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Attached or not attached-evidence from crustal stress observations for a weak coupling of the Vrancea slab in Romania

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The crustal stress pattern of Romania provides key insights into whether the Vrancea slab with its seismogenic volume between 70 and 175 km depth is still coupled to the crust and thus acts as a stress guide, or whether it is already in a state of detachment from the crust. Knowledge of the state of the slab under Vrancea is particularly critical because the slab attached to the crust can result in future strong earthquake occurrence in the crust and even in the currently aseismic zone between 40 km and 70 km depth, potentially causing severe damage. Our analysis of the contemporary tectonic stress observations in the context of potential stress sources and the comparison with numerical modelling shows that the crustal stress pattern in Romania is heterogeneous and does not contain a long wave-length stress pattern that would be expected if there is a strong present-day coupling between the subducted slab and the upper plate, or if lateral plate boundary forces would control the regional stress pattern. Therefore, we conclude that the crustal stress pattern of Romania is characterised by small differential horizontal stresses where local stress sources (third-order effects) are responsible for the observed heterogeneity of stress orientations and that the subducted slab under Vrancea is only weakly coupled to the crust.

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1. Introduction

The crustal stress pattern of the SE-Carpathian region is expected to reflect both crustal tectonics as well as deep-seated mantle processes resulting from the Vrancea slab. In several papers the pattern of maximum compressive horizontal stress S_H of Romania is described as a long wave-length pattern with preferred SW-NE orientation in western Romania, that is ascribed to a NE-push of the Adriatic plate, and a swing to NW-SE orientation in the Vrancea region believed to result from a NW-push from the Vrancea region (*Morley*, 1996; *Bada et al.*, 1998; *Gerner et al.*, 1999). Mantle processes in this region are dominated by subducted lithosphere beneath the SE corner of the Carpathian arc (*Morley*, 1993; *Tomek and Hall*, 1993; *Nemcok et al.*, 1998). The type of Miocene subduction underneath Vrancea (oceanic or continental) is still under debate (*Chalot-Prat and Gîrbacea*, 2000; *Sperner et al.*, 2001; *Cloetingh et al.*, 2004). *Sperner et al.* (2004, 2005) consider the Vrancea slab as resulting from the last stage of late Miocene subduction of a part of the Tethys ocean (*Csontos*, 1995; *Stampfli and Borel*, 2002) with subduction retreat, slab roll-back and finally slab break-off (Fig. 1C).

Today the slab is in a nearly vertical position extending to a depth of ca. 350 km as identified from seismic tomography (Fig. 1B; *Wortel and Spakman*, 2000; *Martin et al.*, 2006). The north-eastern subcrustal part of the slab contains a narrow volume of high seismicity at intermediate depths between 70 and 175 km underneath a seismically quiet depth interval from 40 to 70 km (Figs. 1A,B). The seismically quiet interval is interpreted as the potential depth of ongoing slab detachment (*Sperner et al.*, 2005). From historical data the frequency of strong earthquakes within the last 600 years results in three earthquakes with $M_w \geq 7.2$ per century (*Radu and Oncescu*, 1980; *Oncescu et al.*, 1999).

The strength of the coupling between the subducted high-velocity body and the upper crust is a topic of considerable discussion especially for seismic hazard assessment (*Roman*, 1970; *Lankreijer et al.*, 1997; *Gîrbacea and Frisch*, 1998; *Sperner et al.*, 2001; *Ismail-Zadeh*, 2003; *Tarapoanca et al.*, 2003; *Cloetingh et al.*, 2004; *Sperner et al.*, 2004). If the subducting slab is still attached stress build up in the crust can be expected. Unfortunately, the resolution of the tomography is insufficient at the relevant depth range between 40 and 70 km for a direct interpretation in terms of coupling degree (*Martin et al.*, 2006).

The investigation of the crustal stress pattern can help to answer the question of whether the Vrancea slab is still attached to the crust and is acting as a stress guide. In this stress guide the seismogenic volume of Vrancea could extend to shallower depths and thus future strong earthquakes could occur in the today seismic inactive zone between 40 and 70 km depth or even at crustal levels leading to severe damage. If there remains a strong coupling of the Vrancea slab to the crust, the crustal stress observations are expected to reflect the effect of a down bending crust and lithosphere by indicating a systematic pattern of stress orientations and regimes around the coupling region.

This paper has three principal aims. First, we contribute new data to the database of contemporary tectonic stresses of Romania. We analyse stress information from 125 wells in terms of borehole breakouts. Furthermore, we apply the method of *Moos and Zoback* (1990) that allows to constrain the tectonic regime from the depth distribution of breakouts in 17 deep drill holes with good control on breakout depth distribution. Second, we analyse and interpret the data in order to identify regional and local stress patterns in terms of stress orientations and tectonic regimes. We use the smoothing of S_H orientations as a tool for stress pattern identification and show that the choice of the appropriate smoothing radius is critical for a sound spatial wave-length analysis of the stress pattern. Third, we discuss the potential stress sources for Romania and infer a weak coupling of the Vrancea slab to the crust. This conclusion is based on the heterogeneity of stress orientations and tectonic regimes which are not likely to be observed if a pulling slab was present.

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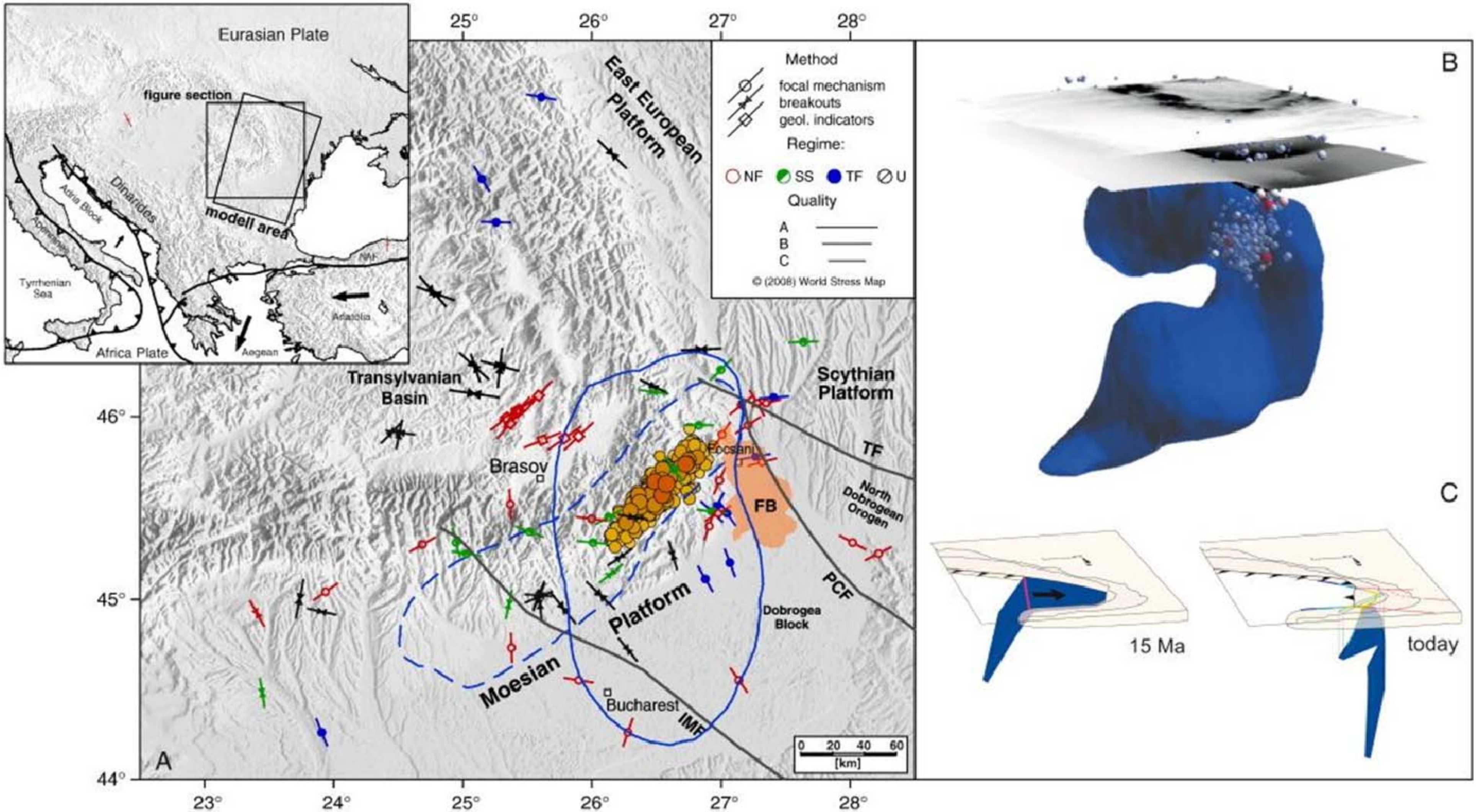

