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THE 1992 SUUSAMYR EARTHQUAKE AND THE AFTERSHOCK STRAIN FIELD

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The paper presents analysis of seismotectonic strain associated with the aftershocks of the 19 August 1992 M = 7.3 Suusamyr earthquake. Surface rupturing produced by the main shock falls into the zone of maximum uniform strain. The earthquake caused reorientation of stress axes on the ends of the major rupture accompanied by rift-type aftershocks. The nearly horizontal N-S orientation of the principal P axis remained invariable and that of the T axis changed 25 years before the main shock and during the aftershock and post-aftershock activity, which is consistent with the trend of maximum regional compression.

Aftershocks, seismic strain, large earthquake

INTRODUCTION

Seismotectonic crustal strain is as a rule analyzed from focal mechanisms of earthquakes but rarely based on their aftershocks. We consider stress and strain fields associated with the aftershocks of the M_s = 7.3 Suusamyr earthquake that struck the Northern Tien Shan on 19 August 1992, at 02:04 GMT. In order to investigate the geodynamic environment of the region, we constructed maps of stress-strain fields for the time 25 years before the main shock, within two years after it, and the following thirty months from 19 August 1994 to the end of 1997. The calculation methods from [1–4] were adapted to the conditions of aftershock activity [5].

SOURCE AREA

The Suusamyr earthquake was the largest event to strike the Northern Tien Shan for several recent decades. Its epicenter ($\varphi = 42.1°$ N; $\lambda = 73.6°$ E) occurred in the Suusamyr basin, in a region of weak seismic activity (Fig. 1). The main shock reached intensity MM IX and produced a long system of non-gravity surface breakage north of the epicenter [6, 7]. Two largest surface ruptures in the Suusamyr basin and along the Aramsu Range, both of a roughly west-east strike, separated by a 25 km wide zone of surface breakage (landslides), show reverse faulting with a minor right-lateral strike-slip component. The whole system of W-E tectonic and gravity ruptures totals a length of ~50 km. The major rupture plane dips to the south at about 70°.

Solutions for the focal mechanism of the main shock have been largely reported [8–10]. We used the Harvard CMT solution showing a west-east trending thrust fault on both nodal planes (Fig. 1). One plane dips to the south at 60° and the inferred reverse slip along it with a minor right-lateral strike-slip component agrees with the strike and dip of the surface rupture. Slip on the other plane, dipping to the north at 31°, may be a thrust. The main shock originated 20 km south of the rupture plane. With the dip of 60°, the hypocentral depth may reach 35 km (13 km according to [11]). The principal stresses in the source are along a nearly horizontal north-south P axis, a nearly vertical T axis, and a nearly horizontal west-east intermediate axis.

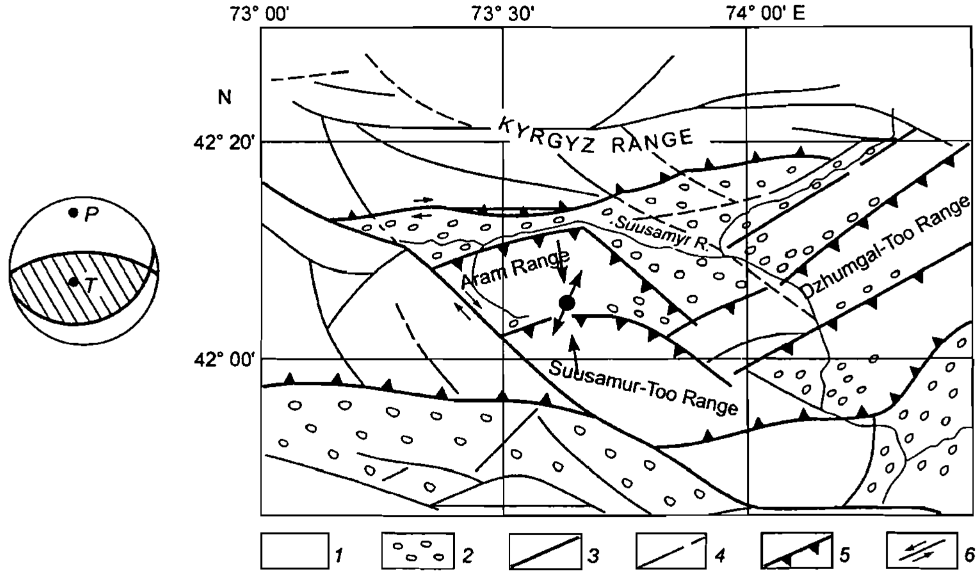

Fig. 1. Generalized geologic and tectonic setting of Suusamyr earthquake. ***1*** **— pre-Cenozoic deposits,** ***2*** **— Cenozoic deposits,** ***3*** **— master faults,** ***4*** **— hypothetical faults,** ***5*** **— reverse and thrust faults,** ***6*** **— strike-slip faults. Arrows show** ***P*** **and** ***T*** **strain axes in source of Suusamyr earthquake. Stereoplot is Harvard CMT solution (upper hemisphere).**

