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Review Article

Precursor-Like Anomalies prior to the 2008 Wenchuan Earthquake: A Critical-but-Constructive Review

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Results published since the last three years on the observations of the precursor-like anomalies before the May 12, 2008, Wenchuan, M_s8.0 earthquake are collected and analyzed. These retrospective case studies would have provided heuristic clues about the preparation process of this inland great earthquake and the predictability of this destructive event if the standards for the rigorous test of earthquake forecast schemes were strictly observed. At least in some of these studies, however, several issues still need to be further examined to confirm or falsify the connection of the reported observations with the Wenchuan earthquake. Some of the problems are due to the inevitable limitation of observational infrastructure at the recent time, but some of the problems are due to the lack of communication about the test of earthquake forecast schemes. For the interdisciplinary studies on earthquake forecast, reminding of the latter issue seems of special importance for promoting the works and cooperation in this field.

1. Introduction

At least partly due to the tremendous loss of life and property and the intense social impact [1], the Wenchuan earthquake that occurred on May 12, 2008, in Sichuan Province of southwest China, has attracted widespread attention not only in seismological communities but also in other scientific communities. Since the occurrence of the Wenchuan earthquake, there have been some 300 papers published related to the precursor-like anomaly observations prior to this great earthquake, making it necessary for a systematic collection and comprehensive analysis of these materials. The necessity of such collection and analysis is further highlighted by the fact that over 3/4 of these publications are in Chinese with/without English abstract (with some of them being similar to, or just simply a repetition of the English publications) and quite a few of these publications are actually not known to international seismological communities. This is, similar to the situation of other developing countries [2], a characteristic of the scientific publications in China.

In the study of earthquake forecast/prediction, China seems of special features in that earthquake forecast/prediction has been kept for a long time as a nationwide scientific goal, even if there were intense debates on the predictability of earthquakes in the international seismological communities [3]. From merely the number of papers published, the Wenchuan earthquake might be one of the special, or even unique, events with so many studies on its forecast or pre-shock anomalies. If these anomalies could be confirmed, it would be an important event in the study on earthquake predictability; otherwise if these anomalies could not be confirmed, then it would be a useful sample for reminding of how the studies on earthquake forecast/prediction should be conducted in an efficient way. After the Wenchuan earthquake, there have been several studies trying to collect, compare, and analyze the (published and/or internal) data, including the data from the authors themselves (e.g., [4–11]). There are also some papers on the reflection of the earthquake forecast/prediction approaches based on the lessons of this earthquake [3, 12–15], with a diversity of ideas and data. The present paper is, to much extent, a continuation and extension of such collection and analysis works, but with different emphases in the analysis, highlighting the test of earthquake forecast/prediction schemes, and with a wider range of collection stressing interdisciplinary studies.