Fig. 1. A) Crustal stress map of Romania based on the A–C quality data of the World Stress Map database release 2008 (*Heidbach et al.* 2008, 2009). Plotted are the orientations of maximum horizontal compression (S_H) for depths of 0–40 km with topography as base map. The data show no consistent tectonic regime and have rather irregular S_H orientations. Major crustal fault zones: the Peceneaga-Camena Fault (PCF), the Trotus Fault (TF), and the Intramoesian Fault (IMF). Note the concentration of earthquakes from intermediate depth between 70 and 175 km beneath the Vrancea region (orange circles). Blue lines indicate the shape of the high-velocity body (2.5% vp anomaly) at 100 km (dashed) and 180 km (continuous) depth, respectively. The orange surface indicates the area of Quaternary sedimentation of the Focsani Basin. B) Shape of the slab from the tomography results of *Martin et al.* (2006). View is from SE towards NW. Top layers are topography and Moho. Blue isosurface is the 2.5% vp anomaly and the spheres within the volume are the earthquakes from intermediate depth. Red spheres indicate the location of the four strong earthquakes of the 20th century. Note that all earthquakes are within a small seismogenic volume of the slab located just above the lateral tear-off zone. C) Sketch of the evolution of the slab geometry. Note that the earthquake activity is within the shallow part of the slab between the aseismic depth interval (40–70 km) and the lateral tear-off of the deeper slab section at ~200 km.

2. Crustal stress in Romania

A variety of stress indicator types covering a wide range of depths and rock volumes is available in Romania, including focal mechanism solutions (*Radulian et al.*, 1999), geological fault-slip data and data from borehole breakout analysis (Table 1). All data are quality ranked according to the World Stress Map (WSM) quality ranking scheme (www.world-stress-map.org, *Heidbach et al.*, 2010 - this issue; *Sperner et al.*, 2003; *Zoback and Zoback*, 1989, 1991). In the following we first present an overview on the data availability and the results of data analysis within this study and then present the interpretation in terms of patterns of maximum horizontal stress orientations (S_H) and tectonic regimes. The tectonic regimes are based on the relative magnitudes of the principal stresses $\sigma_1 > \sigma_2 > \sigma_3$ with compression being positive. Under the assumption that one principal stress is vertical (S_v), the orientation of maximum horizontal stress S_H and the orientation of minimum horizontal stress S_h are principal stress orientations, too. According to *Anderson* (1951) the relative stress magnitudes define the tectonic regime: in a normal faulting regime (NF) the vertical stress S_v is the maximum stress, in a strike-slip (SS) regime it is the intermediate stress, and in a thrust-faulting (TF) regime it is the minimum stress.

2.1. Quality ranking

All stress data records have been quality ranked according to the criteria of the World Stress Map (www.world-stress-map.org, *Heidbach et al.*, 2010 - this issue, *Sperner et al.*, 2003; *Zoback and Zoback*, 1989, 1991; Tables 1 and 2) in order to guarantee comparability of the stress data that originate from different stress indicator types. The qualities range from A to E, with A being the highest quality and E the lowest. A-quality means that the S_H orientation is accurate to within ±15°, B quality to within ±20°, C quality to within ±25°, and D quality to within ±40°. For most stress indicators these quality classes are defined through the standard deviation of the S_H orientation. E-quality data records do not provide sufficient information and are not included here. For the figures and the interpretation we use the A-C quality data only since they are the most reliable indicators for tectonic stresses.

2.2. Earthquakes and focal mechanism solutions

The World Stress Map catalogue of Romanian crustal earthquakes from 0 to 40 km depth contains 79 A-D quality focal mechanism solutions with magnitudes up to $M_w = 5.8$ (*Radu and Oncescu*, 1980; *Radu and Oncescu*, 1990; *Gerner et al.*, 1999; *Radulian et al.*, 1999; ROMPLUS catalogue, first published as *Oncescu et al.*, 1999). Most crustal earthquakes are located in the Carpathian foreland between the NW and SE trending Pecenega-Camena Fault (PCF) in the north and the Intramoesian Fault (IMF) in the south (Fig. 1). The crustal earthquakes are more widely distributed than the earthquakes at intermediate depth between 70 and 175 km which concentrate beneath the Vrancea region in a small seismogenic volume (*Oncescu*, 1984; *Oncescu and Trifu*, 1987; *Oncescu et al.*, 1999; *Raileanu et al.*, 2007).

The S_H orientations and tectonic regimes that are derived from crustal focal mechanisms between 0 and 40 km depth are strongly varying and they do not show any systematic variation neither laterally, nor with depth (*Bala et al.*, 2003). The focal mechanisms in the Vrancea seismogenic body at intermediate depth (70-175 km) show a homogeneous NW-SE maximum horizontal compression orientation and indicate a thrust-faulting regime, which is consistent with the concept of a subducting slab (*Oncescu*, 1987; *Plenefisch*, 1996).

2.3. Geological stress indicators

Fault-slip data can be used to calculate the contemporary principal stress axes (e.g. *Angelier and Goguel*, 1979; *Angelier*, 1984, 1989; *Michael*, 1984; *Yamaji*, 2000). *Gîrbacea* (1997) analysed data from young basins (Brasov Basin and surroundings) which started to subside about 4Myr ago. Fault-slip data of Quaternary rocks yield a consistent NE-SW S_H orientation (Fig. 1A). In all cases fault-slip data indicate a normal faulting stress regime, and, thus S_H represents the intermediate stress axis (the maximum compression axis is vertical) and the extension direction is perpendicular to the symbols in Fig. 1A. According to *Gîrbacea et al.* (1998) and *Chalot-Prat and Gîrbacea* (2000) these basins are considered as localised graben structures evolving when high uplift rates in the Carpathians caused gravitational collapse towards the subsiding foreland basin (Focsani Basin). This block movement towards the SE resulted in NW-SE extension in the Brasov region and in NW-SE compression in the foreland during Pliocene-Quaternary. As described in *Morley* (1996), some of the normal faults could result from the arc geometry. According to *Leever et al.* (2006) the pattern of vertical movements changed dramatically at the beginning of the Quaternary, when subsidence in the western part of a proto-Focsani Basin changed to uplift while subsidence was still ongoing in the adjacent foreland basins. Since the age of faulting has only a lower limit through the age of the affected rocks (youngest age: Early Pleistocene; 0.8-1.8 Ma), it is likely that the geological indicators reflect the Early Quaternary stress field and a continuation of this stress field until recent times is not certain.

