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Rupturing History of Active Faults during the Last 1000 Years in the Central Japan

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1. INTRODUCTION

For the purpose to understand a seismotectonic environment, it is essentially important to describe clearly an active tectonic framework that would be illustrated by long-term deformation. An individual large seismic activity is one of major key factors to construct active structures as an incremental strain step. In this paper, the author discusses about rupturing history of faults in central Japan where it is well known that many large earthquakes caused severe damages. Tsukuda (1987) examined historical earthquakes in the Kinki and the Chubu areas from the earthquake catalog by Usami (1987). He pointed out that clustering and eastward migration of earthquakes since the early 16th century are significant in the central Kinki area. It was concluded that the 1596 Fushimi earthquake caused by the movement of the Arima-Takatsuki tectonic line and Rokko fault system from distribution of damaged area and some faulting evidences at the archeological excavation sites. The faults of the 1995 Hyogo-ken nanbu earthquake, which probably did not move during the 1596 earthquake, are located in the southwestern margin of the above cited fault system. This estimation had been examined by the many trench excavation surveys after the earthquake. Tsukuda (1987) also forecasted that the future seismic activity would be concentrated outside of the past faulting area and this seems to be correct. Faulting areas for historical earthquakes are discussed according to recent geological studies and their migration patterns are shown as well. Historical earthquakes are listed in Table 1 and major active faults are shown in Fig. 1.

2. LARGE EARTHQUAKES FROM THE 16TH TO 19TH CENTURY IN THE KINKI DISTRICT

Sangawa (1986) investigated the detailed topography of the Konda-yama tumulus (burial mound, 430 m long) in the eastern end of Osaka plain. This tumulus is said to have been built for the Emperor Ohjin in the forth or fifth century. He found that the tumulus was deformed by the Konda fault of 4 km long with vertical displacement of 1.8 m, which may represent historic destructive events. He concluded that the event was the 1510 earthquake because there was

Table 1. Historic earthquakes greater than or equal to M6.5 during the past 1300 years. Original data are obtained from Usami (1987).

Date(Y/M/D)	Magnitude	Location(Earthquake name)	Long.(E)	Lat.(N)
715/07/04	6.5-7.5	Tenryu river	137.8	35.1
715/07/05	6.5-7.0	Mikawa	137.4	34.8
734/05/18	7.0	Kii	136.1	34.3
745/06/05	7.9	Mino	136.5	35.4
762/06/09	>=7.0	Mino,Hida,Shinano	137.5	36.0
827/08/11	6.5-7.0	Kyoto	135.75	35.0
841/?/?	>=6.5	Matsumoto	138.0	36.2
863/07/10	>=7.0	Ecchu-Echigo	138.1	37.1
868/08/03	>=7.0	Harima, Yamashiro	134.8	34.8
887/08/26	7.4	N. Shinano	138.1	36.6
938/05/22	7.0	Kyoto, Kii	135.8	35.0
976/07/22	>=6.7	Yamashiro,Omi	135.8	34.9
1070/12/01	6.0-6.5	Yamashiro, Yamato	135.8	34.8
1185/08/13	7.4	Omi, Yamashiro, Yamato	135.8	35.0
1317/02/24	6.5-7.0	Kyoto	135.8	35.1
1325/12/05	6.25-6.75	Northern Omi	136.1	35.6
1449/05/13	5.75-6.5	Yamashiro, Yamato	135.75	35.0
1502/01/28	6.5-7.0	SW Echigo	138.2	37.2
1510/09/21	6.5/7.0	Settsu, Kawachi	135.6	34.6
1586/01/18	7.7-7.9	Hida, Mino (Tensho)	136.9	36.0
1596/09/05	7.25	Kyoto, Settsu (Fushimi)	135.6	34.65
1640/11/23	6.25-6.75	Kaga-Taiseiji	136.2	36.3
1662/06/16	7.3-7.5	Yamashiro, Omi	135.95	35.2
1666/02/01	6.75	W. Echigo	138.2	37.1
1718/08/22	7.25	Ina, Mikawa	137.9	35.3
1751/05/20	7.0-7.4	Echigo, Ecchu	138.1	37.1
1799/06/29	6.5	Kaga	136.6	36.6
1819/08/02	7.0-7.5	Ise, Mino, Omi (Hikone)	136.3	35.2
1830/08/19	6.5 +/- 0.2	Kyoto	135.6	35.1
1847/05/08	7.4	Nagano (Zenkoji)	138.2	36.7
1854/07/09	7.0-7.5	Iga-Ueno, Yokkaichi	136.0	34.75
1858/04/09	7.0-7.1	Kaga, Echizen (Hietsu)	137.2	36.4
1891/10/28	8.0	Mino, Owari (Nobi)	136.6	35.6
1909/08/14	6.8	(Anegawa)	136.3	35.4
1918/11/11	6.5	(Omachi)	137.88	36.45
1925/05/24	6.8	(N.Tajima)	134.8	35.6
1927/03/07	7.3	(N.Tango)	135.15	35.53
1930/11/26	7.3	(N. Izu)	139.0	35.1
1943/09/10	7.2	(Tottori)	134.08	35.52
1945/01/13	6.8	(Mikawa)	137.0	34.7
1948/06/28	7.1	(Fukui)	136.20	36.17
1952/03/07	6.5	Ishikawa pref. (Off Taiseiji)	136.20	36.48
1961/08/19	7.0	E. Fukui pref. (Kita-Mino)	136.46	36.01
1963/03/27	6.9	Wakasa bay (Off Echizenmisaki)	135.77	35.78
1966/08/03-	6.4	(Matsushiro)	138.2	36.5
1969/09/09	6.6	(C. Gifu pref)	137.04	35.47
1974/05/09	6.9	(Off. Izu Pen.)	138.48	34.34
1978/01/14	7.0	(Off. Izu-Oshima)	139.15	34.46
1984/09/14	6.8	(W. Nagano pref)	137.56	35.82
1995/01/17	7.2	(S. Hyogo pref.)	135.03	34.36