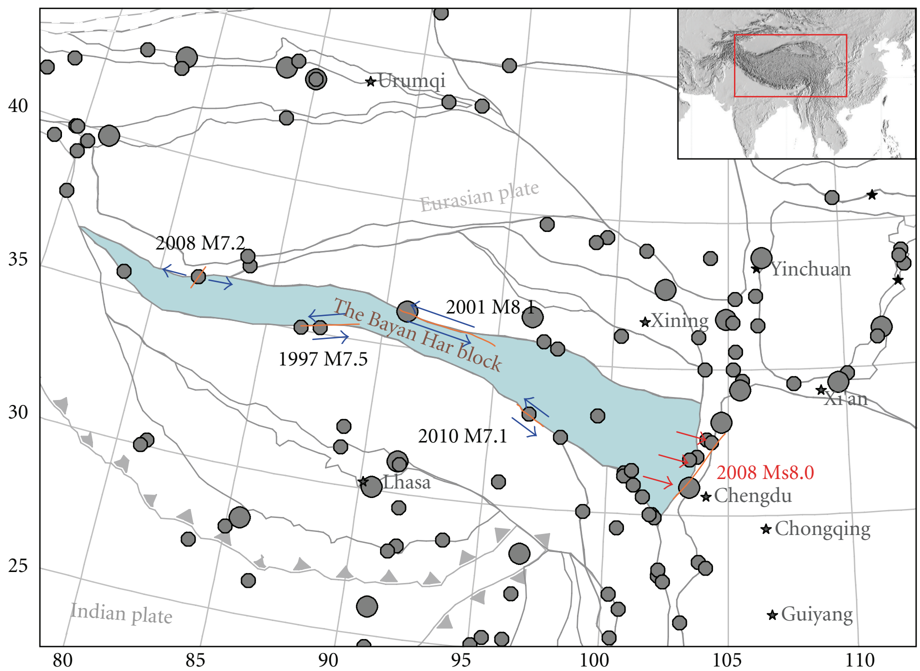


FIGURE 1: Distribution of major-to-great earthquakes around the Bayan Har block since 1997, with the 2008 Wenchuan earthquake located to the east, as shown by the text and arrows in red. To the top right is the indexing figure showing the position of the map. In the figure, orange lines show the earthquake ruptures, and blue arrows show the focal mechanism types of the earthquakes. Gray dots show the epicenters of historical major to great earthquakes. Gray solid lines indicate the boundaries of the tectonic blocks (according to [19]), with the Bayan Har block highlighted in the figure.

2. Materials Collected and Used for the Analysis

Although it has been only three years since the 2008 Wenchuan earthquake, because publications related to the precursor-like anomalies are within different research fields, the collection of such publications is still difficult to be completed. The collecting process was in two steps. For the materials published in English, searching terms "(ti = Wenchuan or ts = Wenchuan) and (ti = precursor or ts = precursor or ti = before or ts = before or ti = prior or ts = prior)" were used to the SCI-E database via the Web of Science (http://www.isiknowledge.com/). From 2008 to mid-2011, a total of 151 results hit the search. Removing the terms not directly related to the main topics, which are basically on the subjects of earthquake engineering and geological disasters, 61 articles were selected. For the materials published in Chinese, the China National Knowledge Infrastructure (CNKI) database (http://www.cnki.net/) was used with ("topic/title/keywords" = "(wenchuan) and (precursor or before or prior to)", in Chinese) as the search terms. Another two databases, the VIP database (http://www.cqvip.com/) and the Wanfang database (http://www.wanfangdata.com.cn/), were used as complementary sources. Using the screening criteria similar to that of the English publications, 261 articles in Chinese were collected. Abstracts of symposia [16–18] are not included, since most of the results were published after these meetings. Due to the same reason, diplomatic theses are not included in the References. We eliminated the "repeated publications" as much as we could. If there are two papers with exactly the same contents in English and in Chinese, respectively, we just keep the English one in the reference list. If there were two papers, with extremely similar contents and similar author teams, but published in different journals, then we just leave one of them (in the journal with higher impact factors) in the reference list. To keep the paper as concise as it could be, we also screened out the publications which are concentrating on the mechanisms of the phenomenology based on other studies rather than providing the ("fresh") phenomenological report.

Ranking by the number of papers published, these papers appear mainly in Journal of Geodesy and Geophysics (Wuhan, with the English edition Geodesy and Geophysics), Earthquake (Beijing), Acta Seismologica Sinica (the Bulletin of the Seismological Society of China, Beijing, with the English edition Acta Seismologica Sinica, changing to Earthquake Science since 2009), and Chinese Journal of Geophysics (the Bulletin of the Chinese Geophysical Society, Beijing, with the English edition Acta Geophysica Sinica or Chinese Journal of Geophysics), publishing no less than 15 papers in each of them. Journals publishing the related papers numbers up to 53, reflecting the diversity of the related results.

