*Wallner*, 2011). It was communicated as a tectonic earthquake with an $M_L = 2.9$ (*Grünthal*, 1988) corresponding to $M_w = 2.7$. In the course of the flooding of the mine, the seismicity has not exceeded an $M_w = 2.0$ (*Mittag et al.*, 2004) and is therefore not subject of this paper.

3.7. Dam induced seismicity

The triggering of earthquakes with $M_w \geq 2.0$ in connection with artificial water reservoirs, especially in their filling phase, is known in the study area from dams in France and in Switzerland (*Gupta*, 2002; *Gupta and Rastogi*, 1976). In France it is the Vouglans dam where in 1971 a $M_w = 4.5$ shock occurred (*Rothé*, 1973; *Božović*, 1974; *Goldsmith and Hildyard*, 1984). In Switzerland seismic events in connection with artificial water reservoirs are described in *Gupta* (2002) for the Emmosson dam, the Salanfe dam, and the Contra dam. The locations of these dam-induced events are shown in Fig. 4. The strongest shocks are given in Table 2f. The magnitudes of these seismic events in 1953 and 1954 were not determined instrumentally but converted from a maximum observed intensity of 4.5 (cf. Section 5). The resulting common $M_w = 3.5$ represents a rather uncertain estimate only. The events ranked beyond the first ten in Table 2f have all magnitudes below $M_w = 3.5$.

3.8 Rain-triggered seismicity related to karst geology

Induced or triggered seismicity due to intense precipitation in the study area is described for a local region of Mt. Hochstaufen near Bad Reichenhall in the outermost southeastern part of Germany (*Hainzl et al.*, 2006; *Kraft et al.*, 2006a,b) and in Switzerland (*Roth et al.*, 1992; *Husen et al.*, 2007; *Deichmann et al.*, 2006, *Deichmann*, 2011). Since rain is a natural phenomenon, these events can also be seen as naturally induced/triggered earthquakes, where the use of the term “triggered” is more appropriate.

Miller (2008) showed that heavy rain alone cannot explain the triggering of earthquakes. The rain-triggered seismicity occurs unambiguously in areas of karst geology.

The Mt. Hochstaufen area almost coincides with a prominent salt mining area with practically continued exploitation for the past 7000 years; i.e. since the bronze age. The very

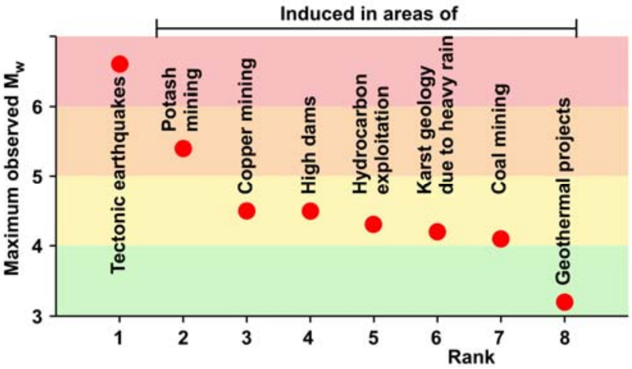

Fig. 5. Ranking of maximum observed magnitudes for different sources of seismicity in Central Europe.

precise locations of these events in recent years show that their origin is not related to the salt mining. It can be assumed that the pre-instrumental and historical earthquakes in the Mt. Hochstaufen area are probably also rain-triggered (Wassermann, personal communication). Under this assumption these events can be traced back up to the 14th century in the particular area of Mt. Hochstaufen. Since 1965 their magnitudes reached $M_w = 3.4$.

In Switzerland, the Swiss ECOS-09 catalogue (*Fäh et al.*, 2011) does not differentiate between "normal" tectonic earthquakes and those which are precipitation-induced. In Fig. 4 the rain-induced events are shown which are related to the intense rainfall from 19 to 23 August 2005, especially in areas where the cumulative precipitation exceeds 200 mm (*Husen et al.*, 2007). Their magnitude did not exceed $M_w = 2.3$.

