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Seismicity variations associated with aseismic transients in Guerrero, Mexico, 1995-2006

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1 **Abstract**

2 Primarily aseismic deformation transients in subduction zones, sometimes asso-
3 ciated with tremors and low-frequency earthquakes, are a newly recognized mode
4 of deformation. Stressing in the up-dip seismogenic zone is increased episodically
5 due to down-dip transient slips, and each event may make it more prone to fail-
6 ure in a large thrust earthquake. It is important for seismic hazard assessment to
7 search and identify patterns of seismicity variation associated with transients. The
8 Guerrero, Mexico, region is chosen for this study because of long-term continuous
9 geodetic observations and abundant seismicity in the shallow subduction zone. We
10 search the GCMT and NEIC catalogs for earthquakes with depths less than 100
11 km between 1995 and 2006 within the area covering the region affected by major
12 transients since 1996. A completeness magnitude of $M_c = 4.5$ is determined for the
13 NEIC catalog used in this study, based on the maximum likelihood method.

14 Three large transients in 1998, 2001-2002 and 2006 are all temporally correlated
15 with high seismic rates in the studied area. In particular, transients are either pre-
16 ceded by a cluster of extensional earthquakes relatively far inland from the trench,
17 or followed by shallow thrust earthquakes close to the trench. In some cases, such
18 as the 2001-2002 transient, both types of activity are found bordering the transient.
19 The assembled evidence suggests that transients may serve as a mechanism of stress
20 communication between distant seismicity clusters in shallow subduction zones.

21 *Key words:*

22 Aseismic transient, Seismicity variation, Guerrero subduction zone

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23 1 Introduction

24 Aseismic transients with as yet no obvious relation to large earthquakes are a
25 newly recognized mode of deformation along major fault zones. Short-period
26 transients (several months to years) have recently been detected in shallow-
27 dipping subduction zones, such as Alaska-Aleutian [*Ohta et al.*, 2006], Casca-
28 dia [*Dragert et al.*, 2001; *Rogers and Dragert*, 2003; *Szeliga et al.*, 2004; *Mc-*
29 *Causland et al.*, 2005], Guerrero, Mexico [*Lowry et al.*, 2001; *Kostoglodov et*
30 *al.*, 2003; *Larson et al.*, 2004; *Lowry*, 2006], Hikurangi, New Zealand [*Douglas*
31 *et al.*, 2005; *Wallace and Beavan*, 2006], central and southwest Japan [*Hi-*
32 *rose et al.*, 1999; *Ozawa et al.*, 2002; *Hirose and Obara*, 2005], along the San
33 Andreas Fault [*Murray and Segall*, 2005] and on a detachment beneath the
34 south flank of Kilauea volcano [*Segall et al.*, 2006]. *Natawidjaja et al.* [2004;
35 2007] also suggested the occurrence of aseismic slip episodes, in 1962, 1968,
36 1975 and 1984, on the Sunda Megathrust along the coast of Sumatra, based
37 on the annual banding of corals, and *Meltzner et al.* [2007] have noted coral
38 evidence for an aseismic uplift event in late 2003 in central Simeulue Island
39 between the December 2004 and March 2005 megathrust slip zones. Aseismic
40 transients in some subduction zones are accompanied by deep non-volcanic
41 tremors, which are difficult to locate due to lack of distinct P or S-wave ar-
42 rivals. Tremors or low-frequency earthquakes, which are possibly components
43 of tremor sequences, may be distributed over a broad depth range [northern
44 Cascadia, *Kao et al.*, 2005], or clustered in a tabular zone along the thrust in-
45 terface [Shikoku, SW Japan, *Shelly et al.*, 2006] at the depths where transient
46 deformation is inferred to take place.

(Kristine M. Larson).

47 Transient deformation is estimated to be due to slow slips down-dip from the
48 locked region. Stressing in the up-dip seismogenic zone is increased episodi-
49 cally, and each transient can make it more prone to failure in a large thrust
50 earthquake. Thus, it is very important for seismic hazard assessment [*Mazzotti*
51 *and Adams*, 2004] to search and identify patterns of spatiotemporal seismic-
52 ity variation associated with transients. Such patterns are indeed detected
53 for some regions. For example, *Segall et al.* [2006] reported swarms of high-
54 frequency earthquakes, which accompanied, and are hypothesized to be trig-
55 gered by silent slip events on Kilauea volcano, Hawaii. During the Tokai slow
56 slip event [*Ozawa et al.*, 2002; 2005], *Yoshida et al.* [2006] reported variations
57 in the slab and crustal seismicity concurrent with changes in the plate slip
58 velocity. *Liu and Rice* [2005] noted that the initiation of the large 2001-2002
59 transient in Guerrero, Mexico, coincided with two normal-faulting earthquakes
60 of $M_w = 5.0$ and 5.8 relatively far inland from the trench, and the transient
61 was followed by several thrust earthquakes closer to the trench. The 2001-2002
62 large transient was suggested to act as a spatial-temporal connection between
63 the two clusters of seismicity. Repeated episodes of apparent switching be-
64 tween down-dip and up-dip earthquake activity have earlier been reported by
65 *Dmowska et al.* [1988] for other regions that have hosted large earthquakes
66 along the Middle America trench (MAT). They suggested earthquakes near
67 the down-dip end of the locked seismogenic zone as a mechanism of commu-
68 nication between these seismicity clusters.

69 The above observed connections between transients and seismicity motivated
70 us to systematically investigate their relation in a region with long-term con-
71 tinuous geodetic measurements and abundant seismicity. Guerrero, Mexico,
72 appears to be a well qualified candidate for this study. Guerrero is along the

73 MAT, where the Cocos plate subducts beneath the North American Plate
74 (Figure 1). The convergence rate varies from 53 mm/yr to 58 mm/yr along
75 the trench in direction N33°E [NUVEL1-A, *DeMets et al.*, 1994]. No signifi-
76 cant seismic energy has been released in the northwest seismic gap ($\sim 260^\circ$ to
77 258.8° E) since the rupture of the December 16, 1911 ($M_s = 7.8$) earthquake
78 [*Ortiz et al.*, 2000]. The most recent large earthquakes in the southeast seismic
79 gap ($\sim 261^\circ$ to 260° E) were in 1907 ($M_s = 7.9$) and 1957 ($M_s = 7.8$). These
80 two segments are roughly within the area affected by aseismic transients, and
81 covered by the Guerrero Global Positioning System (GPS) network. The first
82 continuous GPS station in Guerrero was established at CAYA in January 1997.
83 Permanent and campaign instrumentations were installed subsequently, and
84 now consist of over 10 years of deformation record at some sites [*Larson et al.*,
85 2004]. Locations of the permanent stations are shown in Figure 1. Two large
86 aseismic transients (southward surface displacement of ~ 2 to 5 cm), which
87 lasted for several months in early 1998 and from October 2001 to April 2002,
88 respectively, have been reported from the continuous measurements [*Lowry et*
89 *al.*, 2001; *Kostoglodov et al.*, 2003]. Recently, one transient with a deformation
90 size comparable to the 2001-2002 event was detected from March to December
91 2006 [*Larson et al.*, 2007]. Complete GPS time series of the north-component
92 displacement between 1996 and 2004 are shown in Figure 1 of *Lowry* [2006].

93 **2 Earthquake catalogs and determination of completeness magni-** 94 **tude M_c**

95 The GCMT (Global Centroid Moment Tensor) and NEIC (National Earth-
96 quake Information Center) catalogs are searched for seismic events between

97 1995 and 2006, within the area of latitude 16° to 20°N and longitude 258° to
 98 262°E , which covers the region affected by the major transients since 1996, and
 99 where the permanent Guerrero GPS network is installed. Earthquake depth
 100 is limited to those less than 100 km, to roughly include events only related
 101 to the shallow subduction process. The relocated Centennial catalog [Engdahl
 102 *et al.*, 1998; Engdahl and Villaseñor, 2002] is also used for better constraints
 103 on the locations of particular earthquakes of interest, as will be discussed in
 104 Section 3.