2.4. Borehole data analysis

A major contribution to the database of contemporary crustal tectonic stress in Romania comes from the analysis of borehole breakouts (Fig. 1A). Borehole breakouts occur because of compressional failure of the borehole wall as a result of stress concentrations that develop around a borehole in an anisotropic stress field (*Bell and Gough*, 1979). In vertical well bores breakouts develop perpendicular to the S_H orientation. The orientations of borehole elongations caused by breakouts can be measured with 4-arm-caliper logs (*Gough and Bell*, 1981). Oriented 4-arm-caliper logs have been analysed in 125 wells from which S_H could be successfully determined in 97 wells (*Negut et al.*, 1994, 2000, this study, Table 1).

Less information is available about the tectonic regime. For our study we estimated the tectonic regime based on the depth distribution of borehole breakouts (*Moos and Zoback*, 1990; *Schindler et al.*, 1998). The tectonic regime assignment was tested on wells which showed long logging intervals and numerous breakouts. In 16 wells a regime could be assigned (Table 2). The majority of breakout data gives no indication on the tectonic regime and thus was categorized as U (unknown regime). 24 wells are located close to salt structures (Table 1) and are not considered in this study because the stress orientations might be locally influenced by salt tectonics. In Fig. 1A the A-C quality data which are not influenced by local salt tectonics are displayed.

3. Analysis of the smoothed stress pattern

In chapter 2 we have presented a new compilation of tectonic stress indicators for Romania. In the following we analyse the present-day stress pattern and its wave-length as a base to investigate the present-day coupling degree of the Vrancea slab. As described above, some of the wells in which borehole breakout analysis was performed are located in the vicinity of salt diapirs and the stresses derived from these well logs may be decoupled from the regional stress pattern. Furthermore, the geological stress indicators also do not probably represent the contemporary crustal stress pattern, but show the S_H orientation during the time when bending stresses of the subducting slab where much larger and induced normal faulting tectonic regime with an S_H orientation parallel to the subduction zone.

Table 1
Results of the borehole breakout analysis (A-D qualities only).

	Name	Latitude	Longitude	S_H	Depth	Quality	Regime	S	Location	Number	SD	Totlength	Top	Bot
1	ROU117	46.124	25.081	98	1.397	A	U	*	Bunesti	21	10	484	790	2004
2	ROU148	46.259	25.284	6	0.525	B	U	*	Feliceni	14	17	127	198	852
3	ROU149	46.269	25.084	132	1.045	B	U	*	Porumbeni	35	12	281	437	1653
4	ROU140	46.265	25.281	104	1.093	B	U	*	Feliceni	11	7	158	846	1340
5	ROU133	47.398	26.152	135	1.690	B	U		Malini	19	14	501	1136	2244
6	ROU119	46.659	24.781	109	1.822	B	U		Petrilaca	9	14	300	1183	2460
7	ROU158	45.023	26.055	134	1.906	B	U		Boldesti	39	19	225	1562	2250
8	ROU201	46.666	24.764	139	2.300	B	U		Petrilaca	12	11	227	1589	3010
9	ROU143	44.997	23.731	11	2.960	B	U		Bustuchini	25	17	133	2618	3302
10	ROU144	46.355	26.84	87	4.479	B	U		Capata	9	16	394	4093	4864
11	ROU221	45.91	24.51	97	0.385	C	U	*	Nocrich	17	18	64	148	622
12	ROU198	45.906	24.439	44	0.533	C	U	*	Nocrich	10	23	53	182	883
13	ROU167	45.233	26.209	55	0.551	C	U	*	Carbunesti	5	21	54	201	900
14	ROU199	45.903	24.499	11	0.645	C	U		Nocrich	22	25	108	186	1104
15	ROU131	46.131	26.469	97	0.803	C	SS		Nineasa	14	19	60	641	965
16	ROU134	45.452	26.305	99	0.837	C	U		Berca	29	21	323	350	1324
17	ROU157	45.144	26.136	51	0.846	C	SS	*	Pacureti	27	23	552	290	1402
18	ROU219	46.26	25.09	162	1.053	C	U		Porumbeni	8	22	180	417	1688
19	ROU113	46.164	26.469	116	1.063	C	U		Nineasa	19	19	67	927	1199
20	ROU169	44.716	26.27	141	1.114	C	U		Lipia	6	12	21	477	1750
21	ROU122	44.925	23.896	102	1.171	C	U		Gradistea	7	23	381	406	1935
22	ROU146	44.974	25.348	12	1.223	C	SS		Dragaesti	7	24	409	739	1706
23	ROU105	44.476	23.44	171	1.444	C	SS		Cernatesti	10	13	81	898	1990
24	ROU102	44.968	25.593	174	1.671	C	U	*	Dealul Batra	7	16	79	1496	1846
25	ROU109	45.017	25.585	94	1.874	C	U	*	Colibasi	5	8	463	1350	2398
26	ROU127	45.016	25.578	21	1.963	C	U	*	Colibasi	4	7	293	1469	2456
27	ROU191	44.945	25.766	141	1.989	C	U	*	Margineni	13	13	53	1941	2037
28	ROU107	45.013	25.583	22	2.324	C	U	*	Colibasi	6	12	49	2051	2597
29	ROU108	45.014	25.583	67	2.336	C	U	*	Colibasi	8	14	85	2071	2601
30	ROU139	45.244	26.623	164	2.720	C	U		Barbuncesti	21	19	83	2480	2960
31	ROU136	44.919	23.404	151	3.792	C	NF		Barbatesti	5	10	5	3610	3973
32	ROU204	45.883	24.558	26	0.403	D	U		Sasaus	25	28	75	86	720
33	ROU118	46.383	25.253	140	0.415	D	U		Lupeni	21	31	333	24	806
34	ROU171	45.275	26.385	40	0.429	D	U		Tega	5	15	11	158	700
35	ROU166	45.558	27.817	179	0.453	D	U		Independenta	12	32	27	185	720
36	ROU189	45.493	27.838	28	0.458	D	U		Independenta	3	13	3	191	724
37	ROU177	46.392	25.261	45	0.543	D	U		Lupeni	6	32	28	230	855
38	ROU212	46.983	24.232	68	0.582	D	U		Strugureni	1		2	188	975
39	ROU111	45.571	27.804	127	0.598	D	U		Independenta	12	38	68	190	1006
40	ROU147	45.146	26.142	43	0.653	D	U	*	Pacureti	22	32	547	195	1110
41	ROU130	45.328	26.714	132	0.682	D	TF		Berca	31	27	214	191	1172
42	ROU222	44.47	24.27	71	0.689	D	U		Slatina	15	27	136	327	1051
43	ROU159	46.633	26.35	139	0.720	D	U		Geamana	11	34	28	390	1050
44	ROU187	45.943	24.48	54	0.742	D	U		Altana	5	32	100	293	1190
45	ROU164	46.525	24.573	128	0.816	D	U		Tirgu Mures	4	37	7	398	1234
46	ROU33	46.174	25.232	9	0.842	D	U		Petecu	14	28	483	373	1311
47	ROU112	46.154	26.468	111	1.041	D	U		Nineasa	3	9	18	788	1294
48	ROU173	44.969	25.551	55	1.089	D	U	*	Ochiuri	1		10	999	1178
49	ROU160	46.132	26.448	132	1.110	D	U		Poiana Sarat	3	5	13	945	1275
50	ROU116	45.131	25.781	48	1.117	D	U	*	Burloiu	36	36	634	283	1950
51	ROU110	45.107	25.474	67	1.121	D	U		Stirmini	2		107	722	1520
52	ROU162	46.241	25.295	142	1.155	D	U		Feliceni	18	34	111	594	1715
53	ROU137	44.97	25.522	21	1.175	D	SS	*	Ochiuri	15	32	117	1000	1350
54	ROU115	46.659	24.765	128	1.176	D	U		Petrilaca	3	4	80	597	1755
55	ROU152	46.239	27.255	105	1.195	D	U		Huruiesti	32	40	196	279	2111
56	ROU104	47.633	24.423	54	1.206	D	TF		Sacel	29	35	142	912	1500
57	ROU193	46.21	27.28	159	1.220	D	U		Maldaresti	22	35	192	491	1948
58	ROU142	44.969	25.522	1	1.252	D	U	*	Ochiuri	1		3	1098	1405
59	ROU129	44.962	24.858	165	1.271	D	SS		Colibasi	3	13	69	1085	1457
60	ROU151	44.756	23.423	131	1.295	D	U		Bibesti	19	33	273	683	1907
61	ROU194	46.34	24.909	47	1.304	D	U		Sacel	12	38	178	449	2159
62	ROU141	45.116	25.835	172	1.317	D	SS	*	Runcu	19	32	248	582	2051
63	ROU176	46.285	24.906	36	1.420	D	U		Sacel	16	39	350	683	2156
64	ROU120	46.664	24.424	140	1.526	D	U		Sabed	11	38	251	683	2369
65	ROU220	46.29	27.24	15	1.557	D	U		Ocheni	20	32	396	803	2310
66	ROU215	46.39	24.87	176	1.581	D	U		Soimus	8	32	78	877	2284
67	ROU125	45.044	23.422	40	1.591	D	U		Balanesti	10	30	247	585	2596
68	ROU183	46.417	26.467	78	1.608	D	NF		Sipoteni	16	39	175	837	2378
69	ROU179	47.27	22.178	1	1.650	D	U		Vest Chislaz	1		19	1599	1700
70	ROU211	47.133	26.083	158	1.678	D	U		Dumesnic	2		120	1562	1794
71	ROU153	46.771	26.802	59	1.681	D	U		Roman	19	30	922	986	2375
72	ROU128	46.539	24.848	166	1.699	D	U		Eremieni	3	16	18	991	2407
73	ROU135	46.127	27.286	94	1.747	D	NF		Buda	8	35	232	993	2500
74	ROU121	46.469	24.961	80	1.773	D	U		Ghindari	9	37	496	1093	2453
75	ROU182	46.311	26.545	80	1.775	D	NF		Dofteana	10	37	26	1346	2203
76	ROU180	44.831	23.699	179	1.776	D	NF		Coltesti	33	35	287	902	2650
77	ROU192	46.426	24.779	159	1.781	D	U		Petrilaca	3	7	125	1179	2383
78	ROU200	45.2	27.093	37	1.849	D	U		Rosioru	44	26	230	1191	2507
79	ROU174	45.025	26.034	146	1.897	D	U		Boldesti	15	37	47	1469	2325
80	ROU216	46.92	26.6	170	1.913	D	U		Balusesti	6	36	636	1498	2328
81	ROU114	46.102	26.45	93	1.936	D	U		Poiana Sarat	1		33	1865	2006
82	ROU124	46.535	24.843	163	1.978	D	U		Eremieni	2	2	5	1494	2462
83	ROU202	46.551	24.838	114	2.041	D	U		Eremieni	12	31	92	1481	2601