3. Characteristic Anomalies Reported and Characteristic Time Scales

As a background of the geology and seismicity related to the Wenchuan earthquake, Figure 1 shows the distribution and size of the major-to-great earthquakes around the Bayan Har block since 1997 (using the earthquake catalogue from the China Earthquake Networks Center (CENC)). During this time period, the Bayan Har block is the unique contributor to the major-to-great earthquake activity in continental China. Before this period, for more than 2 decades, there was no major-to-great earthquake occurring around the Bayan Har block. This provides the concepts of the geodynamic origin of the Wenchuan earthquake, and its preparation process.

Precursor-like anomalies, observed at different time scales prior to the Wenchuan earthquake, are in a wide range. Following is a brief summary of the main observations.

3.1. Anomalous Seismicity. Decade-scale quiescence along the Longmenshan fault zone [20, 21]; variation of monthly number of earthquakes since 2000 along the Longmenshan fault zone [22]; six-and-half-year-scale gap of seismicity above M_L4.0, disrupted 1 year before the Wenchuan earthquake [23]; five-year-scale PI "hotspots" along the Longmenshan fault zone, and five-year-scale "accelerating seismic release (ASR)" [21, 24, 25]; five-year-scale preshock increasing activity of intermediate-depth earthquakes [26]; three-year scale quiescence of seismicity above M_L6.0 [10, 27]; three-year-scale large-range seismicity pattern [28]; one-to-three-year-scale variation of "load-unload response ratio (LURR)" presented by seismicity [29, 30]; variation of "modulated earthquakes" 2 years before the Wenchuan earthquake [31]; two-year-scale variation of the homogeneity in seismicity [32]; variation of several statistical parameters of seismicity since the beginning of 2008 [33, 34]; half-year-scale seismic activation identified by PI method [35]. Besides, there are also studies on the potential tidal triggering effect which determines the origin time of the earthquake [36], and relation between Earth rotation and microseismicity [37].

3.2. Anomalies in Deformation Measurement. Decade-scale "locking" along the Longmenshan fault [38–40]; tilt variation from 2005 to 2006 [41]; accelerating fault activity since 2006 [42]; three-to-one-year-scale accelerating deformation [43]; "Oscillation anomalies" of GPS time series since 2007 [44]; one-year scale GPS baseline variation [45]; anomalous changes near the epicenter recorded by tiltmeter, since November 2007 [5]; anomalies of deformation (with resolution 3 months) before the Wenchuan earthquake identified retrospectively by wavelet analysis [46]; anomalies of tilt tidal factor in Shaanxi 3 months prior to the earthquake [47]; half-month-scale anomalous tilt [48]; and anomalies of deformation 3 days and 1 hour before the Wenchuan earthquake [40].

3.3. Anomalies in Strain/Stress Measurements. Five-year-scale perturbation of regional stress field before the Wenchuan earthquake by focal mechanism data [49]; increasing compressional strain since 2004 [50]; two-year-scale increase of regional stress [51]; two-year-scale micro-earthquake swarm, with focal mechanisms approaching to homogeneous [52]; months-to-year-scale disturbance in borehole strain measurement [53] and change of predominant focal-mechanisms of small earthquakes [54]; strain anomalies 3 months before the earthquake, with dominant frequencies depending on the epicentral distance [55]; changes of crustal stress since the end of April, 2008 [11]; week-scale variation of in-situ stress [56]; anomalous variation in in-situ stress measurement 48, 30, 8 hours and 37 minutes before the Wenchuan earthquake [57]; half-an-hour-scale abrupt anomaly recorded by strainmeter near to the epicenter [5, 58].

3.4. Possible Structure Variation. Four-year-scale preshock variation of seismic wave velocity [59]; three-year-scale [10, 60], one-year-scale [61], and two-to-one-month-scale variation of Earth resistivity [60, 61]; two-month-scale step-like resistivity anomalies [62]; one-month-scale increase of gas well pressures in a gas-field in Sichuan [63]; variation of noise correlation function (NCF) five days before the Wenchuan earthquake near the Longmenshan fault zone [64].