105 Among all the events satisfying the above search criterions, the lowest mag-
 106 nitude in the GCMT catalog is $M_w = 4.9$, and the NEIC catalog includes
 107 smaller events down to $mb = 2.5$. However, the number of events at lower
 108 magnitudes may increase with time as an effect of improved seismic instru-
 109 mentation detection capability. That influences our attempts to identify the
 110 natural variations of seismicity rate. Thus, it is necessary to define a com-
 111 pleteness (cut-off) magnitude M_c , above which the catalog can be considered
 112 complete and appropriate for this study. There are basically two approaches
 113 in the literature to determine M_c . One is to calculate what the instruments
 114 should be able to detect, given their configuration, sensitivity, noise level and
 115 observations of which earthquakes particular instruments have or have not
 116 detected, following the procedures in Schorlemmer *et al.* [2006]. This is a very
 117 precise but complicated approach for the purpose of the present study. As a
 118 simple and generally robust approach, we use the maximum likelihood method
 119 [Aki, 1965] to calculate the b value for a wide range of M_c :

$$120 \quad b = \frac{\log_{10}(e)}{\langle M \rangle - M_c} = \frac{0.4343}{\langle M \rangle - M_c}, \quad (1)$$

121 where $\langle M \rangle$ is the mean magnitude of all events equal or higher than the de-

122 tection threshold M_c . For all the NEIC earthquakes between 1995 and 2006,
123 with depths less than 100km, within the dashed-line box, b -value, with 98%
124 error bars, versus M_c is shown in Figure 2(a). b initially increases with M_c
125 when M_c is below the detectability threshold. When M_c is high enough, b
126 becomes statistically constant (e.g., b is roughly constant for different val-
127 ues of M_c within the calculation error), and the catalog can be considered as
128 complete. A completeness magnitude of ~ 4.3 can be roughly determined. In
129 addition, the frequency-magnitude distributions, shown in Figure 2(b), also
130 suggest a M_c around the same value. We assume the drop in the number of
131 events within each 0.1-magnitude bin is caused by the incomplete reporting of
132 events in the NEIC catalog. Adding a 0.2 or 0.3 safe factor to M_c inferred from
133 the statistical analysis [*K. Felzer*, priv. commun.], we choose a completeness
134 magnitude of $M_c = 4.5$. It is also consistent with an average completeness
135 threshold of 4.3 to 4.4 reported for the NEIC catalog in a majority of regions
136 [http://earthquake.usgs.gov/regional/neic/neic_bulletins.php, 2000]. The Cen-
137 tennial catalog has a cut-off magnitude of 5.5 for earthquakes between 1964
138 and April 2002.

139 In Section 3, we present the seismicity variations between 1995 and 2006,
140 showing the distribution of GCMT and NEIC events, the epicentral distance
141 to trench versus time, and the seismicity rate in each four-year span, i.e.,
142 1995-1998, 1999-2002 and 2003-2006. The earthquakes for periods including
143 the three large transients are projected to a vertical cross-section along line
144 AB (Figures 3, 5 and 7), which is perpendicular to the trench. We use the
145 subduction slab geometry, specifically, the thrust interface profile determined
146 by *Kostoglodov et al.* [1996] using the seismicity data of the regional network in
147 Guerrero. The slab profile is also used in the dislocation model of *Kostoglodov*

148 *et al.* [2003] to fit the observed surface deformation in the 2001-2002 transient.

149 **3 Seismicity and transients, 1995-2006**

150 *3.1 1995-1998*

151 Figure 3(a) is the map view of the seismicity from GCMT (beachballs) and
152 NEIC (gray dots) catalogs between 1995 and 1998. Figure 3(b) shows earth-
153 quakes between 1997 and 1998 in the dashed-line box projected to a vertical
154 cross-section along AB (red line). For the same earthquake of interest, we plot
155 the compressional quadrants of the GCMT beachball, the NEIC and Centen-
156 nial (if available in that catalog) locations with the same color.

157 *3.1.1 Possible transient in 1996*

158 Before the first permanent GPS station was installed at CAYA in January
159 1997, survey measurements were conducted in March 1992, September 1995
160 and April 1996, along the coast and inland in Guerrero. For a complete de-
161 scription of campaign sites and operation epoches, see *Larson et al.* [2004]. Ev-
162 idence of a moderate-size transient was found from the 1995 and 1996 survey
163 records at ACAP (Acapulco). The north component of displacement relative
164 to the North American Plate is ~ 2 cm [*Larson et al.*, 2004], almost one order
165 of magnitude larger than the average horizontal surface deformation during
166 the northern Cascadia aseismic transients [*Dragert et al.*, 2001]. However, we
167 need to be cautious on the identification of this transient based on the cam-
168 paign data at a single station, as transient motions can also result from the

169 instability of the monument, localized mass-wasting phenomena, or different
170 conditions in campaign epoches. The possibility that the slow slip was trig-
171 gered by the $M_w = 7.3$, September 1995 Copala earthquake (“091405C” in
172 Figure 3(a)), ~ 100 km east of ACAP, cannot be ruled out.

173 Figure 4(a) shows the temporal variation of the epicentral distance to the
174 trench of NEIC events greater than 4.2 in the dashed-line box between 1995
175 and 1998. Blue and red circles represent earthquakes with normal- and thrust-
176 faulting focal mechanisms, respectively. The duration of the 1996 transient is
177 poorly constrained due to limited measurements. We mark it roughly from
178 November 1995 to February 1996, in Figure 4(a), based on the estimate by
179 *Larson et al.* [2004]. Since the beginning of 1995, no earthquakes with mag-
180 nitude higher than 4.5 were reported in either catalog until December 20,
181 1995, when a $M_w = 5.3$ normal-faulting earthquake occurred near the border
182 between Guerrero and Michoacán, with an epicentral distance of ~ 170 km
183 inland from the trench and a depth of 78 km (NEIC). A similar depth of 76
184 km is determined in GCMT. This extensional earthquake corresponded to the
185 initiation of the possible 1996 transient, and occurred in the subducting slab.
186 A thrust earthquake of $M_w = 5.5$ occurred on April 23, 1996, shortly after the
187 transient, given the estimated duration. While the GCMT centroid location of
188 the April event lies on the trench, NEIC reports an epicenter ~ 40 km inland
189 from the trench, which is probably a more precise estimate using data from
190 regional seismic network in Guerrero. Another cluster of thrust events was
191 reported in middle July, with the largest magnitude of $M_w = 6.6$.

193 About 1 year after the first permanent GPS station was installed at CAYA,
194 a transient motion, starting from early 1998, was observed and lasted for ~ 5
195 months. The reversed motion was later confirmed by displacement at an inland
196 station POSW. Continuous measurements from the beginning of 1997 to late
197 2000 were used to model the aseismic deformation and suggest a total static
198 displacement of 2 mm east, 26 mm south and 16 mm up during this transient
199 [Lowry *et al.*, 2001]. Along-strike propagation, a feature like that exhibited
200 by the Cascadia transients [Dragert *et al.*, 2001], is also implied based on
201 the surface eastward deflection at the beginning and westward deflection at
202 the end of the transient; a simple static slip patch cannot duplicate such a
203 time-varying feature. The deflection signal is consistent with a NW to SE slip
204 propagation motion, as also suggested by the seismicity variation associated
205 with this transient.