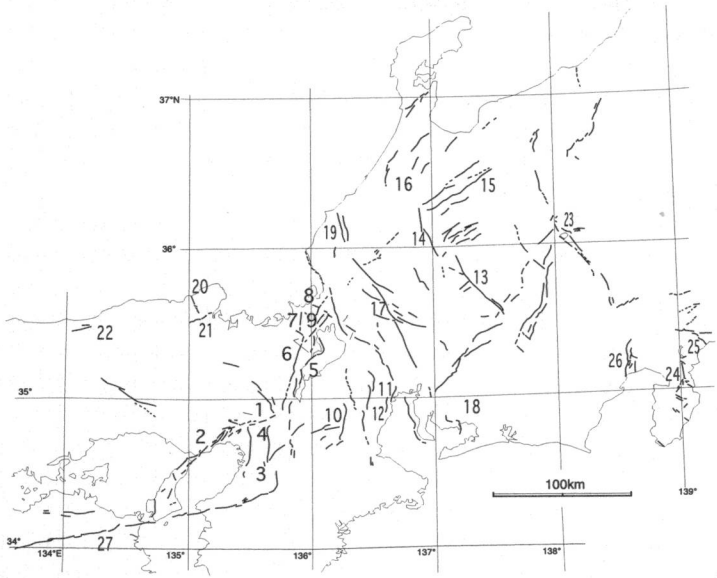

Fig. 1. Major faults in the central Japan (from Research Group for Active Faults of Japan, 1991). 1. Arima-Takatsuki tectonic line fault system, 2. Rokko fault system, 3. Konda fault, 4. Ikoma fault, 5. Western marginal fault system of the Biwa lake, 6. Hanaore fault, 7. Mikata fault, 8. Nosaka fault, 9. Daguchi fault, 10. Kizugawa fault, 11. Kuwana fault, 12. Yokkaichi fault, 13. Atera fault system, 14. Miboro fault, 15. Atotsugawa fault, 16. Morimoto fault, 17. Nobi earthquake fault, 18. Fukohzu fault (Mikawa earthquake fault), 19. Fukui earthquake fault, 20. Gomura fault (Kita-Tango earthquake fault), 21. Yamada fault (Kita-Tango earthquake fault), 22. Shikano fault (Tottori earthquake fault), 23. Itoigawa-Shizuoka tectonic line active fault system, 24. Tanna fault (Kita-Izu earthquake fault), 25. Kannawa and Kozu-matsuda fault zone, 26. Fujigawa fault zone, 27. Median Tectonic Line active fault system.