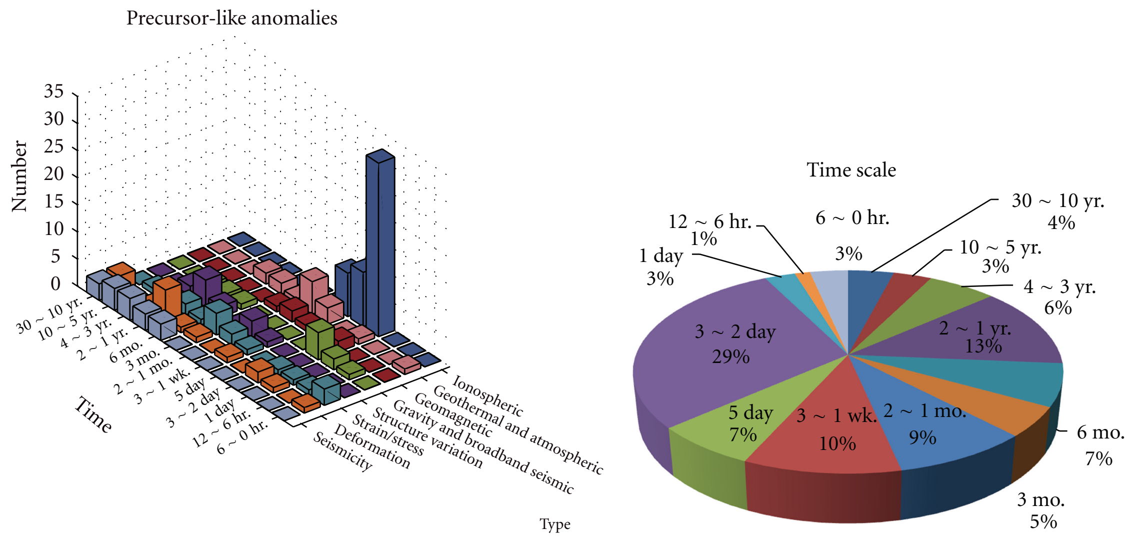
3.5. Anomalous Signals Observed in Broadband Seismic Recordings and Gravity Recordings. Decade-scale variation of gravity before the Wenchuan earthquake [65–68]; anomalous signals (tremors?) in broadband seismic recordings and gravity recordings, starting from about May 9∼10, 2008 [69–75].

3.6. Geomagnetic Anomalies. Geomagnetic anomalies revealed by fractional Brownian motion (fBM) analysis 2 to 3 months before the earthquake [76] and electromagnetic anomalies 2∼1 months before the earthquake [77]; and anomalies 3 days before the Wenchuan earthquake, within a large range surrounding the epicenter [78, 79].

3.7. Ionospheric Anomalies. Ionospheric anomalies 13, 6, 5 days [80], 6 days [11, 81–83], 6∼7 days [84–86], 5 days [87–89], 8∼4 days [90–93], 4 days [94], and 2∼3 days [81–83, 88, 94–118] before the Wenchuan earthquake.

3.8. Geothermal and Atmospheric Anomalies. Extreme meteorological condition 21 months and 10 months before the Wenchuan earthquake [119]; temperature variation near the epicenter since November 2007 [5]; half-year-scale decrease of precipitation [120]; temperature variation since January 2008 [121]; large-scale satellite infrared thermal anomaly, appeared since March 2008 [122]; infrared radiation anomalies about 2 months before the Wenchuan earthquake [123–125]; anomalies of outgoing long-wave radiation 40 days before the Wenchuan earthquake [126]; one-month-scale decrease of the SNR of the VLF radio signal detected by satellite [127]; higher temperature in Sichuan in May, 2008, comparing to the last 30 years [128]; abnormal infrasonic waves received 10 days before the Wenchuan earthquake [11]; abnormal increase of temperature since May 5 [129]; abnormal surface latent heat flux 7 days before the earthquake [130]; abnormal variation in thermosphere 3 days before the Wenchuan earthquake [131]; "earthquake cloud" 5 hours before the earthquake [132].