3.9. Ranking of maximum observed magnitudes of the different types of seismicity

The ranking of maximum observed magnitudes of natural tectonic earthquakes and the different sources of induced seismic events is depicted in Fig. 5. It shows the largest observed tectonic earthquakes with $M_w = 6.6$, as anticipated, on the first rank. The largest observed induced seismic event at geothermal sites ranks clearly lowest with $M_w = 3.2$. The other types of induced seismicity are located between these two end positions. In decreasing order these are the strongest induced seismic events in mining of potash ($M_w = 5.4$), of copper ($M_w = 4.5$), in areas of water reservoirs ($M_w = 4.5$), hydrocarbon exploitation ($M_w = 4.3$), intense precipitation ($M_w = 4.2$), and coal mining ($M_w = 4.1$). The horizontal colour strips in Fig. 5 are basically introduced for a better readability. One may indicate the relevance of certain magnitude classes in civil engineering; i.e. from "gaining attention" (green), to "relevant", to "significant", to "very significant" (rosé). Earthquakes with significance in civil and earthquake engineering are at least with respect to new structures those with $M_w \geq 5.0$. But mainly older structures, especially non-engineered ones, can be affected by even smaller M_w of about $M_w = 4.5$. Substantial structural damage is usually observed beyond M_w 5.0. Probabilistic seismic hazard assessments in most cases make use of a minimum magnitude $M_{min} = 5$ for hazard calculation; i.e. the integration procedure starts with M_{min}.

Especially the values of maximum observed magnitudes of tectonic earthquakes cannot be simply seen as a snapshot in time without any generality, since their observation time extends more than 700 years with respect to the strongest observed earthquakes in the study area; i.e. the probability to exceed the $M_w = 6.6$ is rather low. The knowledge gained to better understand the physics and mechanics of mining induced seismic events will be applied more and more to introduce new technologies, which should be capable of preventing damaging magnitudes.

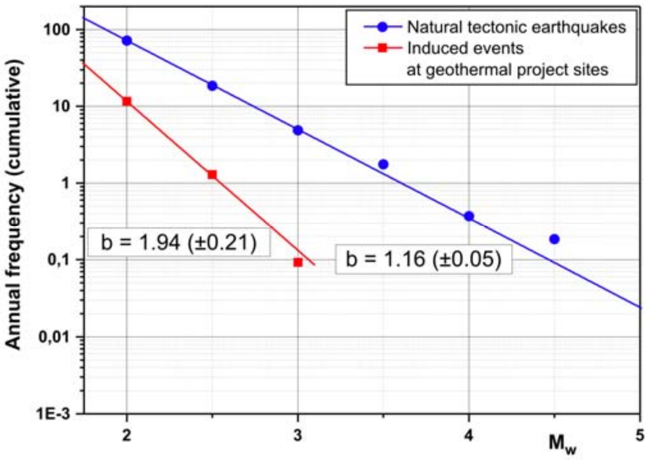

Fig. 6. Annual frequency-magnitude distributions of natural tectonic earthquakes in Germany and induced seismicity at geothermal sites in the study area from June 2000 to March 2011.

4. Frequency-magnitude relations

Frequency-magnitude distributions, also known as Gutenberg Richter relation, are used here as quantitative measure to compare the different types of induced seismicity among each other and to the natural tectonic seismicity. The parameters a and b of frequency-magnitude distributions

$$\log N = a - bM \tag{2}$$

with a as the rate of events greater than equal to zero, are determined on the basis of maximum-likelihood estimations (*Weichert*, 1980), which yields, in comparison to the least square technique, unbiased values. Written in an exponential form and considering a maximum magnitude M_{max} of a region the truncated cumulative relation for the rate $\nu(M)$ reads as:

$$\nu(M) = \frac{\exp[\beta * (M_{max} - M)] - 1}{\exp[\beta * (M_{max} - M_{min})] - 1} \quad M < M_{max} \quad \beta = b \cdot \ln 10 \tag{3}$$

The only normalization, which is applied to the data, is their relation to annual occurrences. Any normalization with respect to sub-areas is avoided to keep the comparisons simple and transparent.