no other destructive earthquake reported in the eastern Osaka plain in our history. Magnitude for the earthquake is calculated to be 7.1 from the equation $M = (\log D + 4.0)/0.6$ (Matsuda, 1975, 1977), where D (in meter) is the surface displacement accompanied with earthquake. The long-term vertical slip rate (S) of 0.25–0.4 m/1000 years for the Konda fault is obtained from terrace deformation analysis. The recurrence interval (R) is estimated at 5000 to 7500 years from the equation $\log R = 0.6\,M - (\log S + 4.0)$ (Matsuda, 1977). From the empirical basis of the relation between magnitude and surface fault length, surface faults of the earthquake of magnitude 7.1 extend at least 20 km. Therefore, it is highly possible that the north-south trending eastern marginal fault system of the Osaka plain composed of the Konda fault and Ikoma fault generated the earthquake of 1510.

The following large earthquake after the 1510 event in the Kinki area is the 1596 (Keicho-Fushimi) earthquake. There were many discussions on the source fault for the 1596 earthquake. On the basis of hazard area illustrated by Usami

(1987), it is suggested that the Arima-Takatsuki tectonic line (ATL) fault system and the Rokko fault system of the northwestern margin of Osaka basin are the source faults of the earthquake. Recently, in some archeological excavation sites were found geologic evidences of faulting between the 15th and 17th century layers. Trench excavation surveys on one segment of the ATL fault system performed in 1995 strongly suggest that the 1596 event had been caused by the fault (Sangawa *et al.*, 1996).

The epicenter of 1662 earthquake (M = 7.8) is located at the western coast of the Biwa lake (Usami, 1987). The western coast region of the lake suffered severe damage and it is reported that a significant area of the western coast had been submerged into the lake, which is examined by Sangawa and Tsukuda (1986b) using ancient picturesque maps of that area for comparison with present topography. The detailed bathymetric map shows the ancient main road is now below the lake water. The tectonic depression caused by the earthquake was estimated at about 2–3 m. Fault scarplets near the coast that cut the terrace dated younger than 5700 years B.P. show 2.0–2.7 m of vertical displacement, the amount of which is comparable with the depression. The submerged zone was recognized along the entire western coast of the Biwa lake. The total length of surface rupture is expected to be more than 50 km for the earthquake magnitude of 7.8. Consequently, it was concluded that the 1662 event was caused by the movement of the western marginal fault system of Biwa lake (WMB), which is composed of en echelon faults and is closely related to the development of Biwa lake. Recent archeological excavations in Biwa lake indicated that the previous events occurred in some time middle of Yayoi period (BC 0 ± 50) and in about 3000 years B.P. (Sangawa and Tsukuda, 1986a, b). The northern half of the Hanaore fault on the west of WMB together with the Mikata, Nosaka and Daguchi faults are also thought to be activated during the 1662 earthquake according to the Recent excavation surveys (Yoshioka *et al.*, 1997; Sugiyama *et al.*, 1998a; Sugiyama and Yoshioka, 1999; Komatsubara *et al.*, 1999).

After the 1662 earthquake, 158 years later, the Hikone earthquake of 1819 (M = 7.4) occurred in central Kinki. The seismic intensity map for the earthquake (Usami, 1987) suggests that the marginal faults of the Suzuka mountains were activated although no geological evidences has not been found yet. The Iga-Ueno earthquake (M = 7.6) occurred in 1854. Yokota *et al.* (1976) found some surface evidences of surface ruptures of the earthquake along a segment of the Kizugawa fault. The seismic intensity map of Usami (1987) suggests the Kuwana and the Yokkaichi faults might be activated during the earthquake. Between the Hikone 1819 and the Iga-Ueno 1854 earthquakes, the so-called Kyoto earthquake ($M = 6.5 \pm 0.2$) occurred locally in the Kyoto city area. After this earthquake, 37 years later, the great Nobi earthquake of magnitude 8.0 occurred in the Chubu district, an adjoining seismic area.