Additionally, preshock macroanomalies [133–137], including animal behaviors [138, 139] and vegetation degeneration [140], are also collected and analyzed. This can act as



(a) (b)

Figure 2: (a) Temporal distribution of the appearance of different types of reported anomalies, as summarized in Section 3. (b) Temporal distribution of the appearance of all the reported anomalies, as summarized in Section 3.

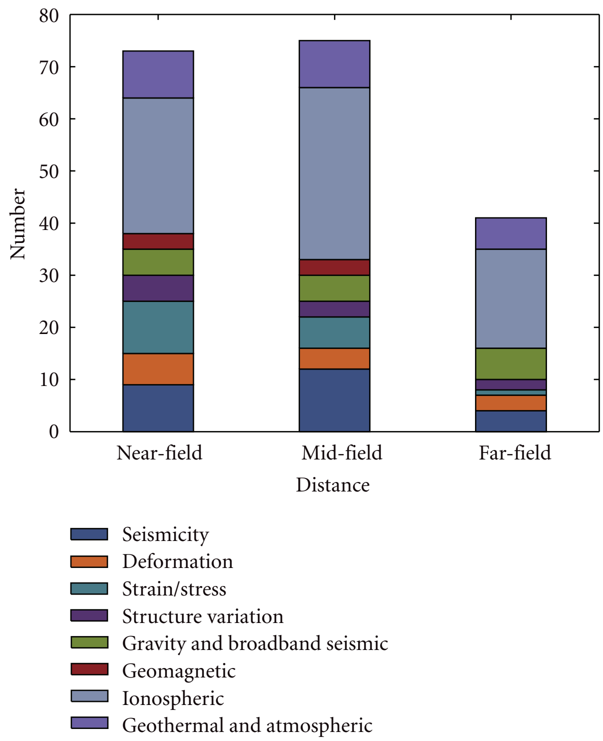


Figure 3: Distance ranges of the reported anomalies, as summarized in Section 3.

a useful reference, but how to confirm or falsify these (almost unrepeatable) observations needs further careful consideration.

At present, it is still hard to draw any definite conclusion on whether the above-mentioned observations, some are independent of others, while some are intercorrelated, may lead to a "unified description" of the earthquake preparation process. Some of the works are not understandable to us at present time regarding their methodology or observational phenomenology (e.g., [141–143]). However, it turns out that some characteristic times seem relatively important. Figure 2 shows, based on the analysis in this section, the "anomaly times" reported. It can be seen from the figure that anomalies detected by seismic, deformation, strain/stress, structure variation, gravity and broadband seismic recordings, geomagnetic, geothermal and atmospheric, and ionosphere observations appeared successively approaching the earthquake. The presently accessible data prevents from a detailed analysis of anomaly-distance dependence. As a conceptual picture, Figure 3 shows the statistics of anomalies with different distance ranges, in which "near-field" means the locations near to the earthquake fault, "mid-field" means the region within the circle centered at the epicenter and radius 1,000 km, and "far-field" means the regions beyond this circle. For those cases with distributed anomalies (an "anomaly field", as detected by satellite TEC), we take the locations within the above three ranges, respectively, in the counting of observation reports. It can be seen that the majority of the reports are within the "near-field" and the "mid-field" regions, with cautions necessary that the sampling of observational sites is by no means homogeneous.

4. Problems in Need of Further Considerations in Future

Except a few studies [10, 24, 25, 35, 79, 144, 145], there are few discussions on the statistical significance of the correlation between the anomalies observed and the earthquake. This is to much extent a problem which needs to be considered seriously in future, because in the test of earthquake forecast/prediction schemes, statistical significance is one of the key factors in need of consideration. Without a rigorous statistical test, some of the arguments, such as the year-to-month-scale long-range low-temperature before strong earthquakes [146], seems questionable.