206 During the transient slip period, an extensional earthquake of $M_w = 5.9$ oc-
207 curred on April 20, 1998, on the NW border between Guerrero and Michoacán,
208 near the epicenter of the 1995 normal-faulting earthquake. GCMT, NEIC and
209 Centennial locations of this April event are shown in Figure 3 by a beachball
210 with blue compressional quadrants, blue dot and blue star, respectively. There
211 is a significant discrepancy of more than 40 km between the GCMT and NEIC
212 horizontal locations, and NEIC has better agreement with the relocated Cen-
213 tennial position. Earthquakes with magnitudes less than 4.5, shown as gray
214 circles in Figure 4(a), near the extensional earthquake epicentral area were
215 also reported preceding or at the early stage of the 1998 transient. Further-
216 more, a group of thrust-faulting earthquakes occurred near Acapulco in July
217 1998, immediately after the transient. It is clear from Figures 3 and 4 that

218 the 1998 transient coincided with an extensional earthquake in the subduct-
219 ing slab at NW Guerrero and was followed by a cluster of shallower thrust
220 earthquakes close to the trench near Acapulco, suggesting a NW to SE slow
221 slip propagation and up-dip stress transfer.

222 Figure 4(b) shows the number of seismic events, above the completeness mag-
223 nitude 4.5 (black bars) and between 4.2 and 4.5 (gray bars), per 10 days for
224 the examined 4-year period. High seismic rate is generally observed in the
225 temporal vicinity of the transient slip events.

226 *3.2 1999-2002*

227 Figure 5(a) is the map view of the seismicity from GCMT and NEIC catalogs
228 between 1999 and 2002. Figure 5(b) shows the earthquakes between 2001 and
229 2002 within the dashed-line box projected to the vertical cross-section along
230 AB.

231 *3.2.1 Large transient in 2001-2002*

232 From early 1999 to late 2001, GPS measurements vaguely suggest three small
233 aseismic transients with the north-component of displacement less than 2 mm,
234 at least an order of magnitude smaller than that of the 1998 transient [Lowry,
235 2006]. Seismicity during the same period is relatively sparse, as shown in Figure
236 6.

237 The Guerrero region became seismically more active since late 2001, signifying
238 the beginning of a large transient. Aseismic deformation is clearly visible on
239 the time series of all permanent GPS stations then operating [Kostoglodov et

240 *al.*, 2003]. The reversed motion was first detected at stations ACAP, CAYA,
241 IGUA and YAIG, near the border of the NW and SE seismic gaps, then
242 about two months later, at a northwest station ZIHP and southeast stations
243 PINO, OAXA (~ 120 km northeast of PINO, not shown in Figure 1). The
244 temporal delay in the transient motion onsets at different stations suggests a
245 bilateral propagation at a speed of about 6-9 km/day [*Kostoglodov et al.*, 2003],
246 similar to the speed inferred for the northern Cascadia and southwest Japan
247 short-term slow slip events. Anomalous surface deformation was observed from
248 October 2001 to April 2002 over an area of more than $\sim 550 \times 250$ km²,
249 resulting in an equivalent moment magnitude of ~ 7.5 .

250 A cluster of earthquakes relatively far inland from the trench coincided with
251 the beginning of the transient. Two of them (“100801B” and “102901B” in
252 Figure 5) are normal-faulting events with $M_w = 5.8$ and 5.0. While the GCMT
253 and NEIC catalogs are ambiguous in the depths of the two extensional earth-
254 quakes, a study reported in an abstract by *Pacheco et al.* [2002] suggests
255 the October 8, 2001 Coyuca earthquake occurred at a shallow depth of 8
256 km and is thus a crustal event. GCMT and NEIC report depths at 10 and
257 15 km, respectively, and are suspected to be fixed depths in both catalogs.
258 As shown in Figure 5(b), the GCMT location of “100801B” is shifted by
259 30-40 km inland from its NEIC epicenter (blue dot). The Centennial cata-
260 log (blue star) and records from the Guerrero Accelerograph Network sta-
261 tions [<http://www.seismo.unr.edu/Guerrero/>] also suggest epicenters close to
262 the NEIC location. The normal-faulting mechanism might be explained by
263 the shallow extensional stresses left in the wake of indentation of the upper
264 plate by the locally steepened section of the slab near 80 km from the trench.
265 The possibility that event “100801B” might have been triggered by the tran-

266 sient is also mentioned by *Kostoglodov et al.* [2003], although their discussion
267 would seem to require an offshore nucleation of the transient slip. Neverthe-
268 less, the epicenters of the two October earthquakes are approximately along
269 the same trench-normal line inland from stations CAYA, ACAP, where the
270 transient episode started. This spatial-temporal correlation provides evidence
271 that stressing from the nearby seismicity may have triggered the transient or
272 had a common origin with it. The seismic rates became higher during the
273 transient; the October 8 Coyuca earthquake produced a large number of af-
274 tershocks (> 300) that lasted ~ 6 months, overlapping the duration of the
275 transient [*Kostoglodov et al.*, 2003]. We also note that toward the end of the
276 transient, in middle April 2002, several thrust-faulting earthquakes occurred
277 close to the trench, more than 100 km west of stations CAYA, ACAP. This
278 is also consistent with the bilateral propagation of the slow slip event. The
279 largest magnitude of the thrust events is $M_w = 6.7$ (“041802B” in Figure 5).
280 Although, GCMT and NEIC horizontal locations have a ~ 30 km discrepancy
281 in the trench-normal distance, the along-strike locations are relatively well
282 resolved, thus wouldn’t affect the consistency with the slow slip propagation
283 direction.

284 3.3 2003-2006

285 Figure 7(a) is the map view of the seismicity from GCMT and NEIC catalogs
286 between 2003 and 2006. Figure 7(b) shows the earthquakes between 2005 and
287 2006 within the dashed-line box projected to the vertical cross-section along
288 AB.

289 *3.3.1 Two possible small transients in 2003 and 2004*

290 *Lowry* [2006] also inferred a small aseismic transient from late 2002 to early
291 2003, as marked on Figure 6 and continued on Figure 8. The deformation
292 signal is most prominent at coastal stations ZIHP and CAYA , which are in
293 the epicentral area of many small earthquakes during that period, suggesting
294 a casual relation between the seismicity and transient. We cannot rule out the
295 possibility that it is an aftermath of the large transient in 2001-2002, as most
296 of the seismicity in late 2002 and early 2003 are close the the trench and many
297 have thrust-faulting focal mechanisms.

298 An even smaller transient was inferred to have occurred in early 2004 [*Lowry*,
299 2006], as marked in Figure 8. We do not discuss that in detail, due to the little
300 constraint on deformation. Similarly, seismicity rate was high during and after
301 this possible transient, with a majority of earthquakes close to the trench.

302 *3.3.2 Large transient in 2006*

303 The most recently detected large transient in the Guerrero region started
304 around March 2006, and the GPS signal began to return to the normal trend
305 at some stations in late September while extending into December at others
306 [*Larson et al.*, 2007]. The size of this transient is comparable to that in 2001-
307 2002; the total horizontal displacement at CAYA is about 6 cm. The reversed
308 motion was continuously observed at all permanent GPS stations, except ZIHP
309 where only a net displacement before and after the transient is obtained due
310 to technical problems. *Larson et al.* [2007] modeled the deformation with four
311 patches of rectangular fault planes, and found the east-component of the slip
312 anomaly can be divided into two stages. In the first stage, from February to

313 June 2006, stations (CAYA, COYU, ACAP, ACYA and CPDP) near the coast
314 experienced a faster eastward movement. That was followed, in the second
315 stage, by a westward motion from May to the end of this transient episode.
316 On the contrary, inland stations (MEZC, IGUA and YAIG) moved faster
317 toward the west in the first stage and continued to move westward but with
318 gradually decreasing slip rates.