The Atera fault system in the Chubu district is known as one of the most active faults in Japan. It cuts central Japan with a northwest-southeast strike and a length of about 60 km. This fault shows left-lateral slip with a vertical component of northeast side up. Lateral slip rate is estimated to be about 3–5 m/

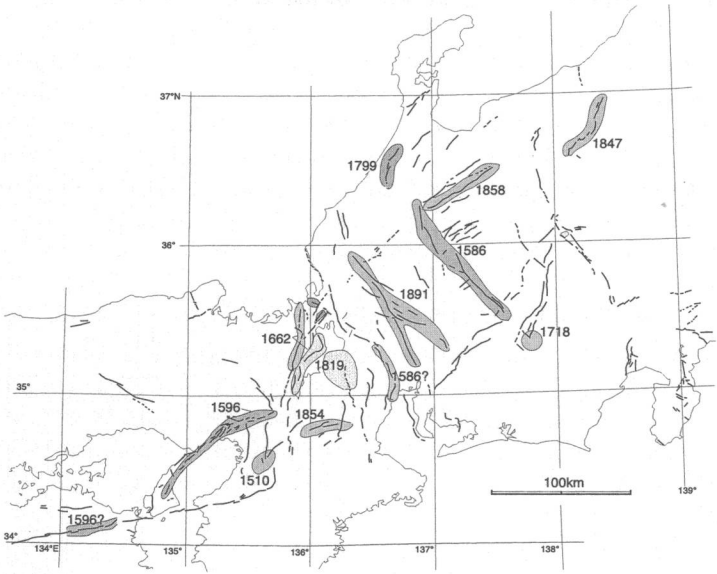

Fig. 2. Faulting areas during the 16th to 19th century, central Japan. Inferred ruptured area is marked by shade. Numbers are earthquake ages.

1000 years (Sugimura and Matsuda, 1965). Many excavation survey had been performed since 1981 (Tsukuda and Yamazaki, 1984, 1986). The latest four events show an average recurrence interval of 1700 years. The most recent event for the Atera fault is estimated to be the great earthquake of 1586 (so-called Tensho earthquake, M = 7.9–8.1 by Usami, 1987) from the following data; (1) Usami (1987) located the epicenter on the northwest border of Gifu prefecture from a damage area distribution. (2) Dai-itokuji, an abandoned temple on the fault is reported to have been collapsed completely during the 1586 earthquake. En-echelon fractures still remain covered by thick forest near the temple. (3) There is a legend that the 1586 earthquake made a pond, which is a wet muddy rice field now which is explained to be a sag pond from a geomorphological view point. (4) It is found recently that large scale land slides occurred during the earthquake to the southeast of the fault system (Matsushima, 1994 personal communications). (5) The existence of 1586 event was supported by recent excavation surveys along the fault by Toda *et al.* (1995).

Therefore, the recognition of the Atera fault as one of precaution faults by Matsuda (1981) is denied (Tsukuda *et al.*, 1993). Sugiyama *et al.* (1991) revealed that the Miboro fault, northwest extension of the Atera fault system also displaced during the 1586 earthquake. This evidence suggests that faults of 1586 Tensho earthquake extends as long as 85 km in total.

After the Tensho earthquake, the 1799 Kaga earthquake was caused by the

movement of the thrust fault (Morimoto fault) at Kanazawa city (Sangawa, 1986) in the northward extension of the Tensho rupture zone. The 1858 earthquake (M = 6.9) on the Atotsugawa fault (Matsuda, 1966; Research Group for Excavation of the Atotsugawa Fault, 1983) is located in the east of the northwest fault termination point of the Tensho earthquake. The Nobi earthquake of 1891 (M = 8.0, Matsuda, 1974) occurred after these seismic activities in the east. It seems that the occurrence of the Nobi earthquake is closely related to the earthquake migration in the Kinki and Chubu districts discribed above.

Faulting areas for the period of the four centuries are shown in Fig. 2.

3. EARTHQUAKES DURING THE 20TH CENTURY

After the Nobi earthquake occurred the 1909 Anegawa earthquake, 1925 Kita-Tajima earthquake, 1927 Kita-Tango earthquake, 1930 Kita-Izu earthquake, 1943 Tottori earthquake, 1948 Fukui earthquake, 1961 Kita-Mino earthquake, 1969 Gihu-ken chubu earthquake, 1974 Izu-hanto oki earthquake, 1978 off Izu Oshima earthquake, 1984 Nagano-ken seibu earthquake, and 1995 Hyogo-ken nabu earthquake (Fig. 3).