The role of a single station analysis is, to some extent, double sided: on one hand, there might be some "special" stations which are especially "sensitive" to some precursory anomalies, even if the anomalies are associated with remote earthquakes; on the other hand, it is hard to draw any definite conclusion only by the records of a single station, while other stations have almost no "reflections." Result of Cheng et al. [8] indicates that, despite the anomalies registered at some individual sites, the routine precursor monitoring networks had no significant anomalies recorded. In the publications, anomalies retrospectively reported at individual stations/sites, ranging by distances from the epicenter, include abnormal strain changes observed at Guza, Sichuan, about one year before the Wenchuan earthquake [147], with epicentral distance $\sim 1.6^{\circ}$; increasing compressional stress in Wudu, Gansu, 7 months before the Wenchuan earthquake [148], and electronic anomalies in Longnan, Gansu [149]; water level variation in Guanzhong, Shaanxi [150]; deformation anomalies in Liujiaxia, Gansu [151]; water level and ground gas Hg anomalies in Zhouzhi, Shaanxi [152, 153]; ground fluid anomalies and electronic anomalies in Yunnan [154–157], with epicentral distance $\sim 5.5^{\circ}$; abnormal variation of fluid temperature in Qinghai [158]; abnormal ground fluid variation at sites as far as Huangyuan, Ningxia [159]; anomalous pre-Wenchuan-earthquake deformation/strain/stress recorded in Shanxi [160–164], with epicentral distance $\sim 10^{\circ}$; electromagnetic radiation anomaly in Gaobeidian and Ningjin, Hebei [165]; anomalous tilt in Tai'an, Shandong [166, 167]; anomalous deformation in Yixian, Hebei [168]; anomalous Earth resistivity from the end of April, 2008, in Qingdao, Shandong [169]; anomalous water level and water temperature variation 6 days before the Wenchuan earthquake, observed at Changli, Hebei [170]; anomalies of water temperature and Radon content in Ningbo, Zhejiang [171], with epicentral distance $\sim 15.6^{\circ}$. Variation of cosmic rays deals with the stations from Yangbajing, Tibet [172] to Guangzhou, Beijing, Irkutsk, Nagoya, and Moscow [173], with epicentral distance up to $\sim 51^{\circ}$. Because the Wenchuan earthquake is a great one, its preparation process may have an extremely large spatial scale. Therefore, we try not to be too skeptical about the reliability of these "remote" anomalies. However, when dealing with such a large spatial scale, and dealing with the situation that only a few sites have the anomalies, some statistical test is important.

For some of the observations, the anomalous/alarmed regions are so large that intuitive visual inspection is hard to provide correct judgments. In this case, statistical test is of special importance. An example is the ionospheric anomalies and the satellite-detected thermal anomalies as mentioned in the last section. Several days before the Wenchuan earthquake, abnormal TEC of ionosphere could be observed even in south China [174, 175], with distance about 11°, giving the idea of the size of the "warning region."

Length of data for "baseline comparison" is another concern when reading the related reports. In quite a few studies, the data for checking the "background variations" are only since 2007. This is to much extent an inevitable problem because several observational facilities are just at their beginning stage. However, this limitation prevents from getting concrete conclusions about the anomalies in the case that there is a lack of sufficient knowledge about the *normal* state. Evidently the continuous accumulation of observations is needed. Some of the papers mentioned objectively that there is still lack of the experiences of a great earthquake (e.g., [176]).

Coseismic changes, or changes before and after the earthquake, are presented by a few analysis (e.g., [39, 57, 81, 91, 127, 147, 177]). But generally, lack of analysis on the coseismic variation seems to be one of the problems for some of the investigations. This is also a problem in need of serious consideration, since in the study of the candidate precursors, coseismic variation may provide useful constraints on the mechanism of such precursors.

Based on the above discussions, we suggest that in future works, the following issues should be paid special attention to (1) Statistical evaluation of the correlation between the anomalies reported and the earthquake needs to be considered, semiquantitatively or quantitatively if possible; (2) distance from the observation station and the "target" earthquake has to be taken into serious consideration, especially, if the distance is too large, then theoretical concepts as per the size of earthquake preparation (e.g., [178]) have to be accounted for, and statistical consideration is needed for the large-scale anomalies; (3) information about the "normal" state, or the "baseline" variations, has to be accounted for in identifying the potential anomalies; (4) comparison of preseismic, coseismic, and postseismic changes would be of help to understand the earthquake preparation process as well as the characteristics of the anomalies.