The observed cumulative annual frequency-magnitude data for induced seismicity at geothermal sites since June 2000 up to March 2011 for induced seismicity exceeding $M_w = 2.0$ is shown together with observed magnitude-frequency data of natural tectonic earthquakes in Fig. 6 within the same time period. All data are non-declustered. Data for the tectonic earthquakes are given for the region of Germany including a margin of about 10-15 km; i.e. an area which also encompasses the induced seismicity at the geothermal sites at Basel in Switzerland and Soultz-sous-Forêts in France. The observed cumulative numbers of induced seismic events in magnitude classes of 0.5 magnitude units form a nearly perfect straight line on the semi-logarithmic graph of the frequency-magnitude data. For optimizing the fit the class of the largest events at geothermal sites encompasses the range $3.0 < M \leq 3.5$; otherwise, classes have their lower margin at full or half-magnitudes. The b-value of 1.94 has a standard derivation

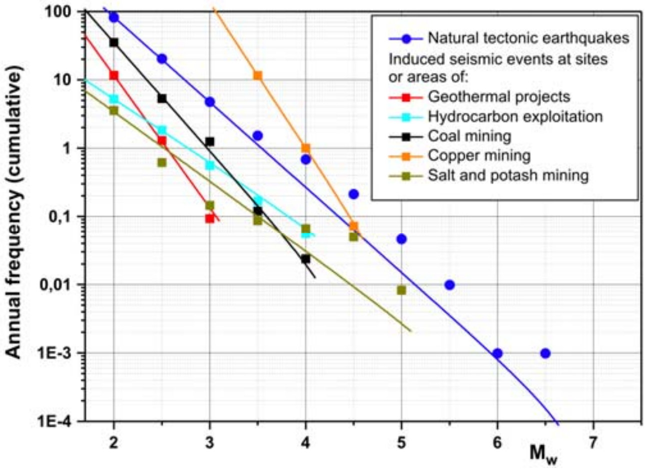

Fig. 7. Frequency-magnitude distributions of all studied sources of observed seismicity normalized to their annual occurrence. Data for natural tectonic earthquakes are given according to observations from the last millennium. A maximum expected magnitude of $M_{max} = 7.0$ is applied to the maximum likelihood fit of natural tectonic earthquakes.

$\sigma = 0.21$. Observed annual numbers of tectonic earthquakes within the same time span also reveal a near to perfect fit with $b = 1.16$ (±0.05). A b of about 1 is the typical value for declustered crustal seismicity.

Fig. 6 shows that the frequency of the occurrence of induced seismicity at geothermal sites for $M_w = 2.25$ is about one order lower than that of the natural seismicity and 1.5 orders lower for about $M_w = 3$. The larger the magnitudes of induced events at these sites are, the larger the number of occurrence of magnitudes of natural seismicity at the same magnitude level is.

Annual frequency-magnitude graphs of all types of induced seismic events together with data of natural tectonic earthquakes of the last millennium (*Grünthal and Wahlström*, 2012) are given in Fig. 7. In order to present the annual frequency-magnitude of natural tectonic seismicity data, which cover such long time spans, their magnitude dependent completeness has to be considered (*Hakimhashemi and Grünthal*, 2012). The $b = 1.25$ (±0.01) according to the long-term data set is near to that for the short time span data from 2000, having highest completeness and lowest uncertainty. Also the annual ν-values at $M_w = 2.0$ are very similar. The difference in the b-value between the short-term and long-term data of natural tectonic earthquakes is due the fact that intensive aftershock sequences or earthquake swarms are lacking in the short-time data set.

The maximum-likelihood fit to the natural tectonic earthquake data makes use of assessments of M_{max} (equation 3) estimated in the range of $M_{max} = 6.8$-7.2 (*Grünthal et al.*, 2009c) and depicted here for $M_{max} = 7.0$, in order to take into account the truncation. Assessments of M_{max} of the different types of induced seismic events are not subject of this paper; regarding this topic reference is made to *Shapiro et al.* (2011).

Striking in Fig. 7 is the fact that the annual frequency-magnitude of the Legnica/Głogów copper mining induced events for $M_w < 4$ are well above the frequency-magnitude of natural earthquakes in entire Germany. The b-value of 2.13 for this type of induced seismic events is the largest of all studied seismicity types and is similarly high as that for induced seismic events at geothermal sites. The b-values of all types of events of Fig. 6 and 7 are summarized in Table 3. The annual magnitude-frequencies of all other types of induced seismic events are below that of natural tectonic earthquakes.