Characteristics of earthquake occurrences in this century is summarized as follows, 1) earthquake magnitude is less than 7.3, 2) earthquakes occurred in the outside of active areas during the 16th to 19th century, like the San'in and the Hokuriku districts, and the Izu peninsula. Large earthquakes of the 1945 Mikawa earthquake and the 1948 Fukui earthquake occurred close to the both ends of the

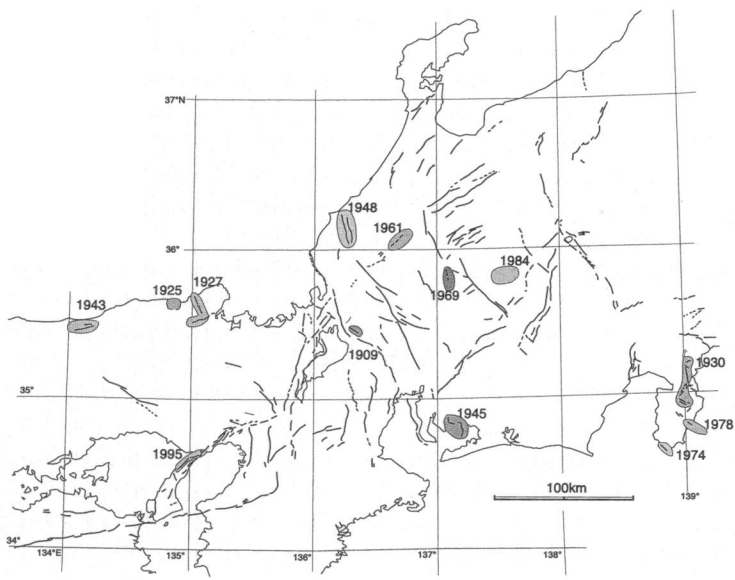

Fig. 3 Faulting areas in the 20th century.

Nobi earthquake faults. The 1925 Tajima earthquake of M = 6.8 and the 1927 Kita-Tango earthquake of M = 7.3 in the tectonic province of San'in zone northwest of central Kinki area, which had not been active during the period of 16th to 19th centuries. The 1943 Tottori earthquake (M = 7.2) occurred also in this zone. The recurrence interval of the Kita-tango earthquake fault is estimated to be more than 6000 years (Tsukuda, 1989a, b; Tsukuda and Sugiyama, 1993).

4. EARTHQUAKES DURING THE 11TH TO 15TH CENTURY

Only one or two large earthquakes are known in this period (Fig. 4). In 1185, the M7.4 earthquake occurred in central Kinki, and damaged Omi, Yamashiro and Yamato areas. The faults of the earthquake have not been identified yet. In 1325, the so-called Seichu earthquake occurred in the north of Biwa Lake. The faults for the earthquake are thought to be the Yanagase fault and the Tsuruga fault by excavation surveys (Sugiyama *et al.*, 1993, 1998b; Yoshioka *et al.*, 1998).

5. FORECAST FOR FUTURE SEISMIC ACTIVITY

Paleoseismological information concerning to central Japan is increasing rapidly. It is very possible to be able to reveal the faulting history during the last 2000 years in the near future. We may be able to see how the gigantic test peace of central Japanese island corrupted and estimate the future rupture area precisely. Figure 5 shows the faulting areas from the early 11th century to 1890. It is very