Table 1 *(continued)*

	Name	Latitude	Longitude	S_H	Depth	Quality	Regime	S	Location	Number	SD	Totlength	Top	Bot
84	ROU203	46.475	24.949	31	2.090	D	U		Ghindari	13	32	306	1469	2710
85	ROU106	45.132	25.927	49	2.233	D	SS	*	Vilcanesti	8	36	189	2041	2424
86	ROU138	45.112	26.073	24	2.296	D	U	*	Magurele	8	16	19	2238	2353
87	ROU197	44.846	23.638	25	2.466	D	U		Totea	3	10	39	1984	2948
88	ROU168	46.338	26.504	106	2.498	D	NF		Nord Pacurit	76	32	430	1639	3357
89	ROU209	44.967	25.783	18	2.670	D	U		Bobolia	1		24	2580	2760
90	ROU156	44.909	26.298	5	2.693	D	U		Cioceni	7	31	79	2000	3386
91	ROU123	44.935	26.46	118	3.295	D	U		Conduratu	24	26	404	2685	3905
92	ROU208	44.95	25.63	70	3.430	D	U	*	Colibasi	1		33	3350	3509
93	ROU172	44.768	25.951	127	3.959	D	NF		Sirna	13	30	29	3614	4303
94	ROU163	47.566	25.814	34	4.124	D	U		Frasin	2	29	3	3874	4374
95	ROU206	44.567	23.683	35	4.274	D	U		Stoienita	1		110	4124	4424
96	ROU195	45.628	26.354	27	4.638	D	U		Sibiciu	6	31	46	4386	4890
97	ROU207	44.883	25.9	172	5.720	D	U	*	Baicoi	3		105	5575	5865

The data are part of the World Stress Map database (*Reinecker et al.*, 2005; *Heidbach et al.*, 2008). Stress orientations for the majority of data have been compiled by *Negut et al.* (2000), the tectonic regime was assigned in this study. Name, well name in the WSM database; Depth, average depth of the breakout occurrence; Quality, quality ranking according to the WSM quality ranking scheme with A as best quality; Regime, is the tectonic regime assignment with NF normal faulting, TF thrust faulting and SS strike-slip faulting; S wells in the vicinity of salt layers or salt structures, Location indicates the location in Romania; Number, number of breakouts that has been identified in the well; SD, standard deviation of the average breakout orientation calculated with the circular statistics according to *Mardia* (1972); Totlength, cumulative length of all breakout intervals; and Top and Bottom, are the top and the bottom of breakout occurrence in the well.

Based on the subset of Romanian stress data within the area covered by Fig. 1, we assembled four different data sets for the following stress pattern analysis : data set 1 ($n = 84$) has all A-C quality data records, data set 2 ($n = 75$) has all A-C quality data records except the geological fault indicator (GFI), data set 3 ($n = 53$) has all A-C quality data records except all borehole breakouts (BO), and data set 4 ($n = 58$) has all A-C quality data records except all geological fault indicator (GFI) and the BO data records that are flagged due to their location close to a diapir structure (see Table 2).

In order to assess the stress pattern we calculated a smoothed stress field on a regular 0.2° grid using the four data sets. For each grid point the mean S_H orientation is calculated using all S_H orientations within the a priori given smoothing radius using also a weighting scheme according to the distance of each data record to the grid point and by data record quality (*Müller et al.*, 2003; *Wehrle*, 1998). In order to determine the appropriate smoothing radius we calculated for each of the four data sets the mean deviation between each mean S_H orientation of the grid and the nearest observed S_H orientation using increasing smoothing radii (Fig. 2). When the mean deviation exceeds the threshold value of 25° we use the corresponding smoothing radius for the smoothed stress maps displayed in Fig. 3. We choose this value since A-C quality data provide stress orientations within 25°.