Table 3
The b-values of different types of non-declustered induced seismic events and natural tectonic earthquakes with their standard deviations σ

Source of seismicity	**b-value with $\pm\sigma$**
Geothermal projects	1.94 (±0.21)
Natural tectonic earthquakes	
Long-term data	1.25 (±0.01)
Short-term data	1.16 (±0.05)
Hydrocarbon exploitation	0.93 (±0.11)
Coal mining	1.59 (±0.05)
Copper mining	2.13 (±0.22)
Salt and potash mining	1.02 (±0.09)

The b-value of 1.59 (±0.05) of induced seismic events in areas of coal mining is also larger than the one of natural earthquakes but distinctly lower than for events at geothermal sites. The induced seismic events in connection with hydrocarbon exploitation have a b-value, which is similar to that for tectonic earthquakes. The b-value for the seismic events in salt and potash mining districts is governed, as it is typical for maximum-likelihood fits, by the data in the magnitude classes with the largest number of events. The occurrence of events with $M_w \geq 4.5$ of this type is larger than expected from the number of events in small magnitude classes. The occurrence of small and large magnitude events of this type obviously does not follow the same exponential model.

The discussed differences in the b-values are characteristic for the different types of seismicity. However, the values of activity rates a have to be seen differently. The long-term activity rates of natural tectonic earthquakes are the result of permanently acting tectonic stresses on seismogenic fault zones. The activity rates of induced seismic events are governed by the level of human activities that are resulting in stress changes, which are at least partly released in induced seismicity. This means, the activity rates are conditionally comparable only. Therefore, the activity rates of induced seismic events of different types are a snapshot of their observed occurrences (cf. Fig. 2) as a result of human activities, normalized by one year. Any change in the exploitation intensity or technology will change the in-situ stress field and thus the picture presented here.

5. Macroseismic intensities of induced events

Magnitudes as a measure of the total seismic energy release of earthquakes do not provide sufficient information on macroseismic effects on the surface; i.e. how strong an earthquake is felt or affects buildings. The strength measure, which is based on such information, is the macroseismic intensity on a 12 degree scale (for more details in a comprised form, see e.g. *Grünthal*, 2011 or *Musson et al.*, 2010). Intensity, as defined in the guidelines to the usage of the European Macroseismic Scale (EMS-98, *Grünthal*, 1998; www.gfz-potsdam.de/EMS98), represents a “classification of the severity of ground shaking on the basis of observed effects in a limited area”. This means that intensity is place related; i.e. from a village up to a medium size town. It would be poor macroseismic practice to assign intensities to a single building. This becomes obvious in the definition of intensity degrees of the EMS-98, where characteristic effects are used in quantitative terms (”few” ~5-15%, ”many” ~20-50%, ”most” ~60-100%). Exemplarily, typical effects of intensities 4 and 5 are given in a simplified form from the EMS-98:

Intensity 4: Felt indoors by many, a few are awakened. Vibration is moderate. Light furniture shakes visibly in few cases. No damage.

Intensity 5: Felt indoors by most, a few are frightened and run outdoors. Strongly felt. Small objects may be shifted or fall down. Damage (hair-line cracks in very few walls, small pieces of plaster falling, loose stones from upper parts falling in few cases) to a few standard, unreinforced masonry buildings and those of higher vulnerability.

Intensity assignments of field data are integer values. A principle in intensity assignment is that "In cases where the data fulfil and exceed the description for intensity 6, but clearly are not compatible with those for intensity 7, the best solution is to treat the intensity as being the lower value" (p. 57 in *Grünthal*, 1998). In case of uncertainties; i.e. when the data can be interpreted equally well as 3 or 4, they can be given as 3-4. This does not mean an intermediate value or even a higher precision.

The macroseismic intensity is usually highest, i.e. in case of the absence of pronounced local site effects, above the centre of energy release of an earthquake (I_{max}) and decreases with distance. Relations of magnitudes M_w with I_{max} require the consideration of focal depths h. A chi-square regression of M_w with I_{max} and h, derived on the basis of 41 well investigated Central European master events, yields (*Grünthal*, 2009b)

$$M_w = 0.667 I_{max} + 0.30 \log(h) - 0.10 \qquad \sigma = 0.31 \dots 0.37 \tag{4}$$

Also for this equation the regression covariances lead to σ-values, which vary with I_{max} and h.