319 The 2006 large transient was preceded by a cluster of earthquakes far in-
320 land on the NW border of Guerrero, in the same epicentral area of the ex-
321 tensional earthquakes in 1996 and 1998. The earliest among the cluster of
322 GCMT events was a $M_w = 4.9$, normal-faulting earthquake on December 14,
323 2005 (“121405A” in Figure 7, colored blue), about two months before the
324 transient. On February 20, 2006, shortly before the transient signal could be
325 detected by GPS, a $M_w = 5.2$ event (“022006A”, colored green) occurred at
326 roughly 150 km (NEIC) inland from the trench. One month later, another
327 normal-faulting event with a similar magnitude was reported in GCMT with
328 its centroid location slightly NW out of the dashed-line box (“032006A”).
329 More earthquakes with large distances to the trench were observed during the
330 transient; the largest with a $M_w = 6.0$ on August 11, 2006 (“081106A”, col-
331 ored orange). All of the three normal-faulting earthquakes in February, March
332 and August 2006 are located at depths ~ 60 km or deeper thus in the sub-
333 ducting slab. The GCMT and NEIC horizontal locations agree relatively well
334 with each other, except for event “022006A”. Toward the end of the transient,
335 the seismicity cluster seemed to migrate closer to the trench. Although all
336 events are too small to have GCMT solutions, their locations suggest a shal-
337 low thrust focal mechanism. We also plot in Figure 7 a recent $M_w = 5.9$ thrust
338 earthquake on April 13, 2007 (“041307A”), which lies southeast from the ex-

339 tensional earthquakes cluster before and during the transient, and is much
340 closer to the trench. Although the GCMT solution suggests the thrust fault
341 plane activated during event “041307A” inclines either toward the ocean or
342 toward the continent at a steeper angle than the subducting slab, the spatial
343 evolution of seismicity cluster is consistent with a northwest toward southeast
344 aseismic slip migration implied from the transient duration offsets at different
345 GPS stations [*Larson et al.*, 2007].

346 4 Conclusion and discussion

347 Recent observations of aseismic deformation transients and sometimes associ-
348 ated deep non-volcanic tremors in the circum-Pacific subduction zones pose
349 significant questions as to their origin, and also relative to existing concepts of
350 interseismic loading of the locked seismogenic regions. Stressing in the up-dip
351 seismogenic zone is increased episodically due to down-dip transient slips, and
352 it can be made more prone to failure in a large thrust earthquake. Thus, it
353 is important for seismic hazard assessment to search and identify patterns of
354 spatiotemporal seismicity variation associated with transients. We rejuvenate
355 the suggestions made by *Dmowska et al.* [1988], which could not be linked to
356 a convincing mechanism at that time, on possible communication between ex-
357 tensional seismicity clusters down-dip in the slab, and later thrust clusters in
358 the shallow seismogenic zone, along the Middle American Trench off Mexico.
359 The pattern seems to continue in the recent seismicity along other region of
360 MAT (Guerrero) that we have studied here.

361 We searched the GCMT and NEIC catalogs for earthquakes in a twelve-year
362 period (1995-2006) in the area affected by the aseismic transients in Guer-

363 rero, Mexico. The seismicity variation patterns are identified to be spatial-
364 temporally associated with the transients observed by the Guerrero GPS net-
365 work since 1996. Three large transients in 1998, 2001-2002 and 2006 are all
366 correlated with high seismic rates in the studied area. In particular, we found
367 that the initiation of the transients occurs in association with a cluster of
368 extensional earthquakes relatively far inland from the trench, in the subduct-
369 ing slab or the overlying crust, and may be followed by a cluster of shal-
370 low earthquakes close to the trench, among which many have thrust-faulting
371 mechanisms. In some cases, such as the transient in 2001-2002, both types
372 of activity are found bracketing the transient period. The beginning of the
373 2006 transient coincided with two normal-faulting earthquakes in February
374 and March, 2006, near the northwest border of Guerrero. Toward the end of
375 the transient, the NEIC catalog shows the seismicity cluster moved closer to
376 the trench, implying hypocenters up-dip in the seismogenic zone.

377 The assembled evidence suggests that aseismic deformation transients may
378 serve as a mechanism of stress communication between distant regions, e.g.,
379 down-dip and up-dip, in subduction zones. The Guerrero transients seem to be
380 initiated by earthquakes far inland from the trench, in subducting slab or the
381 continental crust, or to have a common cause of that activity. They transfer
382 stresses to the locked shallow part in a manner which sometimes results in
383 thrust earthquakes there. That conjecture has been taken into account in the
384 numerical modeling of subduction earthquakes and aseismic transients using
385 the rate and state-dependent friction [*Liu and Rice, 2007*]. When a moderate,
386 step-like stress perturbation, e.g., from a nearby earthquake, is applied to the
387 thrust interface, sequential aseismic transients can be resulted, and the timing
388 of the next large thrust earthquake is affected by three factors, namely, when,

389 where and how large is the stress perturbation.

390 The discovery of aseismic deformation transients is an important development
391 in our knowledge of the seismic cycle along major plate boundaries. It poses
392 significant puzzles and changes the way we should think about the loading
393 of seismogenic zones. Such transients contribute episodic steps in loading to
394 the thrust interface. Their improved understanding seems likely, based on
395 observations for the MAT and on theory, to increase the predictability of
396 earthquakes.

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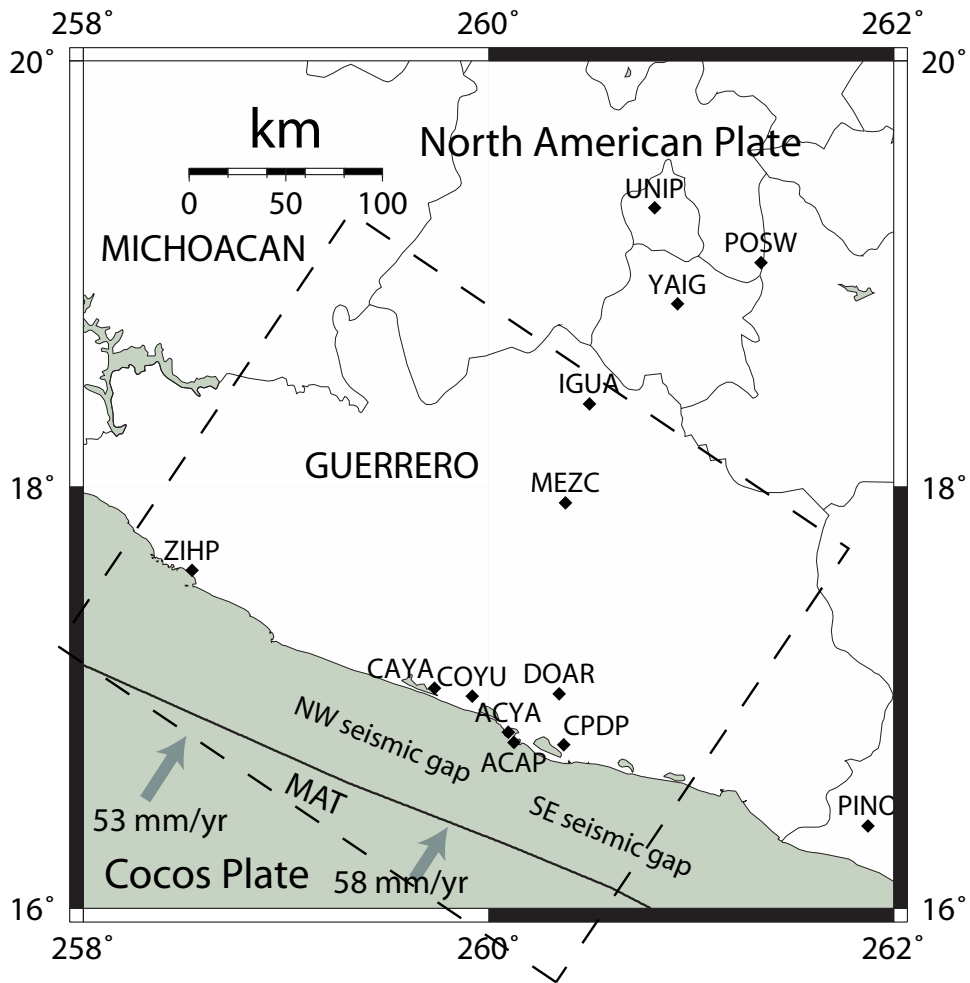


Fig. 1. Tectonic setting of the Guerrero, Mexico, region. Middle American Trench (MAT) defines the plate boundary between the Cocos and North American Plates. Bold arrows indicated the direction and magnitude of subduction, based on NUVEL1-A [DeMets *et al.*, 1994]. Black diamonds show the locations of permanent GPS stations. Dashed-line box is along the subduction direction and surrounds the region where most of the Guerrero permanent GPS stations are installed and mainly affected by aseismic transients, and thus the studied area in this paper.