The above-mentioned "problems," however, do not imply that the publications introduced in this paper are not acceptable. As a matter of fact, all these observations are contributions to the study of the predictability of this earthquake. Especially valuable, among the publications, there are papers debating on the causes of the observed variations [179–182]. Some papers provide "negative" results [144, 183–190] which are useful in excluding the misleading information. Some papers objectively report that some of the observational systems did not show significant anomalies [8, 191], or that some of the observation systems are shown to be unable to capture the precursors [192, 193]. There are reports stating that among the whole set of monitoring stations, the stations with anomalies only occupy a small portion (e.g., [194]). Some works also try to exclude the effect of other factors in identifying the anomalies [195, 196]. Some of the reports (e.g., [197–206]) just provided the observation (before, or before and after the earthquake) but were too prudent to reach any direct conclusion related to earthquake precursors. Analysis tools such as ROC test [25], RTL analysis [10], and RTP [207] were used to the forecast test. If applied to geomagnetic data (e.g., [155]), then more objective conclusions about the correlation between the variation or fluctuation of geomagnetic field and the earthquake could be obtained. The same need exists for the tidal data (e.g., [208]), fluid data [209], electromagnetic radiation data [210], or fault deformation data [211]. Even if for "traditional" seismicity analysis (e.g., [212, 213]), such statistical test would be of help. But generally, however, it is somehow "abnormal" that there have been not so many "alternative" explanations in such a field with so many complexities and controversies. Maybe time is a remedy to this problem.

Last but not least, very few discussions (e.g., [214, 215]) are concerning how to apply the knowledge from these retrospective case studies, such as the observed patterns of seismicity, practically to the decision-making approaches to "operational earthquake forecast" [216]. Complexity of the deformation-related precursors and fluid-related precursors has caused some attentions [217–220]. Considering the observation that earthquakes occur after the restore of some of the anomalies, such as LURR [29], the anomaly-based alarm-oriented forecast problem is shown to be more complicated. Based on gravity measurement, a forward intermediate-term forecast was made [221], but the forecast did not contribute to the reduction of earthquake disasters.

5. Discussion and Conclusions

Systematic collection and comprehensive analysis of the cases of earthquakes regarding the precursor-like anomalies have been an academic tradition in China. In China, *Earthquake Cases* series have been published (in Chinese with English abstract, by the Seismological Press in Beijing) regularly since the 1970s. Contemporary level of informatics allows search and analysis of different data flow including scientific publications themselves. In the case of Wenchuan, what can be seen is that different observations may have some intrinsic consistency to each other, providing heuristic clues to the preparation process of this great earthquake. Remarkably, several characteristic times, such as 2∼4 days and 1∼2 years, may reveal the preparation and approaching process of this inland great earthquake, which is in need of further investigation.

In the study on earthquake forecast/prediction, it is always much easier and much simpler to be critical or skeptical than to conduct concrete observations. Keeping this in mind, the objective of this paper is firstly to summarize what have been done either in China or in other places of the world; secondly to introduce these works, especially to non-Chinese-speaking communities; thirdly to avoid being too demanding or too skeptical in commenting on these works; and at last to propose, in a constructive way, several problems in need of consideration in future—some of them are not complicated but important. We believe that, if these problems were paid special attention to, then to much extent, more useful conclusions would be obtained, and the study on earthquake forecast/prediction would be "accelerated". And this hint is important not only for China but also for other places all over the world.

Being only 3 years after the Wenchuan earthquake, at the present time this work is still far from the stage of systematic evaluation [222–224] and/or empirical semiquantitative analysis [225–228]. More concrete conclusions need more time, although we have had an apparently good start with pretty rich (but complicated) materials.

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