AFTERSHOCK ACTIVITY IN SPACE AND TIME

The Suusamyr earthquake was accompanied by a large sequence of aftershocks. In order to isolate the aftershock sequence, in the absence of distinct criteria, we compared seismicity maps of the region for the time 25 and 10 years before the main shock and selected representative $M > 2.5$ events since 1966. For 25 years before the Suusamyr earthquake, the region was struck by thirty $M = 2.5$ events, seven $M = 3.0$, and two $M = 3.5$ shocks (Fig. 2, *a*). For ten past years there was only one $M = 3.0$ earthquake and thirteen $M = 2.5$ events. Thus, one or two $M \geq 2.5$ events occurred yearly in the region of the future earthquake, and all $M \geq 2.5$ shocks that fall within the Suusamyr epicentral area during two years after the main event can be considered aftershocks, located in a west-east trending zone (Fig. 2, *b*). The densest cluster of epicenters matches the general trend of the aftershock zone and the strike of the rupture plane of the main shock. Large aftershocks (M = 5–6.2 and M = 4–4.5) are limited to a small area mostly to the west and smaller shocks (M = 3.0–3.7) distributed more uniformly cover a larger region to the west and east of the main shock (Fig. 2, *b*). The aftershock zone expanded slightly with time at the account of $M < 4$ events that spread towards its WNW end along the W-E rupture plane of the main shock. The post-aftershock activity continued for another two years (from 19 August 1994 to 31 December 1997) as numerous earthquakes with magnitudes below 3.5 exceeding the background seismicity.

METHODS

Aftershock seismotectonic strain was analyzed based on the concepts of residual displacement in a group of earthquake sources [1–4] adapted to aftershock activity [5]. The components of strain tensor were determined by summation of contributions from each aftershock (with regard to its seismic moment) to the total deformation of an elementary volume of averaging, as

$$E_{ij} = \frac{1}{2\mu V} \sum_{n=1}^{N} M_0^{(n)} Q_{ij}^{(n)}; \quad i, j = x, y, z,$$

where μ is the shear modulus $3 \cdot 10^{11}$ dyne/cm^2, V is the elementary volume, $M_0^{(n)}$ is the seismic moment of the

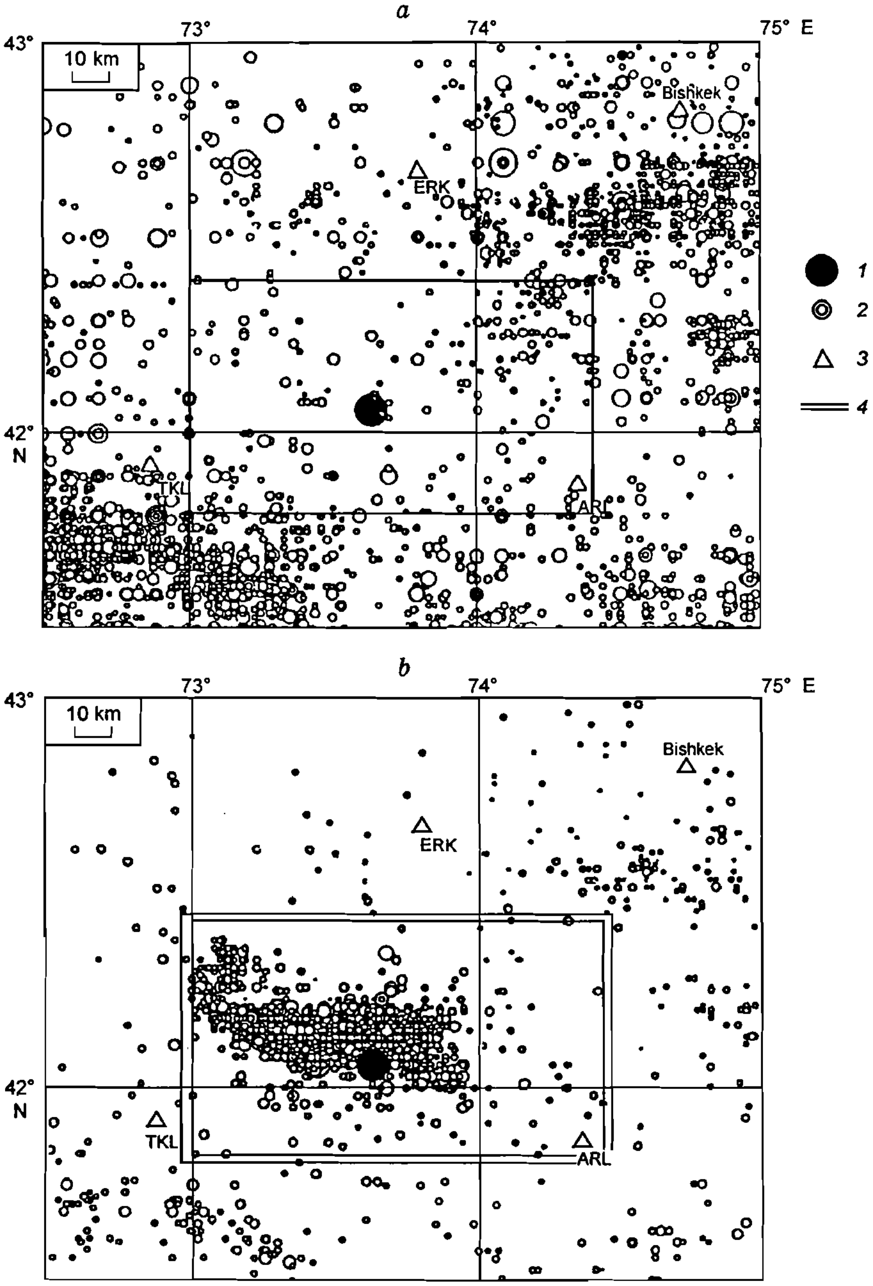

Fig. 2. Epicenters of instrumental seismicity before 19 August 1992 (*a*) and aftershocks of Suusamyr earthquake (*b*). *1* — source of Suusamyr earthquake (M_s = 7.3); *2* — sources of $M \approx$ 1–6.5 earthquakes; *3* — Kyrgyz seismic stations; *4* — aftershock zone.