Fig. 8 shows the magnitude depth combination, which generates intensities 4, 5 and 6 with one and two standard deviations 1σ and 2σ. It becomes obvious that already fairly small magnitudes of 2.5 can produce an intensity of 4 in case of small focal depths. Magnitudes M_w and depth of the respective strongest seismic events at the geothermal sites Unterhaching, Landau i. d. Pfalz, Soultz-sous-Forêts, and Basel are depicted in Fig. 8 as well. The position of the M_w-h data pairs in Fig. 8 imply the respective levels of expected macroseismic intensities for these events.

However, reliable macroseismic data exist only for the M_w 3.2 Basel event (*Ripperger et al.*, 2009). Macroseismic maps with a representative number of interpreted felt effects have been published by *Baer et al.* (2007) and by *Deichmann* (2011). For the city of Basel the intensities were assigned for 14 zip-code areas to achieve a sufficient areal resolution of macroseismic information. In twelve of these 14 zip-code areas the intensity 4 was determined, only in two areas (in the most western part of the town) the intensity reached 5. If one would assign the intensity to the whole town of Basel, it would result in the value of 4-5 as rather conservative intensity assignment. The intensity estimate of 4 is confirmed by instrumentally recorded peak ground velocities (PGV), which were converted to intensities by *Ripperger et al.* (2009) and by a 3D simulation of the M_w 3.2 event in terms of PGV.

According to the same authors, of 403 observations from Basel 23 (or 5.7%) reported non-structural damage to buildings, like hair-line cracks or of minor pieces of plaster falling.

As described by *Ripperger et al.* (2009) further on, the private industry consortium Geopower Basel AG, which operated the geothermal project site Basel, launched a request for damage claims several days after the M_w 3.2 event and well after the macroseismic inquiry had ended. According to this request, more than 2000 reports on damaged buildings were submitted, some 900 from the city of Basel, which constitute about 4.7% of the entire building stock. These numbers, although regarded as preliminary by the authors, differ considerably from those according to the well-organized macroseismic survey several days earlier.

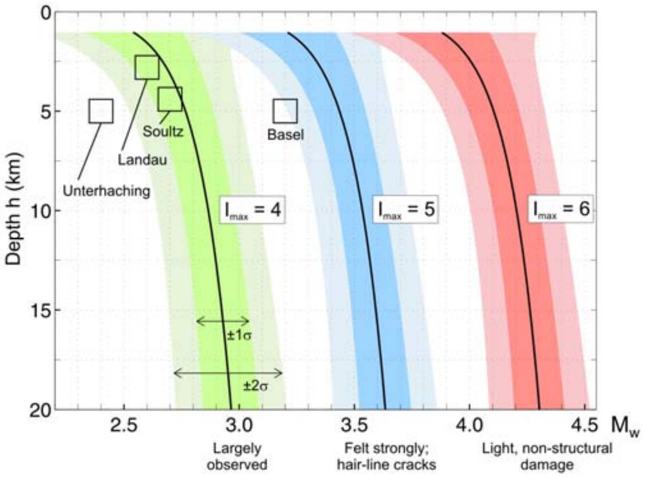

Fig. 8. Relationship between moment magnitude M_w and focal depth h for macroseismic intensities 4, 5, and 6 for Central European master events. Uncertainty ranges of $\pm 1\sigma$ and $\pm 2\sigma$ are after the empirical relation by *Grünthal et al.* (2009b). Inserted quadratic boxes are data pairs of M_w and h of the strongest observed seismic events at the four geothermal sites. For event depths shallower than 1 km the displayed relation is not valid.

According to the information presented in Fig. 8 the $M_w = 2.7$ Soultz-sous-Forêts seismic event should be connected most likely with an $I_{max} = 4$. Respective macroseismic observations are not available to the author.

The $M_w = 2.6$ Landau i. d. Pfalz seismic event has been studied by an *Expert Team* (2010) also with respect to the macroseismic effects. Each questionnaire collected for this event has been separately used to assign 200 intensity values mostly within the town Landau i. d. Pfalz and a few in the suburbs with $I = 5$ as a maximum. This is, as already described at the end of the first paragraph of this section, poor macroseismic practice. Looking at the data published one would rather expect an EMS-98 $I = 4$ or as a rather conservative estimate an $I = 4$-5 for Landau i. d. Pfalz, which can be a rough guess only. Equation (4), graphically represented in Fig. 8, would, most likely, predict an intensity of 4.