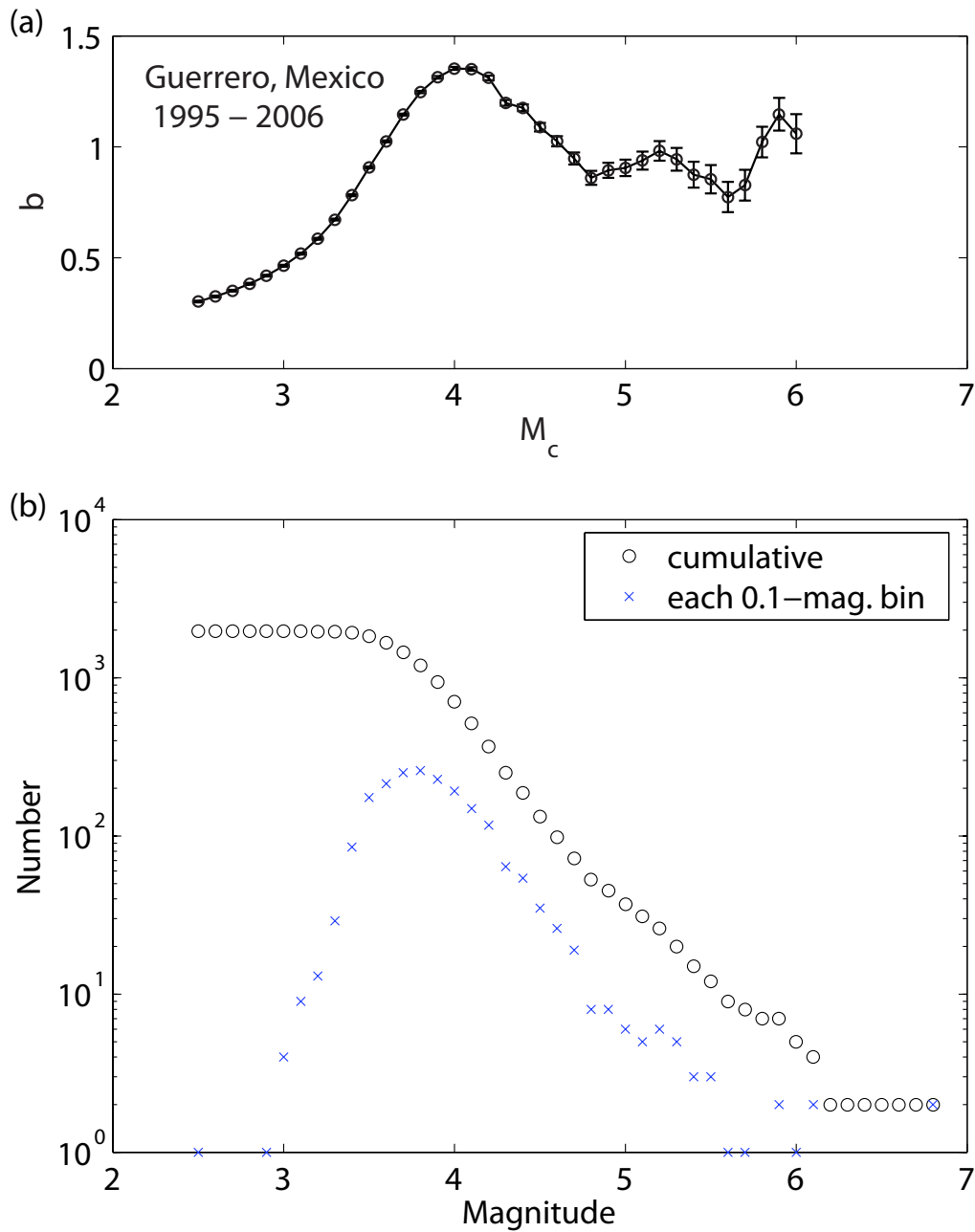
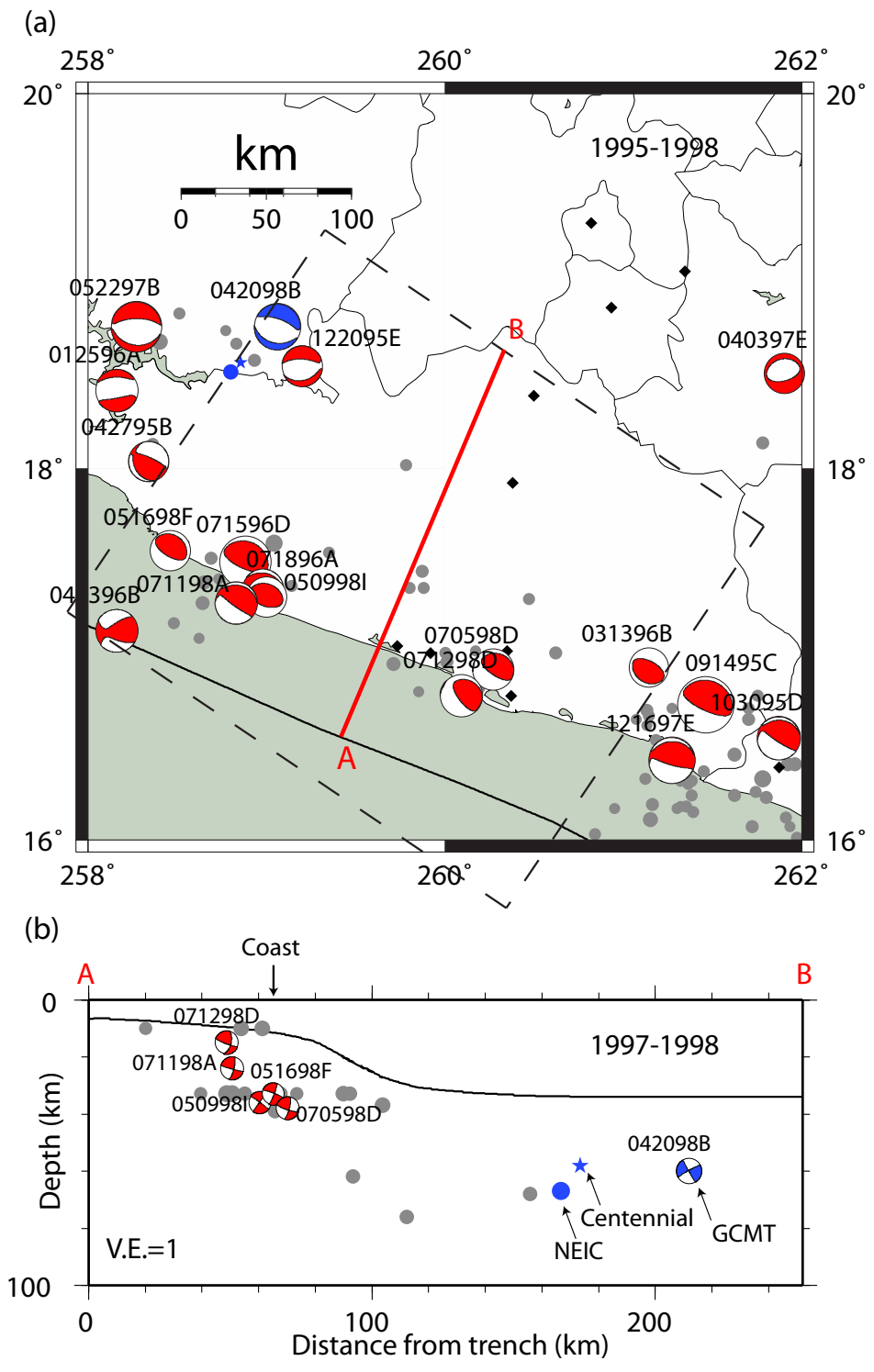