n-th aftershock, and $Q_{ij}^{(n)}$ are the components of the unit tensor of the seismic moment of the n-th aftershock in geographic coordinates expressed through the parameters of focal mechanism [2]. Seismic moments were found from relationships with earthquake magnitude or energy class [2]. The E_{ij} strain tensor components obtained in geographic coordinates were then recalculated into principal components.

Strain rates were considered as mean values over each elementary volume which includes a number of aftershocks.

INITIAL DATA

The presented analysis of seismotectonic strain (Table 1) is based on 129 mechanisms of M = 2.0–6.0 aftershocks of the Suusamyr earthquake ($\varphi = 41.8–42.4°$; $\lambda = 73–74.4°$) from 19 August 1992 to 19 August 1994.

The mechanisms were obtained using P-wave first motions [12]. The wave type was determined on the basis of the Tien Shan regional travel-time curve [13]. Some of the analyzed aftershock mechanisms are from [14] and others are from [15]. The mechanisms of two largest M = 5.6–6.0 and eight M = 4.5 aftershocks could not be determined, the former in the southwest and the latter in the center of the aftershock zone. In addition, we used mechanisms of the earthquakes that occurred within the study territory since 1966.

Fault plane solutions were obtained at the Kyrgyz Institute of Seismology (from 1966 to 1977), at the Tajik Institute of Seismic Engineering and Seismology (from 1978 to 1990), on the basis of data from seismic stations in Kyrgyzstan, Kazakhstan, Tajikistan, and Uzbekistan, and then again at the Kyrgyz Institute of Seismology, based on data from local and regional seismic stations in Kyrgyzstan and some stations in Kazakhstan.

Data were averaged on a 0.2° grid. The thickness of the seismoactive layer was assumed 30 km based on the depth distribution of seismic events [11]. As a result, we imaged the field of seismotectonic strain associated with the Suusamyr aftershock activity (E_{zz}, E_{yy}, and E_{xx} components) in regions of strongest and weakest deformation in the vertical, north-south, and west-east directions (Fig. 3), and the distribution of principal strain axes (Fig. 4).

SPACE AND TIME DISTRIBUTION OF DEFORMATION IN THE SOURCE AREA

We analyzed deformation in the source area 25 years before the Suusamyr earthquake (from 1966 to 19 August 1992) and during the aftershock (19 August 1992—19 August 1994) and post-aftershock (from 19 August 1994 to 31 December 1997) periods.

Before the main shock the epicentral area was very rarely struck by events stronger than M = 3.5 (Fig. 2, *a*). The crust experienced nearly horizontal NE compression (shortening) and nearly vertical W-E extension (uplift) in the western part of the area, and nearly vertical compression and NW extension in the south and in the north. In the east it was mainly north-south shortening and west-east extension (Fig. 4, *a*). Seismic strain on the periphery of the area reached 10^{-12}–10^{-8} (Fig. 3, *a*).

During the aftershock activity, the vertical strain component (E_{zz}) showed a quite intricate pattern. The greatest portion of the region and the very source area experienced extension, with maximum positive values up to 10^{-7} in the center (Fig. 3, *b*). In the west and in the east, compression was associated with the ends of the major surface rupture, the maximum negative strain attaining -10^{-5} and the minimum -10^{-10}. The E_{yy} component behaved in almost the same way as E_{zz} but was of the opposite polarity. Extension along E_{xx} was observed in the central and western parts of the region and increased westward. Compression in the east was small and negative and in the west it reached -10^{-8}. The maximum E_{xx} strain is one to three orders of magnitude as low as that on the E_{zz} and E_{yy} axes (Fig. 3, *b*).

The aftershock principal strain axes were oriented to the northwest and north-south, and crustal shortening along them was accompanied by NE and W-E extension (Fig. 4, *b*). On the periphery of the region, maximum compression was nearly vertical. The crust on the ends of the rupture was subject to thinning and nearly horizontal north-south extension, which is an unusual setting for this region.

The behavior of strain components was studied separately in two periods of the aftershock activity: from 19 to 26 August 1992 ($M \ge 4.5$ aftershocks) and from 27 August 1992 to 19 August 1994 (decay of seismic activity, $M < 4.5$ aftershocks). Changes were observed in the style of deformation and in the distribution of energy released in aftershocks. The largest events (M = 5–6) occurred only within the first eight days, when E_{zz}, E_{yy}, and E_{xx} strain (Fig. 3, *c*) determined the dynamics of the whole aftershock process. In the second period, aftershocks spread over a larger area but were smaller in energy and strain (Fig. 3, *d*). Shortening on the E_{zz} axis in the west of the aftershock zone gave way to extension, and the E_{yy} and E_{xx} strain also switched to the opposite polarity. Over the rest of the territory, the E_{yy} and E_{xx} components retained their sign through the second period, and E_{zz} strain in the center of the zone took low negative values (Fig. 3, *c*, *d*).