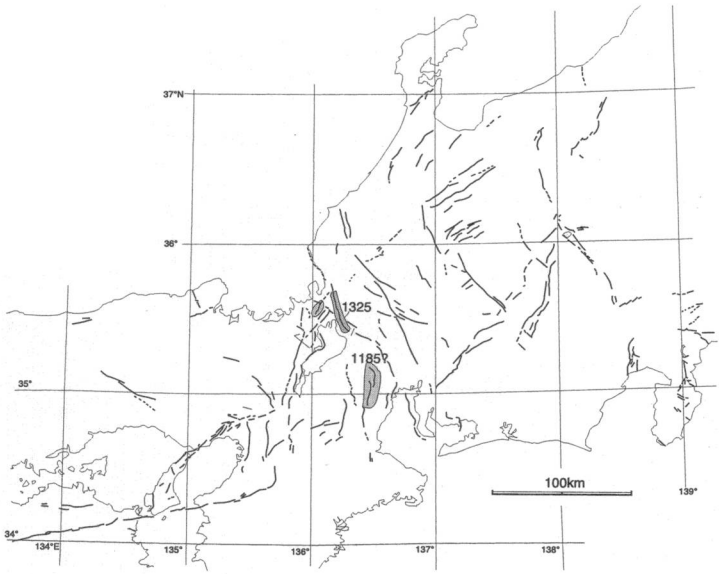

Fig. 4. Faulting areas during the 11th to 15th century.

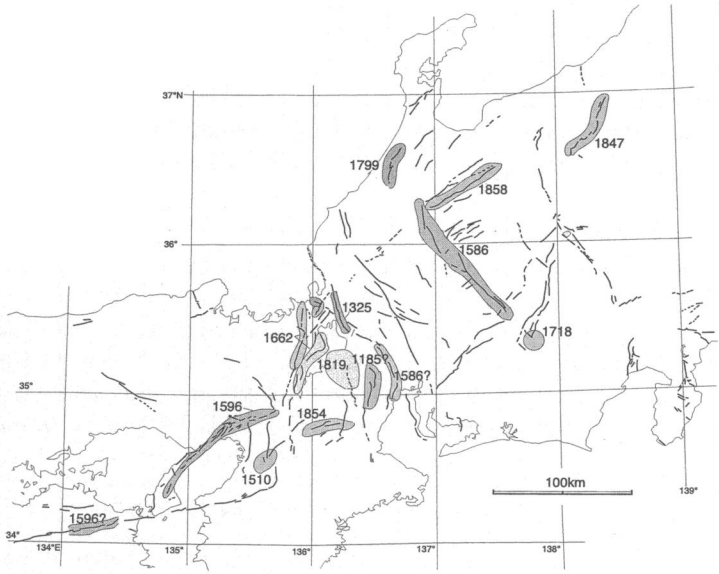

Fig. 5. Faulting areas from the early 11th century to 1890.

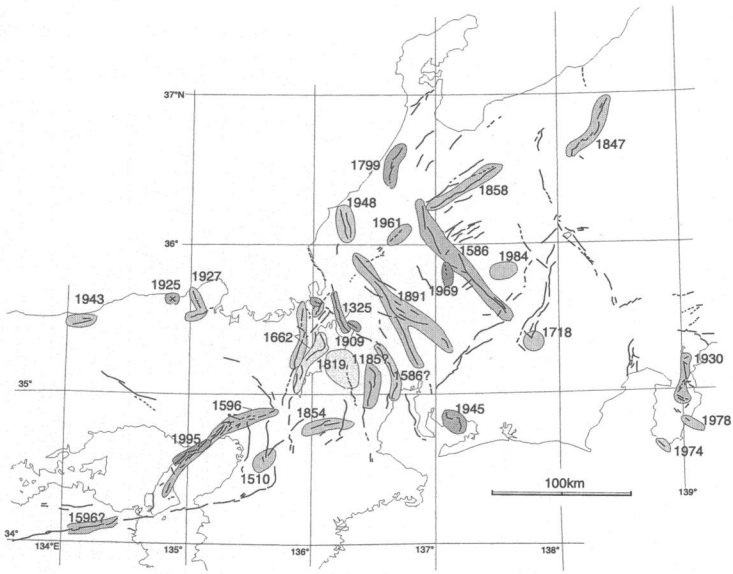

Fig. 6. Faulting areas during the last 1000 years (since the 11th century).

clear to be vacancy in earthquakes along (1) NW-SE trending fault zones of Itoigawa-Shizuoka Tectonic Line and (2) the Nobi-Mikawa-Fukui earthquakes, and (3) the Chugoku-San'in zone. Zone (2) looks almost ruptured in the last 110 years. Zone (3) has four major earthquakes of 1925, 1927, 1943, 1995. In the case of Zone (1), only Izu peninsula was activated in the 100 years, and still major faults are remain with high possibility of movements, as the Itoigawa-Shizuoka tectonic active fault zone, the Kannawa and Kozu-matsuda fault zone, and the Fujigawa fault zone (Fig. 6).

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