Fig. 2. (a) Calculated b -value versus completeness magnitude M_c for all NEIC events, 1995-2006, depth less than 100 km, within the dashed-line box shown in Figure 1. 98% error bars are shown on b . As M_c increases, the number of analyzed events decreases, and the errors on b becomes larger. b becomes statistically constant for $M_c \geq 4.5$. (b) Number of events: cumulative (circle) and within each 0.1-magnitude bin (cross), for the same data set. Decrease of seismic activity for magnitude lower than ~ 3.8 is assumed to be due to the incomplete report of the NEIC catalog. A completeness (cut-off) magnitude of $M_c = 4.5$ is used for subsequent analysis.

Fig. 3. (a) Map view of seismicity in the Guerrero region, 1995-1998. Beachballs show the centroid locations and focal mechanisms of GCMT events. Labels on top are in order “Month/Day/Year/Event of that day”. Gray dots show the epicenters of NEIC events larger than the completeness magnitude $M_c = 4.5$. Dot size is proportional to event magnitude. GCMT and NEIC epicenters sometimes deviate by tens of km. NEIC events within the dashed-line box are used in the seismicity analysis. For reference, black diamonds represent locations of permanent GPS stations. (b) Seismicity, 1997-1998, within the dashed-line box projected to a vertical cross-section along AB (red line). Subduction thrust interface is adopted from *Kostoglodov et al.* [1996; 2003] and *Manea et al.* [2004]. The blue dot and beachball with blue compressional quadrants are NEIC and GCMT locations of the extensional earthquake “042098B”, respectively. Blue star represents its position from the relocated Centennial catalog [*Engdahl et al.*, 1998; *Engdahl and Villaseñor*, 2002].



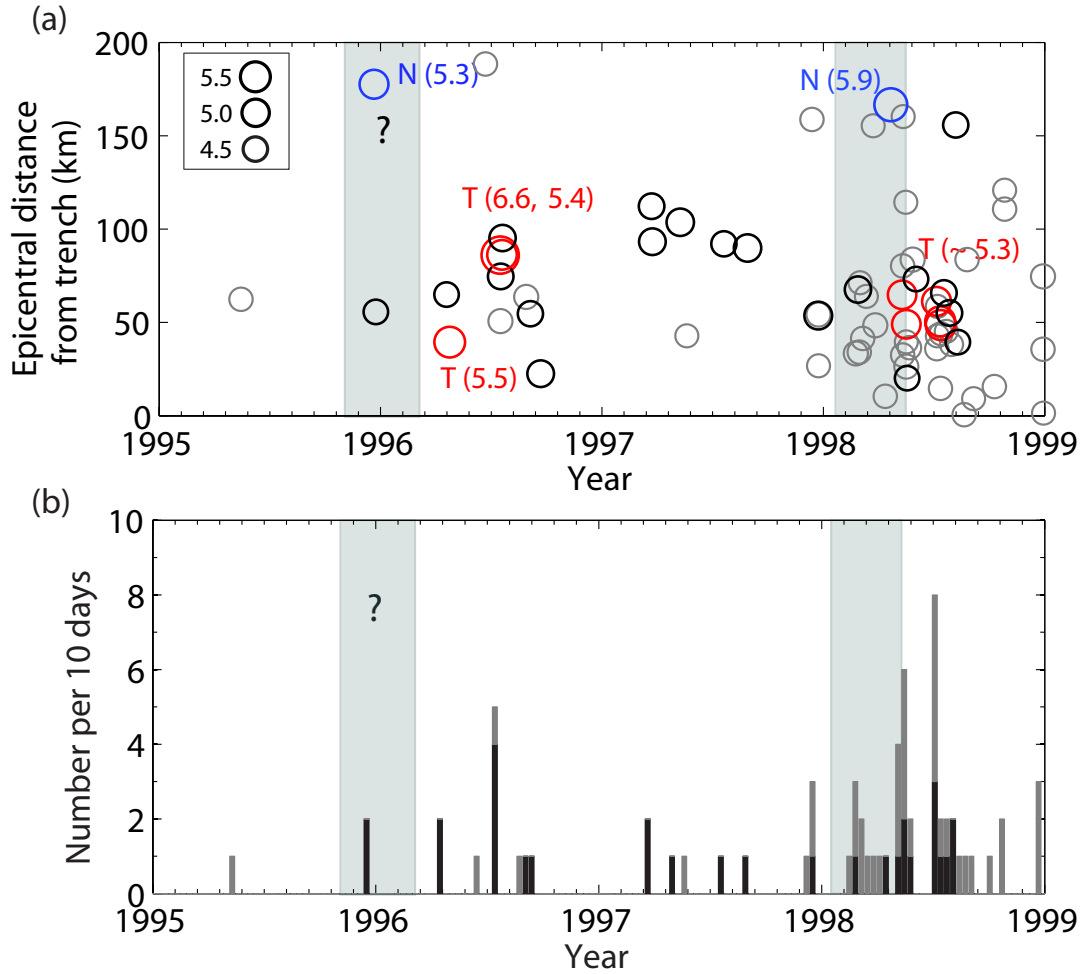


Fig. 4. (a) Spatial-temporal variation of NEIC events with magnitude greater than 4.2, within the dashed-line box, 1995-1998. Circle size is proportional to event magnitude. Blue and red circles are NEIC events that have GCMT solutions; blue: normal-faulting (N), red: thrust-faulting (T). Numbers in the parenthesis are moment magnitudes by GCMT. Only an average number is marked for a cluster of earthquakes, e.g., “T(\sim 5.3)” for the five thrust-faulting earthquakes after the 1998 transient. Gray circles represent events below $M_c = 4.5$, but greater than 4.2. (b) Number of earthquakes in every 10 days, 1995-1998. Black bars show numbers of events greater than $M_c = 4.5$. Gray bars show numbers of events between 4.2 and 4.5. Two light gray strips approximately mark the durations of aseismic transients in, possibly, 1996, and 1998.