The direction of principal strain axes of the first period (Fig. 4, *d*) remained almost invariable during the whole aftershock cycle (Fig. 4, *b*), as the later aftershocks contributed much less to the total deformation than the earlier events. In the second period the crust mostly experienced north-south shortening and uplift, and nearly horizontal extension in the west-east direction (Fig. 4, *e*).

During the post-aftershock activity (from 19 August 1994 to 1997), $M \ge 2.5$ earthquakes occurred most often

Table 1

Source Parameters of Aftershocks of 1992 Suusamyr Earthquake

Date			Origin time		Hypocentral location		*H*, km	*M*	*P*		*T*	
year	month	day	hr	min	φ	λ			*Pl*	Az	*Pl*	Az
1			2		3		4	5	6		7	
1992	8	19	2	4	42.07	73.63	15	7.3	76	171	17	21
1992	8	19	2	34	42.10	73.57	10	5.4	49	149	40	317
1992	8	19	3	12	42.13	73.27	15	6.4	11	192	79	3
1992	8	19	7	45	42.18	73.47	10	3.9	86	290	5	136
1992	8	19	8	51	42.15	73.18	10	4.4	44	46	66	202*
1992	8	19	9	3	42.23	73.67	5	3.9	7	211	90	110
1992	8	19	10	17	42.18	73.15	25	5.4	79	177	48	77*
1992	8	19	11	48	42.12	73.57	10	3.4	86	136	4	346
1992	8	19	13	36	42.30	73.50	10	3.4	21	11	89	102
1992	8	19	13	42	42.12	73.62	10	3.9	2	307	38	113
1992	8	19	13	44	42.18	73.37	10	4.4	12	127	80	277*
1992	8	19	14	17	42.18	73.43	15	4.4	83	10	69	103*
1992	8	19	15	46	42.03	73.95	5	3.4	78	131	23	7
1992	8	19	15	51	42.35	73.67	5	3.9	83	282	17	176
1992	8	19	16	36	42.15	73.72	0	3.9	21	11	89	102
1992	8	19	20	40	42.27	73.05	15	3.4	40	189	68	306
1992	8	19	22	45	42.22	73.30	10	4.4	80	173	72	79*
1992	8	19	23	17	42.15	73.63	20	3.4	78	349	30	244
1992	8	20	0	59	42.17	73.77	5	3.9	18	193	74	358
1992	8	20	1	28	42.12	73.53	10	3.9	87	283	25	17
1992	8	20	2	34	42.05	73.77	10	4.4	50	337	81	239
1992	8	20	2	46	42.17	73.60	10	4.4	83	320	83	230*
1992	8	20	6	52	42.15	73.53	10	3.9	44	311	71	62
1992	8	20	7	18	42.03	73.80	25	2.8	25	320	70	175
1992	8	20	12	21	42.17	73.33	10	4.4	83	343	28	86
1992	8	20	12	59	42.17	73.17	5	3.9	90	313	25	42
1992	8	20	16	30	42.10	73.68	10	4.4	72	170	26	39
1992	8	20	19	44	42.17	73.60	15	3.4	70	317	39	201
1992	8	20	21	35	42.15	73.62	10	3.9	77	329	34	80
1992	8	21	4	14	42.17	73.57	10	4.4	83	338	28	81*
1992	8	21	6	22	42.17	73.57	5	3.4	54	214	45	345
1992	8	21	8	0	42.15	73.40	10	2.8	36	103	79	357
1992	8	21	8	23	42.10	73.37	10	2.8	63	125	27	305
1992	8	21	9	18	42.12	73.57	10	3.4	82	124	76	32
1992	8	21	9	49	42.13	73.53	10	3.4	90	285	0	236
1992	8	22	3	57	42.20	73.58	5	3.4	19	215	75	356
1992	8	22	7	49	42.17	73.58	10	3.4	61	150	60	259
1992	8	22	8	52	42.20	73.58	10	4.6	62	326	89	57*
1992	8	23	7	15	42.18	73.53	10	3.9	85	328	14	82
1992	8	23	9	4	42.22	73.55	10	4.4	71	340	55	236*
1992	8	23	13	21	42.15	73.53	10	2.8	85	33	15	140
1992	8	23	14	1	42.17	73.60	10	3.9	16	232	87	332