The result clearly shows that independent of the data set the smoothing radius is small (35-65 km) in comparison with data sets from the Alberta basin and southern Germany, two regions which show homogeneous stress orientations on plate and regional scales. This is an indication for far-reaching stress sources (long wave-length stress pattern), whereas small radii indicate short wave-length stress patterns, as is the case for Romania. For Alberta, even large smoothing radii >200 km will not reach the 25° threshold, whereas Romania requires rather small smoothing radii of 35-65 km to reach a mean deviation of <25°.

The smoothed stress pattern of Romania supports the impression given by the measured data because it is characterised by small patches of different stress orientations. This corresponds also to the rapid change of along strike fault kinematics (*Matenco et al.*, 2007). Our analysis thus differs from the analysis of *Bada et al.* (1998) who see a uniform regional WNW stress trend in this region. According to *Heidbach et al.* (2007a), there are three potential reasons for this difference: (a) the smaller number of stress data used by *Bada et al.* (1998b) that cannot adequately represent a variable stress pattern, (b) different smoothing parameters that greatly emphasize the regional trend and show less data fidelity, and (c) *Bada et al.* (1998) might have used the subcrustal intermediate depth Vrancea earthquakes in the smoothing, whereas our stress analysis is based on crustal stress data records from a depth between 0 and 40 km only.

Table 2
Distribution of qualities (according to the WSM quality ranking scheme with A being the best quality) and tectonic regimes for the different types of crustal (<40 km) stress indicators in Romania.

Type	A	B	C	D	TF/TS	SS	NF/NS	U	Total
Borehole breakouts	1	9	21	66	1	8	7	81	97
Geological indicators	-	9	-	-	-	-	9	-	9
Focal mechanisms	-	1	56	22	23	22	34	-	79

The tectonic regimes are based on the relative magnitudes of the principal stresses $\sigma_1 > \sigma_2 > \sigma_3$ with compression positive. According to *Anderson* (1951) the relative stress magnitudes define the tectonic regime: in a normal-faulting regime (NF) the vertical stress S_v is the maximum stress, in a strike-slip (SS) regime it is the intermediate stress, and in a thrust-faulting (TF) regime it is the minimum stress.

4. Interpretation of the results

The crustal stress field in Romania does not show a long wave-length pattern, but is irregular (Figs. 1 and 3) with S_H orientations having a standard deviation between 46° and 56° dependent on the data set. Furthermore the tectonic regime is changing on small spatial scales. The following local stress patterns could be identified:

1. The westernmost part of the Moesian Platform (Getic Depression) is characterised by N–S compression with strongly scattered data as indicated by both earthquake and borehole breakout data.
2. S_H orientations derived from shallow geological stress indicators in the intra-Carpathian basins (e.g. Brasov Basin and easternmost Transylvanian Basin) are NE–SW oriented in a normal faulting regime.
3. The S_H orientation at the northern tips of the Intramoesian and Peceneaga-Camena Fault show high local variation. Along the Peceneaga-Camena Fault NF as well as TF regimes and frequently fault normal compression occur.
4. South of the Intramoesian Fault normal faulting is predominant.
5. In between the Intramoesian Fault and Peceneaga-Camena Fault to the SE of the Carpathians S_H is oriented roughly NW–SE.

From this stress pattern we draw three conclusions:

a) The high variability of regimes and S_H orientation indicates low differential stresses, i.e. the magnitudes of the principal stresses S_v, S_H, and S_h are close to each other.
b) Therefore, local stress sources, such as lateral density contrasts from crustal heterogeneities, topographically induced stresses, stress concentrations at fault tips etc., can lead to localised stress reorientations and are responsible for seismicity and breakout occurrence.
c) A downward pull of the crust by the Vrancea slab would result in a long spatial wave-length stress pattern that is definitely

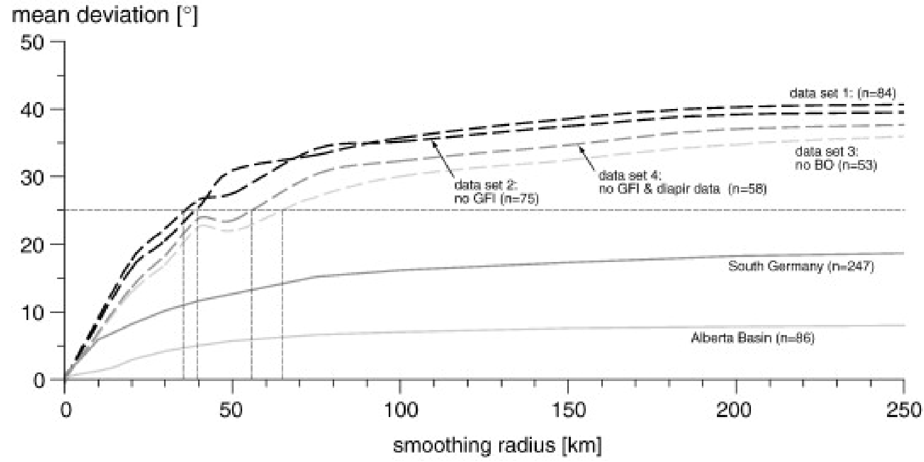

Figure 1. Wave-length analysis of the stress field of the area of Romania shown in Fig. 1. Mean value of the deviation between the orientation of maximum horizontal compressive stress (S_H) of each WSM data record shown in Fig. 1 and the smoothed value dependent on of the smoothing radius r of the smoothing algorithm. Numbers in brackets indicate the number of WSM data records of the four different data sets used in this study. In comparison we show the same analysis for the Alberta region and southern Germany which are regions of similar dimension. Note the steep increase of mean deviation with increasing search radius in Romania where local (third-order) stress sources may have a dominating effect in comparison to the small increase in South Germany and the Alberta basin where regional to plate-scale first- and second-order stress sources control the stress orientations. Dashed lines indicate the smoothing radius of each data set where the mean deviation exceeds 25°. This smoothing radius is used in Fig. 3 to calculate the smoothed stress pattern for the four data sets.

not seen in the observed S_H orientations. The Romanian stress field is not characterised by the dominance of first- or second-order stress sources like the push from the counter-clockwise rotation of the Adriatic plate or a lateral push in the Vrancea region as proposed previously (*Bada et al.*, 1998). First-order stress patterns would extend laterally over several times the lithospheric thickness and second-order stress patterns would extend laterally over several times the crustal thickness (*Zoback et al.*, 1989; *Zoback*, 1992; *Müller et al.*, 1992). Both are not observed in Romania. Therefore, we interpret the variability of stress orientations and tectonic regimes as indication that the Vrancea slab is mechanically not or only weakly coupled to the crust of the Eastern Carpathians.

5. Discussion

Crustal stresses are caused and affected by a number of processes acting on different scales in time and space. Stresses can result from the long wave-length forces driving plate tectonics (*Solomon et al.*, 1975), density variation effects (*Fleitout and Froidevaux*, 1982, 1983; *Zoback and Mooney*, 2003), and from processes at depth related e.g. to the remnant effects of subducting bodies. Localised short-scale effects arise because of crustal heterogeneities and by topography-induced stresses or influence of slip along faults (*Chinnery*, 1961).