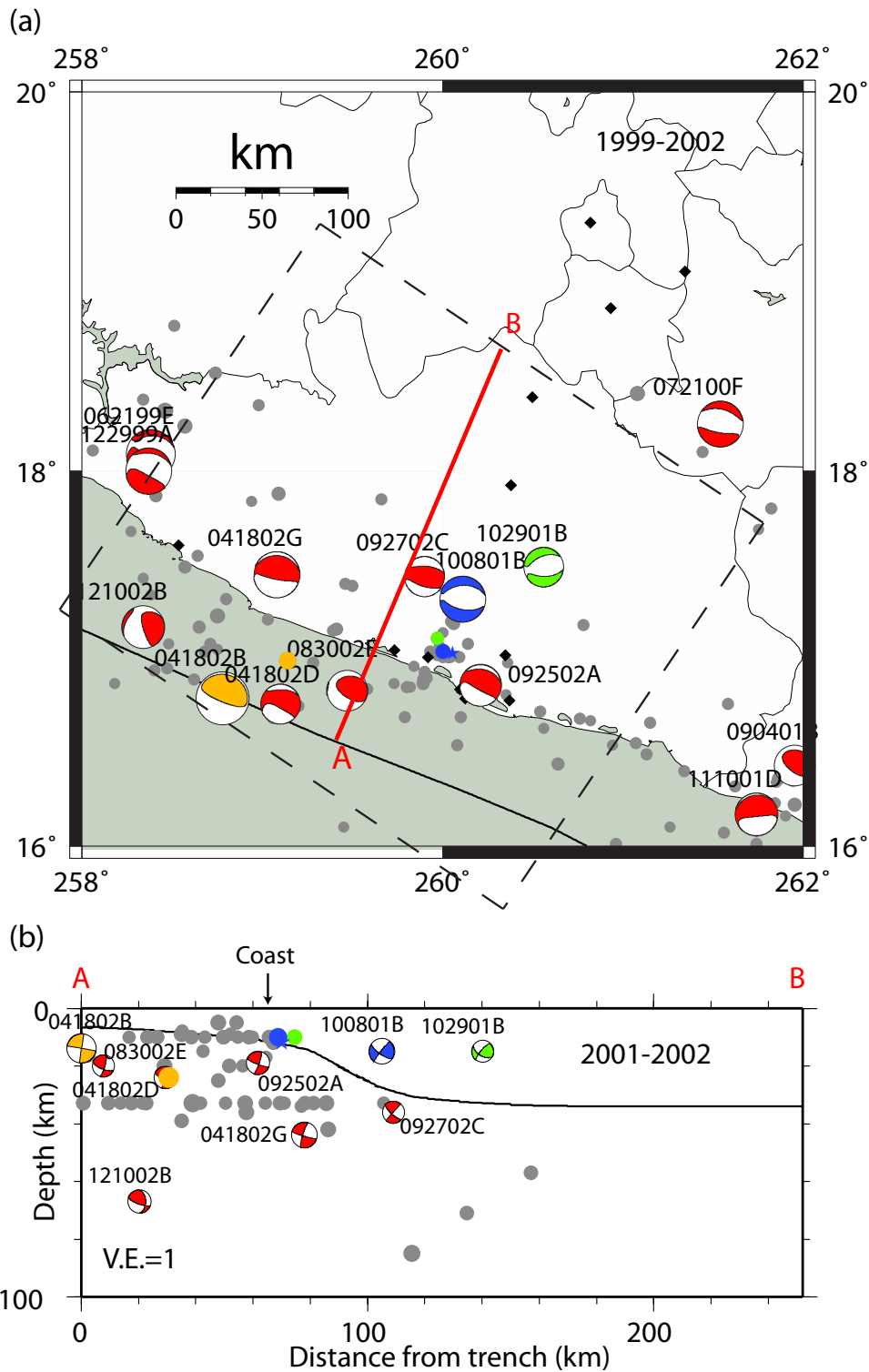


Fig. 5. (a) Map view of seismicity in Guerrero, 1999-2002. Extensional earthquakes “100801B” and “102901B” are colored in blue and green, respectively. Thrust event “041802B” is colored in orange. NEIC and Centennial locations of “100801B”, represented by blue dot and star, almost overlap. (b) Seismicity, 2001-2002, within the dashed-line box projected to a vertical cross-section along AB. Legends are the same as in Figure 3.

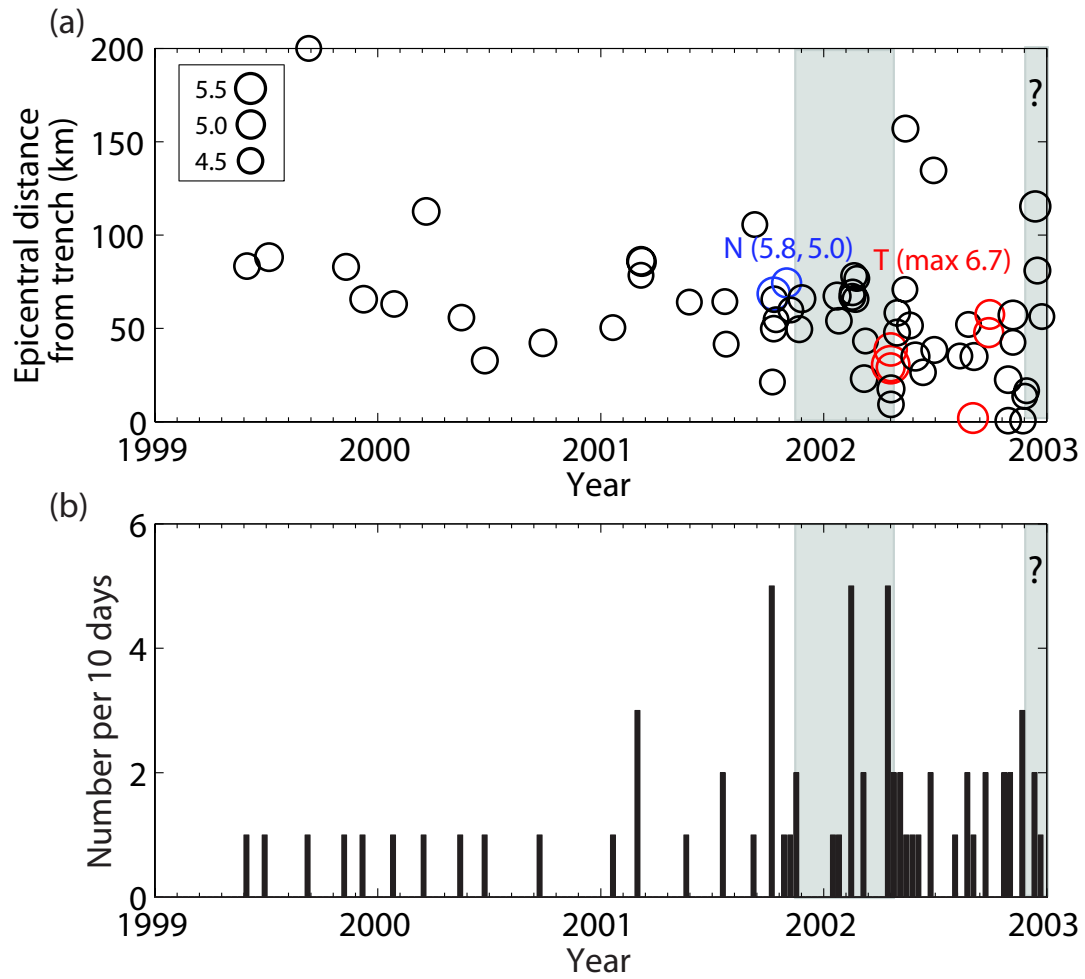


Fig. 6. (a) Epicentral distance from trench and (b) seismicity rate, 1999-2002. Symbol representations are the same as in Figure 4. NEIC events above the completeness magnitude $M_c = 4.5$ are shown here. “T (max 6.7)” represents the largest moment magnitude among the thrust-faulting earthquakes (red circles) following the 2001-2002 transient is 6.7. The transient marked from late 2002 continues on Figure 8.