Table 1 **(continued)**

1			2		3		4	5	6		7	
1992	8	23	18	40	42.15	73.73	10	3.4	25	1	89	273
1992	8	23	20	35	42.20	73.52	10	4.4	89	154	22	62*
1992	8	25	20	14	42.12	73.72	5	3.4	23	176	72	32
1992	8	26	4	0	42.15	73.37	10	3.4	76	310	36	201
1992	8	26	7	40	42.10	73.42	10	4.4	57	135	48	262*
1992	8	26	20	44	42.15	73.63	10	3.4	82	11	32	113
1992	8	26	22	1	42.18	73.57	15	4.7	75	323	19	178
1992	8	27	2	4	41.97	73.27	25	2.8	72	330	65	230
1992	8	27	3	14	42.18	73.78	5	2.8	88	342	17	246
1992	8	27	18	4	42.17	73.58	10	3.4	37	161	54	328
1992	8	28	2	34	42.12	73.67	10	3.4	52	248	39	94
1992	8	28	4	33	42.13	73.72	5	3.9	46	308	72	198
1992	8	29	1	50	42.13	73.33	10	2.8	83	21	68	289
1992	8	29	7	6	42.13	73.37	5	3.4	16	178	69	32
1992	8	30	23	56	42.18	73.57	15	3.4	56	341	34	161
1992	8	31	16	20	42.13	73.42	10	3.4	25	172	65	2
1992	9	1	8	48	42.22	73.60	5	3.4	72	338	19	153
1992	9	1	16	17	42.15	73.75	10	3.4	20	281	84	33
1992	9	2	11	35	42.17	73.55	10	3.9	27	183	87	279
1992	9	2	20	47	42.08	73.42	15	3.4	81	264	9	101
1992	9	3	9	4	42.18	73.18	10	3.4	51	187	73	291
1992	9	5	16	11	42.20	73.58	5	3.4	81	319	10	163
1992	9	7	5	9	42.10	73.72	10	3.4	77	153	23	30
1992	9	7	6	49	42.12	73,53	10	3.8	75	159	25	34
1992	9	7	7	56	42.15	73.32	10	3.4	86	137	28	41
1992	9	7	8	22	42.15	73.35	10	3.4	59	8	32	178
1992	9	7	8	33	42.15	73.35	15	3.8	37	111	78	4
1992	9	8	0	51	42.13	73.38	20	3.4	52	134	39	318
1992	9	8	10	24	42.12	73.43	5	3.4	90	230	4	145
1992	9	8	10	44	42.20	73.47	5	3.9	88	44	4	284
1992	9	10	6	7	42.32	73.13	5	3.4	77	31	26	151
1992	9	10	8	50	42.13	73.65	10	3.4	87	94	19	355
1992	9	11	21	26	42.12	73.75	10	3.4	69	152	29	13
1992	9	19	5	31	42.13	73.33	10	3.4	49	308	74	208
1992	10	2	4	10	42.12	73.42	10	3.9	54	19	83	273
1992	10	7	0	17	42.18	73.65	5	3.4	85	17	10	251
1992	10	9	11	13	42.12	73.40	10	3.4	86	136	28	40
1992	10	10	18	17	42.10	73.80	15	3.4	61	329	30	144
1992	10	15	6	21	42.05	73.77	15	3.4	72	238	44	346
1992	10	15	22	51	42.12	73.75	5	3.4	50	145	51	12
1992	10	17	11	7	42.27	73.03	10	3.4	85	186	54	278
1992	10	18	16	14	42.18	73.22	10	3.9	62	173	32	26
1992	10	21	22	39	42.02	74.17	5	3.4	89	235	3	81
1992	10	22	13	14	42.17	73.18	10	3.4	81	312	38	55
1992	11	17	17	2	42.13	73.27	10	3.9	24	207	66	27
1992	11	19	13	9	42.27	73.10	15	3.4	84	148	29	29
1992	12	11	12	41	42.12	72.95	10	3.4	62	292	32	83