For the Carpathians, we exclude as potential stress sources lithospheric cooling effects or membrane stresses (*Turcotte*, 1974). The latter arise due to latitudinal plate motion which is insignificant for the last few Ma for the area of investigation. If any membrane stresses had previously been active in Romania, they have disappeared due to viscous relaxation. We cannot exclude remnant stresses due to past tectonic events, but since the subduction under Vrancea is the most recent tectonic event, we concentrate on the subduction related stresses within the crust. These long-term processes can be superimposed by short-term effects such as stress relocations because of post-seismic strain variations. In the following we discuss a number of potential sources of tectonic stresses in Romania in view of the results of the crustal stress observations.

5.1. Plate boundary forces

Plate boundary forces have a key influence on the stress pattern: ridge push can cause deviatoric compression in the order of 20– 30 MPa in the adjacent plates and pull by subducting slabs creates tensile stresses in the same order of magnitude (*Solomon et al.*, 1980; *Bott and Kusznir*, 1984; *Park*, 1988). Forces resisting convergence at zones of continental collision may be responsible for intraplate stresses in Europe north of the Alps (*Zoback*, 1992; *Müller et al.*, 1992). According to *Bird* (1978), collision related shear stress at the base of the Himalaya is 20–30 MPa, which is confirmed by numerical modelling of *Solomon et al.* (1980), who used 20 MPa of resistive force to obtain a fit with intraplate stress orientations. Numerical models of the Pannonian Basin and surroundings identify the counter-clockwise rotation and northward indentation of the Adriatic microplate (Adria-push) against the Dinarides as the main cause for the regional stress pattern (*Morley*, 1996; *Bada et al.*, 1998, 2007). *Bertotti et al.* (2001, 2003) interpret the pattern of post-Sarmatian vertical movements in the SE-Carpathians to result from horizontal loading. However, the main phase of deformation in the Dinarides occurred during Oligocene and early Miocene (*Horváth*, 1984). From the analysis of contemporary stress data *Bada et al.* (2007) show that there is a gradual change from thrust-faulting ($\sigma_1 = S_H > \sigma_3 = S_v$) in the Dinarides to transtensional tectonics ($S_H \cong S_v$) in the central Pannonian Basin. Hydrofrac measurements in the Pannonian Basin show that the magnitude of S_h equals the vertical stress (*Gerner et al.*, 1999). Under the assumption that the vertical stress remains laterally constant, this represents a decrease of the S_H magnitude with distance to the Adriatic. This is also the result indicated by numerical modelling studies (*Bada et al.*, 1998, 2001). In a regional numerical plane stress model of the Pannonian Basin and the Carpathians *Bada et al.* (2001) applied an Adria-push of 30-50 MPa which created decreasing S_H magnitudes from maximum values of 100 MPa in the SW Pannonian Basin directly adjacent to the Dinarides to less than 20 MPa in the southern and eastern Carpathians. Since $S_H > S_v$, the horizontal differential stresses would be in the order of only a few MPa. Since the Pannonian Basin is not actively deforming at present, horizontal differential stresses should be rather low, again indicating that the Adria-push makes only a minor contribution.

5.2. Lateral variations of density within the lithosphere

They can lead to intraplate stress variations on long wavelength scale (several 100km). According to e.g. *Fleitout and Froidevaux* (1982, 1983) thickened lithosphere tends to be more in compression than normal lithosphere because of positive mass anomaly. Negative mass anomaly (crustal) roots and elevated

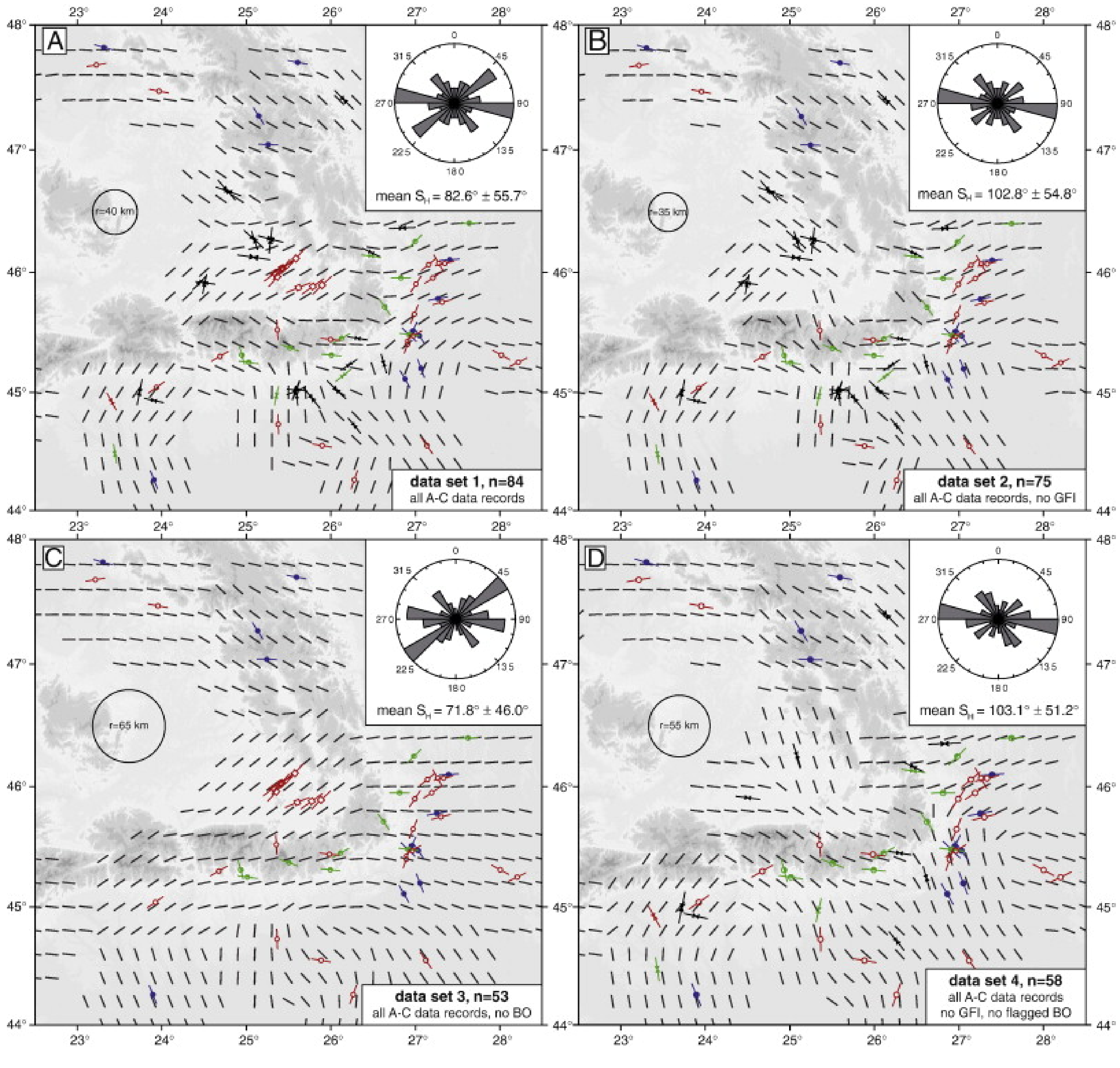

Figure 3. Smoothed stress maps for the four data sets on a 0.2° grid in comparison to the observed stress data and rose diagrams for the data sets. For explanations of stress symbols see Fig. 1. The smoothing algorithm (*Müller et al.*, 2003) is a modified version of the algorithm of (*Hansen and Mount*, 1990) and uses a weighting based on the data quality and the distance between grid point and stress observation locations within the smoothing radius around the grid point. Note that for all four data sets the smoothing radius is small indicating that no long wave-length pattern exists.

regions (because of their higher gravitational potential energy (*Coblentz et al.*, 1994)) create tensile stresses within the orogen and compression in the foreland. In the SE-Carpathians, no crustal root is visible in the refraction seismic data (*Hauser et al.*, 2001, 2007) and also no thickening of the lithospheric mantle is known. The most severe lateral density contrasts inside the lithosphere are the Focsani Basin in the foreland of the SE-Carpathian bend and a (related?) step in the Moho from 37 km beneath the Carpathians to 46 km beneath the Focsani Basin.