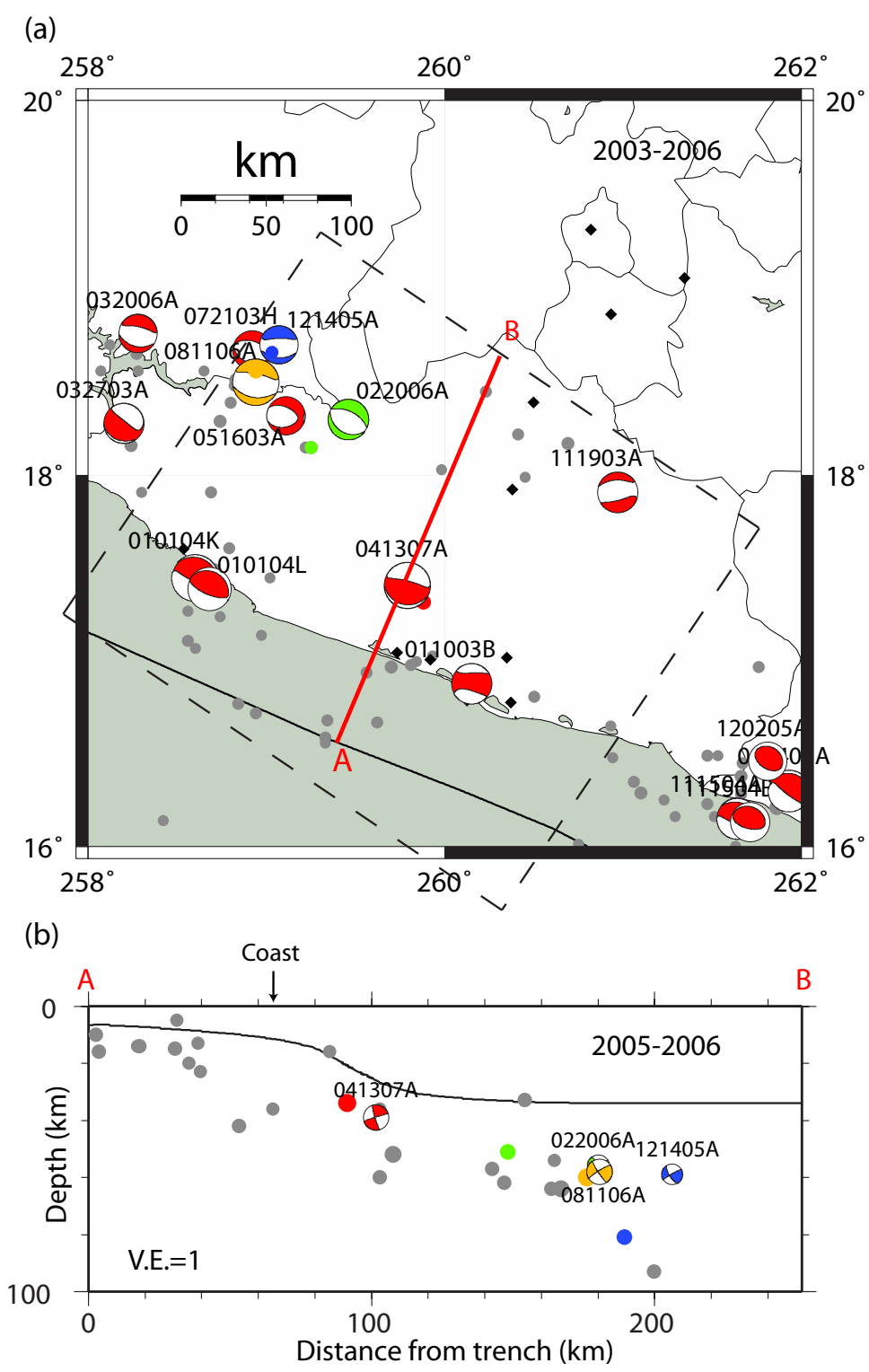


Fig. 7. (a) Map view of seismicity in Guerrero, 2003-2006. Extensional earthquakes “121405A”, “022006A” and “081106A” are colored in blue, green and orange, respectively. A recent thrust earthquake “041307A” following the 2006 transient is also shown. (b) Seismicity, 2005-2006, within the dashed-line box projected to a vertical cross-section along AB. Legends are the same as in Figure 3.

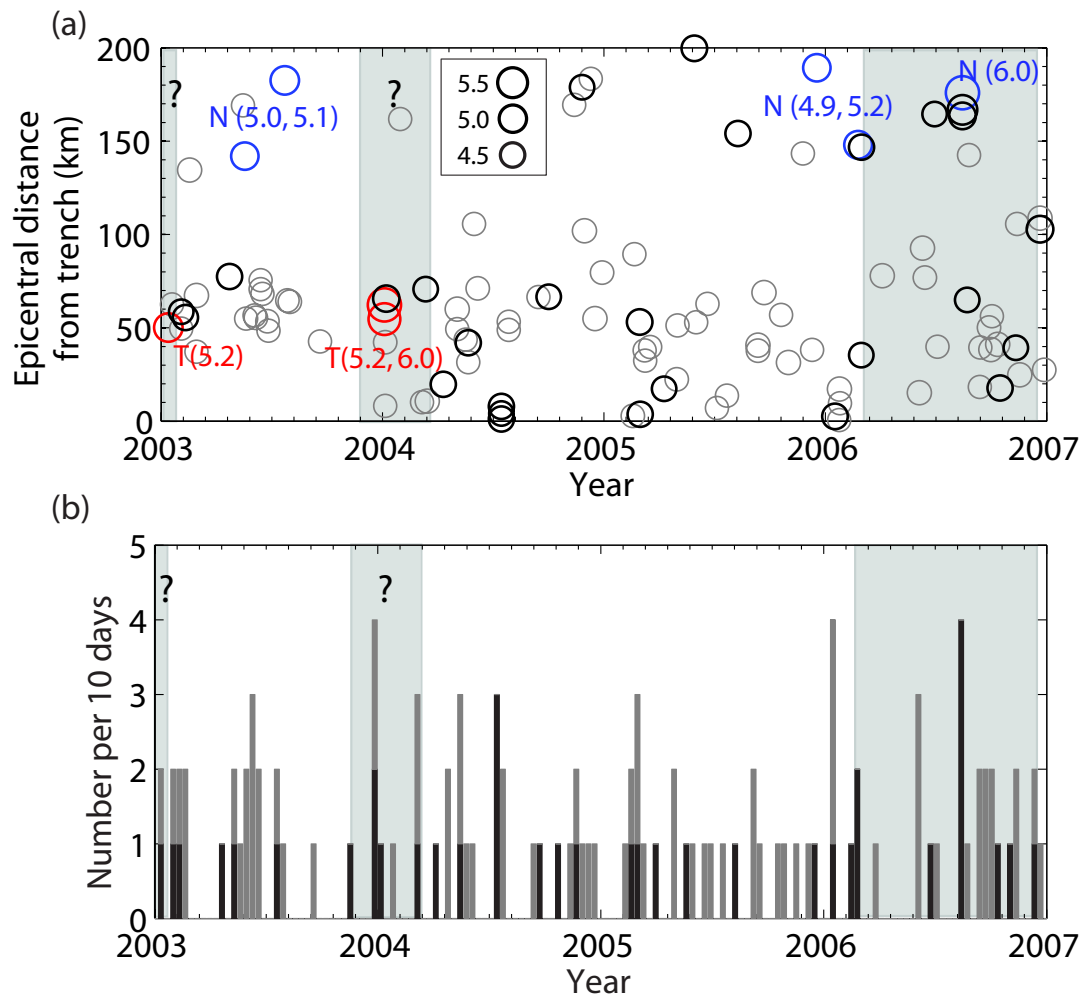


Fig. 8. (a) Epicentral distance from trench and (b) seismicity rate, 2003-2006. NEIC events above 4.2 are shown here. Symbol representations are the same as in Figure 4. The transient marked for early 2003 is continued from late 2002, as shown in Figure 6.