Table 1 **(continued)**

1			2		3		4	5	6		7	
1993	1	14	16	51	42.12	73.62	10	3.9	64	166	32	32
1993	1	17	10	43	42.18	73.15	10	3.4	68	308	44	62
1993	2	2	21	5	42.12	73.43	10	3.4	88	135	27	41
1993	2	9	10	27	42.12	73.42	10	3.4	86	289	54	26
1993	2	18	15	29	42.17	73.27	10	3.4	68	147	29	12
1993	3	4	11	33	42.13	73.43	10	3.4	52	173	43	28
1993	3	20	2	21	42.20	73.60	10	3.4	68	328	26	182
1993	4	14	5	42	42.02	73.80	5	3.4	79	167	10	331
1993	4	18	22	15	42.35	73.18	5	3.4	84	16	8	142
1993	4	23	0	16	42.15	73.60	10	2.8	73	330	4	220
1993	5	12	0	24	42.22	73.52	0	2.8	84	57	15	305
1993	5	17	7	25	42.17	73.53	5	2.8	51	320	42	112
1993	6	30	1	36	42.12	73.58	15	2.8	76	234	27	346
1993	7	4	22	52	42.10	73.55	15	3.4	81	5	19	244
1993	8	17	19	25	42.17	73.20	15	3.9	60	358	34	146
1993	8	28	3	18	42.15	73.38	5	3.4	15	232	75	28
1993	12	12	12	11	42.25	73.70	20	3.4	26	328	76	211
1994	1	29	13	29	42.28	73.73	5	2.8	82	240	22	349
1994	5	8	8	29	42.13	73.72	10	2.3	83	350	12	115
1994	5	8	20	19	42.08	73.80	10	1.8	82	33	6	215
1994	5	12	22	15	42.07	74.27	10	1.8	31	276	58	89
1994	5	15	5	41	42.37	73.10	10	1.8	85	4	8	146
1994	6	21	15	51	42.22	73.12	10	3.4	26	175	78	285
1994	7	2	4	44	42.15	73.35	10	3.4	43	189	66	306
1994	10	4	1	26	42.08	73.37	15	2.8	60	156	32	360
1994	11	10	13	49	42.15	73.68	25	3.9	23	321	78	77
1996	6	12	3	38	42.12	73.35	5	3.4	12	301	79	115
1997	1	12	8	16	42.13	73.35	5	2.3	75	306	14	160
1997	1	12	10	54	42.10	73.40	5	2.3	24	150	60	7
1997	1	13	13	39	42.10	73.40	10	2.8	43	315	43	97
1997	1	12	8	16	42.13	73.35	5	2.3	75	306	14	160
1997	2	20	22	57	42.58	73.85	10	2.3	46	223	18	322
1997	2	22	13	44	42.15	73.78	10	2.3	29	334	61	156
1997	3	8	4	26	42.58	73.85	5	2.8	61	128	25	344
1997	4	21	12	1	42.12	73.75	10	2.8	17	117	50	6
1997	4	23	16	29	42.60	73.27	10	2.8	70	192	18	336
1997	5	8	7	2	42.15	73.60	5	2.3	15	205	53	316
1997	5	19	11	14	42.10	73.72	5	2.3	16	313	48	205
1997	5	26	2	20	42.08	73.55	15	3.4	11	170	51	275
1997	9	7	11	17	42.07	73.38	10	2.3	8	101	70	352
1997	9	11	21	50	42.07	73.47	16	2.8	21	317	50	71
1997	9	15	22	44	42.07	73.72	5	2.8	6	306	59	209
1997	11	4	19	40	42.60	73.65	5	2.3	35	336	43	205
1997	12	17	13	55	42.35	74.08	5	2.3	52	72	25	310

Note. ***Pl*** **is angle of** ***P*** **or** ***T*** **axis to vertical,** ***M*** **is magnitude.**
***After [15]; others are after [14].**