Topography and crustal density inhomogeneities of the Carpathians have been used to estimate stress and strain in 2D numerical models by several authors (*Tresl*, 1992; *Bada et al.*, 1998, 2001). Along a N-S profile through the Carpathians *Tresl* (1992) calculated average deviatoric tensile stresses of 30 MPa at the highest elevations (2000 m). This compares to the results of *Bada et al.* (2001) who showed in a parameter study that topography of 1-3 km causes deviatoric tensile stresses up to 22 MPa in the mountains and deviatoric compression up to 12 MPa in the foreland.

5.3. Shear stresses at the base of the lithosphere

Shear stresses beneath the SE-Carpathians induced by the sinking slab have been modelled by a corner flow model (*Ismail-Zadeh*, 2003). The resulting contemporary shear stresses at the base of the crust in the vicinity of the Vrancea slab are approximately 5 MPa. Herein we follow a simple approach of *Melosh* (1977) to obtain the horizontal stress contribution from basal shear drag σ_b at a plate of thickness H with stress free surface: for this configuration the shear stress σ_{xz} within the plate varies linearly with depth z: as $\sigma_{xz} = z/H\ \sigma_b$. Neglecting gravity the equation of equilibrium is $\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xz}}{\partial z} = 0$ and thus the mean horizontal normal stress in the lithosphere is $\sigma_{xx} = L/H\ \sigma_b$ with L length of the trajectory where σ_b is acting. If $H = 40$ km and $\sigma_b = 5$ MPa, the horizontal shear has to act over $L > 400$ km to reach values of 50 MPa of horizontal normal stress. For shorter distances, drag forces at the base of the crust provide only a minimal contribution to the crustal stress pattern.

5.4. Influence of faults

From numerical models of local stress perturbations in the vicinity of active dip-slip faults *Maerten et al.* (2002) conclude that there is a strong influence of the geometry of large-scale faults on the spatial distribution of stresses and thus the generation of secondary faults in their neighbourhood. Their results show that stress concentrations occur close to bends along major faults and close to fault intersections.

According to *Saucier et al.* (1992) the stresses induced by slip along undulatory strike-slip faults decay exponentially away from the fault. In a numerical parameter study *Connolly et al.* (2003) show that the influence of faults on the stress pattern is restricted to the immediate vicinity around the fault tips for frictionally controlled faults, as well as for faults with an elasticity contrast between fault gouge and surrounding material (weak inclusion model). The two main fault zones of the SE-Carpathians, the Peceneaga-Camena (PCF) and the Intramoesian Fault (IMF), cannot be attributed to be active along their whole fault lengths, furthermore, they show variations in their along strike kinematics (Matenco et al., 2007). Therefore, they may influence the stress pattern especially in the vicinity of the fault tips, as suggested from the observed S_H orientations (see above).

5.5. Buoyancy effect and bending stresses of an attached Vrancea slab

Slab pull can be a significant source of stress in the order of several 10s MPa acting on the unsubducted part of the plate. Furthermore, bending stresses that arise from flexure due to topographic loads (islands, glaciers) or from the down bending of the lithosphere at subduction zones can reach extremely high magnitudes (>1000 MPa; *Park*, 1988). *Royden and Karner* (1984) concluded that the flexure of the foreland beneath the foredeep sediments of Romania is too intense to be explained by the load of the overthrusted Outer Carpathians and thus an additional slab pull of an oceanic slab was necessary to explain the subsidence with the highest subsidence rates in the Sarmatian (12.5-10.5 Ma, *Bertotti et al.*, 2003). *Tarapoanca et al.* (2004) explain the depth of the basin by the load of the present topography with extra 500-800 m topography or a 86 km long oceanic slab attached at the base of the lithosphere. Because the subducted slab under Vrancea has steepened into a vertical position in the late Miocene we argue that initial bending-related stresses have been decayed already.

If the pull forces of a slab that is attached to the crust would exist in the SE-Carpathians, a distinct stress pattern with horizontal radial tensile stresses in the region of the subducted slab (Vrancea) would be visible. Furthermore, the resulting high stresses would locally overcome the strength of the lithosphere and cause geologically significant strain rates which are not observed either (*Matenco et al.*, 2007).

In order to assess the effect of an attached slab on the crustal stress field we accomplish a numerical experiment by means of a 3D geomechanical model with elastic rheology that solves the equation of equilibrium of forces. The model takes into account the inhomogeneous distribution of rock density and elasticity parameters within the major geological units such as the Focsani Basin, the basement and the Moho (Fig. 1; *Heidbach et al.*, 2007b). It also incorporates the topography and the major active faults as contact surfaces where relative movement is allowed. The lateral dimensions of the model are 550 km×380 km which are displayed in the overview inset of Fig. 1. Boundary conditions are gravity, a free surface, and no displacement perpendicular to the model sides and its bottom, i.e. we neglect the effect of any far-field plate boundary forces. The pull effect of the slab is parameterized and applied as a boundary condition applied at the Moho in a vertical direction.

Using the volume of the slab based on the tomography results of *Martin et al.* (2006, Fig. 1B) which is $\sim 4.9 \times 10^{15} m^3$ and a density contrast of 0.1 g/cm^3 the resulting mass excess of the slab is 4.9×10^{17}kg. This is a minimum assessment due to the low density contrast we assumed and thus the excess weight is three orders of magnitude less than the slab models considered by *Conrad and Lithgow-Bertelloni* (2002) which range in the order of 1.3-7 $\times 10^{20}$ kg. They consider a minimum of 15% of the excess weight to act as net pull in subduction zones. Thus, the net slab pull based on the Vrancea excess mass should be in the order of 90 MPa if the coupling region (the region where the slab is attached to the crust) has a diameter of 50 km. This value is also in the order of the results of *Schellart* (2004), who calculated net slab pull forces in the order of 41–61 MPa (or ca. 10% of the buoyancy forces) for a 100 km thick lithosphere.

Our choice of a circular coupling is based on the first-order geometrical interpretation of the tomography results of *Martin et al.* (2006) and our interpretation as sketched in Fig. 1C. Both indicate that the slab is only, if at all, attached in a small area NW under Focsani Basin (Fig. 1). For such a slab pull we expect a significant long wave-length radial symmetric stress pattern with a distinct NF regime around the Vrancea region. We varied the slab pull forces of that circular coupling from 3.5 to 128 MPa and present in Fig. 4 the results for 56 MPa slab pull. Similar results are obtained for 14 and 28 MPa. The numerical results indicate that even this fractional value of slab pull, would yield a pattern of the S_H orientation that is radially symmetric (circular) around the coupling region. The deviation of the modelled S_H orientations from the observed stress data is high (Fig. 4), indicating that this amount of slab pull is not appropriate to explain the stress observations. This result is independent of the location of the circular coupling area. Furthermore different coupling geometries, e.g. an elliptical shape would still result in a more elliptical pattern around the coupling area. From these results we conclude that the pull at the base of the crust has to be less than 14 MPa. Thus, we infer that in Vrancea actually only a small fraction of the net slab pull is transferred to the crust.