Macroseismic data for the $M_w = 2.4$ Unterhaching seismic event are too scarce to reliably assign an intensity. Few reports on felt effects on the M_L 2.3 ($M_w = 2.2$) Unterhaching event on 10 February 2008 have been assigned as $I = 3$ EMS-98 (Wassermann, pers. communication 2011).

The observed or predicted macroseismic intensities of the strongest seismic events at the geothermal sites studied here, are well below the range where structural damage can occur. Structural damage starts at intensity 6 in few buildings of high vulnerability. Only for expected intensities of $I > 6$, earthquake-resistant measures due to natural tectonic earthquakes are taken into account in respective building codes. The seismic zoning maps of the German national building code for earthquake resistant design DIN 4149:2005-4 (*Grünthal*, 2005) is based on an intensity based probabilistic seismic hazard assessment (*Grünthal et al.*, 1998) for a 10% exceedence probability within an assumed 50-year mean-life-time-span for buildings. The studied geothermal project sites are located in the following seismic zones of the building code or corresponding areas of macroseismic intensities: Landau i. d. Pfalz in the seismic zone 1 (with a calculated $I = 6.5$), Unterhaching outside any seismic zone ($I = 5.5$). Although Soultz-sous-Forêts and Basel are just outside of the area where the code is applied, but very close to Germany, the extrapolation would result for Soultz-sous-Forêts $I = 6.5$ like Landau i. d. Pfalz and for the city of Basel, which is part of the study area in *Grünthal et al.* (1998), $I = 7.5$. The maximum observed intensities at the geothermal sites are 2 to 2-3 intensity degrees lower than those of the respective seismic hazard assessment.

6. Conclusions

The occurrence of induced seismicity at geothermal project sites has been compared with all other types of induced/triggered seismicity as well as with natural tectonic earthquakes in the study area. Other types of induced seismicity include seismic events in connection with coal mining, hydrocarbon exploitation, salt and potash mining, ore mining, heavy rainfall in karst geology and artificial water reservoirs. The induced seismicity due to underground construction work in the study area is minor and not part of this study.

The following conclusions can be drawn from the comparison of all types of seismicity with respect to the occurrence of seismic events at geothermal sites:

- Induced seismicity at geothermal sites is one of the different sources of observed induced/triggered seismicity in the study area.
- The maximum observed magnitude of induced seismicity at geothermal sites is the smallest of the eight types of induced/triggered seismicity with $M_w = 3.2$ which is by far smaller than natural tectonic earthquakes ($M_w = 6.6$).
- The induced seismicity at geothermal project sites generates a well constrained cumulative frequency-magnitude relation of non-declustered data. Its relation of the occurrence of the number of small to larger magnitudes, described as the b-value of 1.94, is among the highest of all types of induced seismic events and natural tectonic earthquakes. The latter generate a b of about 1.16, which is characteristic for shallow non-declustered crustal tectonic earthquakes. The high b-value of induced seismicity at geothermal sites means that, in comparison to other types of seismicity, a relatively large number of small events have to occur to enable the generation of larger ones.
- The rate of observed occurrence of relevant magnitudes M_w (e.g. in the range of $2.75 \geq M_w \geq 3.25$) at geothermal sites is the lowest of all types of induced events; i.e. one to two orders lower than for tectonic earthquakes and, e.g., two to three orders lower than for induced seismic events in the Legnica/Głogow copper mining area.
- The maximum observed macroseismic intensities at geothermal sites were moderate only, with a few cases of weakest non-structural damage and without structural damage.
- In comparison to the intensity-based probabilistic seismic hazard map, which is the basis for the current national German building code, the differences in intensity between those which were maximally observed at geothermal sites and those of the seismic zoning map of the code amount to 2.5 intensity degrees.

The public concern about the occurrence of perceptible induced seismicity at geothermal sites is understandable; it should not be seen isolated but in relation to all other types of seismicity which occur in a region. The research activities on seismic safety of geothermal sites focus on understanding the generation of maximum magnitudes and on minimizing the magnitudes of induced seismic events.

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