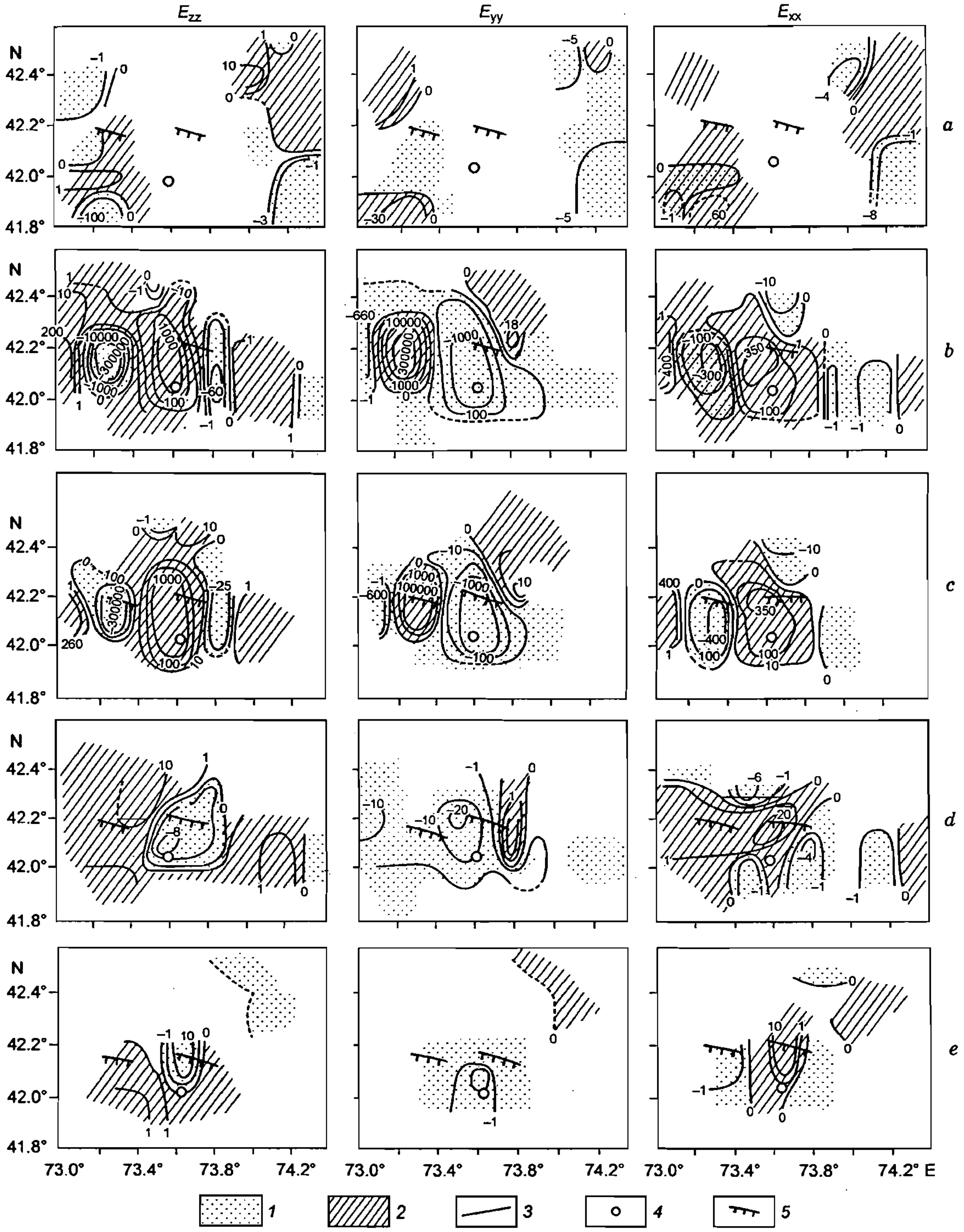

Fig. 3. Distribution of E_{zz}, E_{yy}, and E_{xx} strain components in source of Suusamyr earthquake (accuracy to 10^{-10}). *1, 2* — zones of positive and negative strain; *3* — strain contour lines; *4, 5* — source of Suusamyr earthquake and coseismic rupture [6] exposed to day surface. *a* — strain from 1966 to 19 August 1992 (Suusamyr earthquake); *b* — aftershock strain in source area of Suusamyr earthquake within two years from 19 August 1992 to 19 August 1994; *c* — aftershock strain within eight days, period of $M \geq 4.5$ aftershocks, from 19 August 1992 to 26 August 1992; *d* — aftershock strain for following two years, from 27 August 1992 and to 19 August 1994; *e* — aftershock strain for thirty months of post-aftershock activity, from 19 August 1994 to 31 December 1997.

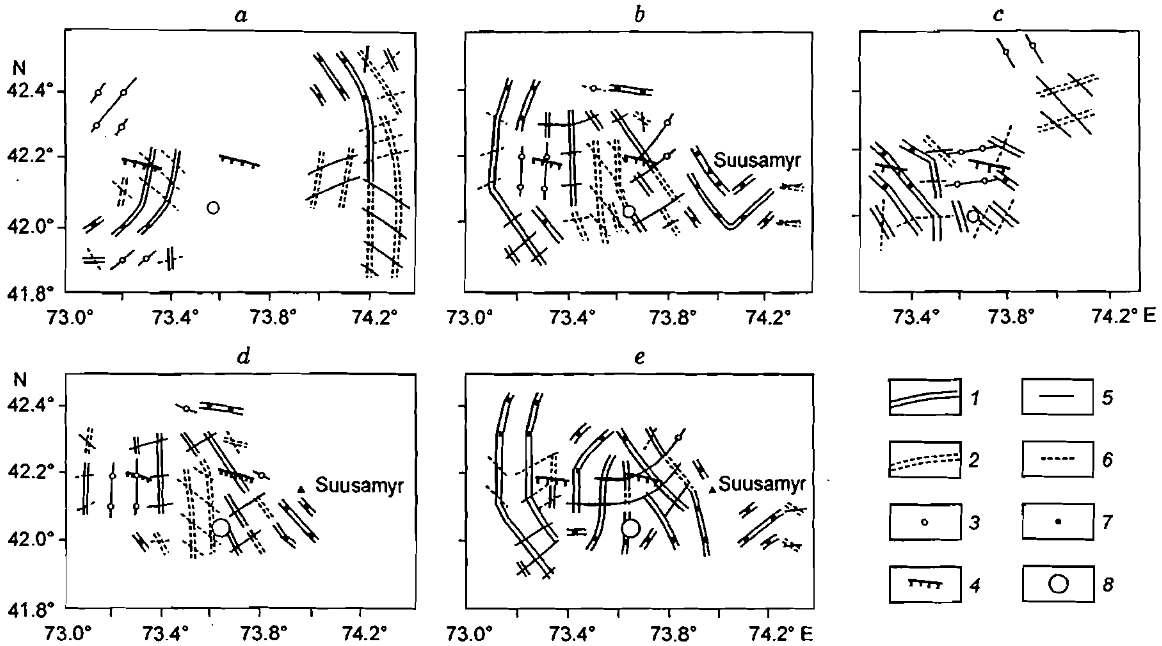

Fig. 4. Distribution of principal strain directions in source area of Suusamyr earthquake. ***1*** **— nearly horizontal compression;** ***2*** **— compression at medium angle to horizon (30–60°);** ***3*** **— nearly vertical shortening;** ***4*** **— strike of ruptures produced by Suusamyr earthquake;** ***5*** **— nearly horizontal extension;** ***6*** **— extension at medium angle to horizon (30–60°);** ***7*** **— nearly vertical extension;** ***8*** **— source of Suusamyr earthquake.** ***a*** **— strain from 1966 to 19 August 1992 (Suusamyr earthquake);** ***b*** **— aftershock strain in source area of Suusamyr earthquake within two years from 19 August 1992 to 19 August 1994;** ***c*** **— aftershock strain for thirty months of post-aftershock activity, from 19 August 1994 to 31 December 1997;** ***d*** **— aftershock strain within eight days, period of** $M \geq 4.5$ **aftershocks, from 19 August 1992 to 26 August 1992;** ***e*** **— aftershock strain for following two years, period of** $M < 4.5$ **aftershocks, from 27 August 1992 to 19 August 1994.**

in the center of the epicentral area of the main shock. The principal strain axes within this period followed the direction of the aftershock strain (Fig. 4, *c*), which may indicate that the aftershock activity still continues.