5.6. Small-scale stress variations because of regional and local stress superpositions

Local stress sources interfere with regional stresses, resulting in a stress field that is dependent on both the magnitudes and angular differences between the two stress sources (*Sonder*, 1990). Local stresses with principal axes at an oblique angle θ_L with respect to the regional stress orientation cause the resultant stress field to rotate by the angle a relative to the regional stress field. Furthermore, the stress regime might change, e.g. from strike-slip faulting to normal faulting. The amount of rotation a of the total stress field relative to the regional stress field is a function of the ratio between the regional differential stress and the locally induced stresses and is given as

$$\alpha = \frac{1}{2}\tan^{-1}\left(\frac{\sin 2(90-\theta_L)}{(S_H - S_h)/\,_{\sigma}\mathrm{L} - \cos 2(90-\theta_L)}\right)$$

with σ_L as local stress (*Sonder*, 1990). If the local stress field is large in comparison to the regional differential stress, the resultant stress field orientation aligns with the local stress. The superposition of local and regional stresses would explain the observed variability of the stress pattern of Romania. The contrasting styles of crustal deformation (reverse faults in the basement, normal faulting in the distal parts of the Carpathian foreland and contemporaneous sinistral and dextral strike-slip movements (*Morley*, 1996; *Matenco et al.*, 2007)) provide further evidence for the important role of local stress sources.

6. Summary and conclusions

The contemporary crustal stress pattern (tectonic regime and stress orientation) was analysed on the basis of 97 A–C quality crustal stress indicators from earthquake focal mechanisms, borehole break-outs, and geological fault-slip data. The modern stress data of Romania show a significant short-scale (in the order of 10 s of km) variability of S_H orientations and regimes, which is in contradiction to previous publications. We have shown that this difference most probably results from the application of different smoothing algorithms without control of the mean deviation between observed and smoothed S_H orientations, and the usage of subcrustal data in previous analyses (*Bada et al.*, 1998). This variability in the stress pattern does not agree with either a dominating lateral push from the Adriatic to the NE or with a push to the NW in the region of Vrancea. Furthermore, it does not fit to a radial extensional stress pattern that is expected if a sinking slab is mechanically coupled to the crust.

We have compiled studies on potential sources of regional scale tectonic stresses and conclude that the intraplate regional horizontal differential stresses arising from basal drag forces or lateral plate boundary forces do not exceed the order of 20 MPa. From the strong variability of stress orientations and tectonic regimes we infer that local stress sources such as lateral density variations (Focsani Basin with 10-15 km of sediments), gravitationally induced stresses caused by varying topography and stress perturbations due to faults disturb the regional stress field. These local stress sources create additional stresses at least in the order of magnitude of the far-field differential stresses.

Our main conclusions are:

1. The contemporary tectonic stress pattern of Romania shows small-scale patches of homogeneous stress orientations and tectonic regimes (areal extent<35-50 km) and no long wavelength features.
2. Plate boundary forces are thus considered to make a minor contribution to the crustal stress pattern of Romania, e.g. a dominant effect of the Adriatic push is not visible.
3. The observed variability of stress orientations and tectonic regimes in Romania is likely to be characterised by low horizontal differential stresses. In such a configuration local effects in the order of a few MPa result in significant stress reorientations. We conclude that the magnitudes of the local stress sources (topography, lateral density contrast, and stress reorientation at fault tips) are comparable to (in the order of maximum 20 MPa) or even higher than the regional differential stress magnitudes.
4. The coupling of the subducted Vrancea slab to the crust is estimated to be weak for the following reasons: (a) stress orientations: if the contribution of the slab was significant, a circular pattern of maximum horizontal stress orientations would be expected, but such a pattern is not observed; (b) tectonic regimes: from the discussion of potential stress sources, it follows that the horizontal stresses created from the coupling of the Vrancea slab have to be less than ca. 20 MPa. The buoyancy effect of a fully coupled slab creates a net slab pull of ca. 90 MPa, which would result in dominantly normal faulting tectonics that are not observed in the Vrancea area and surroundings. Our 3D numerical models support this conclusion.

The significant tertiary deformations in Vrancea and intra-Carpathian block rotations resulted from slab pull forces during subduction retreat until mid-Miocene and lateral plate tectonic forces (Adria-push) (*Morley*, 1996; *Sperner et al.*, 2001). From the analysis of the modern stress field it appears that both types of forces appear to have been considerably reduced at present.

One consequence of the weak degree of coupling of the slab to the crust is a reduced stress transfer into the crust in case of intermediate depth earthquakes. An even more important consequence of a slab coupled weakly to the crust is that the seismic gap between 40 and 70 km could be explained as a zone of weakness where no major earthquakes will occur.

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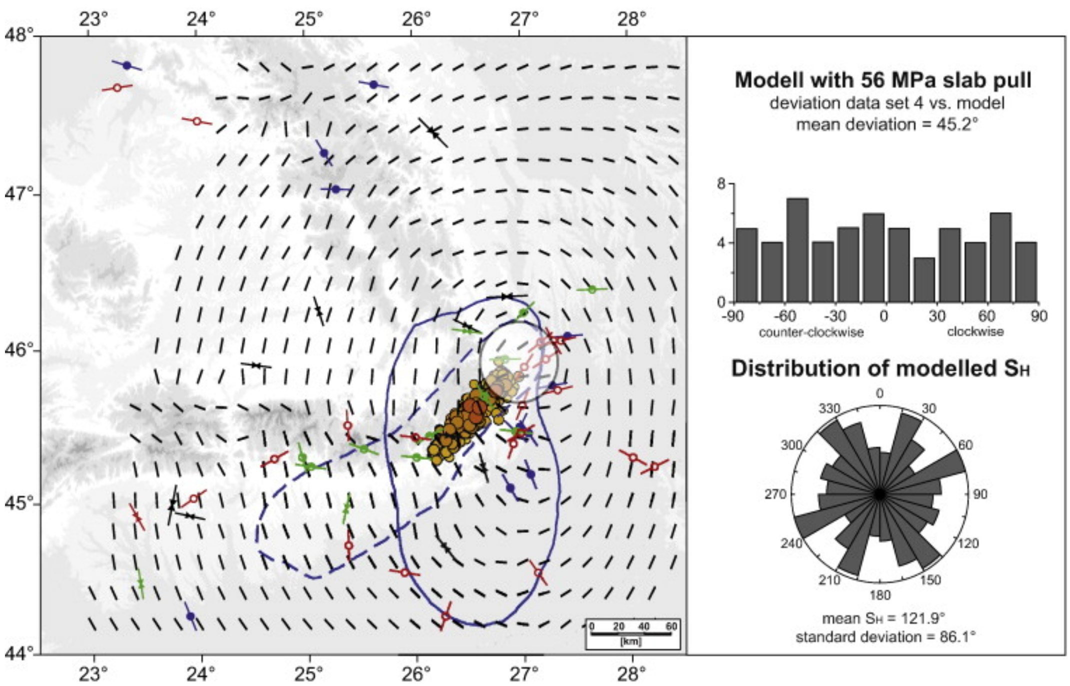

Figure 4. Map view of the geomechanical model results for an elastic model of the Romanian crust with slab pull acting vertically at its base (see the lateral extent of the model in the inlay of Fig. 1). The circle with 50 km diameter indicates the location where the slab pull of 56 MPa is applied. High standard deviation between modelled and observed S_H orientations implies that slab pull is not a relevant crustal stress source for this region.

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