DISCUSSION

An earlier map of regional seismic zoning of Kyrgyzstan placed the region of the Suusamyr earthquake into the zone of intensity VII–VIII, apparently with no regard to evidence of past seismic rupture. However, there exists a report [16] of a Late Pleistocene-Holocene seismic event of intensity IX–X which produced ruptures striking almost parallel to the rupture plane of the 1992 Suusamyr earthquake. The orientation of the strain axes of the Suusamyr earthquake indicates a seismotectonic setting dominated by NNW-SSE horizontal compression. Therefore, the E_{yy} regional compression remained almost invariable for a long time. More evidence of the stability of regional compression comes from landslide activity. The predominant direction of flow in landslides triggered by the Suusamyr earthquake is to the north and to the south [6, 7], which is consistent with the general regularity that slide movement associated with large earthquakes follows maximum regional compression [17].

Although the territory was struck by large earthquakes in the past and a great event occurred within instrumental seismicity, seismic activity has been generally weak ($M < 3.5$) since 1966. Does it mean that the region experiences seismic quiescence? It is difficult to decide unambiguously. Note, however, that the slope of the recurrence curve of $M > 3.0$ instrumental seismicity for the Suusamyr aftershock zone and its surroundings had been about the average (0.47) till 19 August 1992.

Stress changes in the vicinity of a seismic rupture can be investigated through analyzing aftershock deformation. The strain components of the main shock and aftershocks in the center of the source area are compared

Table 2

Strain Components of Main Shock and Aftershocks, Compared

Event	Strain component, $\times 10^{-7}$					
	E_{xx}	E_{yy}	E_{zz}	E_{xy}	E_{yz}	E_{xz}
Aftershocks	0.3	–1.43	1.09	0.69	9.49	–7.12
Main shock	–4.47	–313	317	129	365	47

in Table 2, which shows deformation on the E_{yy}, E_{zz}, E_{xy}, and E_{yz} axes continuing in the same direction as in the main shock. E_{xx} strain is one to three orders of magnitude as low as that along the E_{yy} and E_{zz} axes. The latter thus represent the predominant N-S shortening and uplift of the crust. In the west-east direction, the crust slightly shortened during the main event and extended during the aftershock activity.

The aftershock activity on the periphery of the source area was accompanied by reorientation of the principal strain axes (Fig. 4). The figure shows horizontal extension and thinning of the crust (rift strain type) on the western and eastern terminations of the rupture plane of the main event. Similar changes of tangential and normal stresses at the ends of such ruptures were revealed by modeling and theoretical studies of friction-dependent stress changes in the vicinity of a strike-slip fault [18, 19]. Physical and numerical simulation for the conditions similar to the orogenic environment of the Suusamyr earthquake [18, 19] showed that seismic process that originated in a compressional setting produced zones of extension on the fault ends. The rift-type strain that arose on the ends of the rupture as a result of the Suusamyr aftershocks illustrates well the results reported in [18, 19]. The concentration of rift-type strain on the rupture ends during the aftershock activity indicates that the Suusamyr earthquake, one of few events where the rupture plane was exposed on the surface, created conditions for stress redistribution and origination of reverse-slip aftershocks.

Zones of maximum uniform strain associated with aftershocks were hypothesized [5] to delineate the epicentral area of the main shock and to allow estimates of rupture length in the source. This hypothesis was proven valid by the surface rupture in the Suusamyr earthquake which falls into the zone of maximum strain.

Values of seismotectonic strain can be used to estimate relative surface displacement by aftershocks. The aftershocks of the Suusamyr event caused a displacement of 3 mm, with the 10^{-7} maximum E_{zz} strain in the center of the source area and the 30 km assumed thickness of the seismoactive layer, and the displacement by the main shock was 95 cm, which agrees with the available field data [6].

CONCLUSIONS

Thus, the principal horizontal compression in the region of the Suusamyr earthquake retained its roughly north-south orientation for 25 years before the main shock, during the aftershock activity, and in the post-aftershock period, whereas the direction of principal extension changed.

The aftershock strain behavior does not perfectly follow that of the main shock. Aftershock deformation along the E_{yy}, E_{zz}, E_{xy}, and E_{yz} axes continued in the same direction as in the source of the main event, but the amount of strain along E_{xx} was one to three orders of magnitude as low as along E_{zz} and E_{yy} axes. Thus the main deformation occurred as north-south crustal uplift and horizontal shortening. In the W-E direction the crust was slightly shortened as a result of the main shock and extended during the aftershock activity.

The aftershock strain parameters show space and time variations. The principle T axis in the center of the source area was mostly horizontal and latitudinal within eight days after the main shock and became nearly vertical later, while the direction of the P axis remained invariable. The amount of strain near the source varied from 10^{-7} within first eight days to 10^{-10} within the following two years of the aftershock activity.

The major rupture of the Suusamyr earthquake reached the surface and produced conditions for stress redistribution. The reorientation of the stress axes on the ends of the rupture was accompanied by rift-type aftershocks. Surface breakage associated with the main shock occurred within the zone of maximum uniform strain.

The landslides triggered by the Suusamyr earthquake moved in the direction of maximum regional compression.

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