

Slip Acceleration Generates Seismic Tremor Like Signals in Friction Experiments

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Since their discovery nearly a decade ago, the origin of seismic tremor remains unclear. Recent studies indicate that various driving phenomena such as Earth and ocean tides, regional and teleseismic earthquakes enhance tremor activity. Observations of the coincidence with slow-slip events and of fast migrations of tremors have led frictional slip to be considered as the possible source of tremors. Indeed, laboratory friction experiments succeeded in generating and recording tremor like signals (TLS). Here we show a systematic correlation between the onset of slip acceleration and the emission of TLS in a laboratory friction experiment. TLS are generated when the shear stress reaches the peak static resistance and the dilatancy meets its maximum that is when the mature interface is close to failure. This robust result provides a comprehensive image of how natural seismic tremors might be generated and/or triggered by passing seismic waves, tides or even slow slip events.

Introduction:

Seismic tremors, named also non-volcanic tremors, have now been well documented and studied in many subduction zones [Dragert *et al.*, 2004; Hirose and Obara, 2006; Kao *et al.*, 2005; Obara, 2002; Obara and Hirose, 2006; Shelly *et al.*, 2007b; Shelly *et al.*, 2006] and along some continental fault segments [Ghosh *et al.*, 2009b; Nadeau and Dolenc, 2005; Peng *et al.*, 2009; Peng *et al.*, 2008]. Recent studies indicate that various driving phenomena such as Earth and ocean tides [Thomas *et al.*, 2009], regional and teleseismic earthquakes [Ghosh *et al.*, 2009b; Peng *et al.*, 2009; Peng *et al.*, 2008; Rubinstein *et al.*, 2009] enhance tremor activity. Frictional slip was proposed as the possible source of tremors [Brown *et al.*, 2009; Ghosh *et al.*, 2009a; Ide *et al.*, 2007; Kao *et al.*, 2007; La Rocca *et al.*, 2009; Larmat *et al.*, 2009].

39 Laboratory experiments specifically designed to study seismic tremors are a powerful tool to
40 explore the physical processes at the origin of these signals. Few experiments have been
41 successful in producing tremor like signals (TLS) so far. They involve fluid-flow and fluid
42 processes [Burlini *et al.*, 2009], or frictional processes associated with shear of a deformable
43 sample [Voisin *et al.*, 2007; Voisin *et al.*, 2008]. Our experimental setup (Fig. 1A) is designed
44 to reproduce different frictional behaviors, from stick-slip to stable sliding. We make use of a
45 deformable slider of salt (NaCl) pushed at constant load-point velocity, under constant
46 conditions of normal pressure (0.26 MPa), temperature (22°C) and ambient humidity. Using a
47 salt slider allows for the brittle and ductile deformation to be effective on the time scale of our
48 experiments, aimed to serve as an analogue for natural faults deforming in the brittle and
49 ductile regimes at 20-40 km depth. We continuously record the frictional force and the
50 acoustic emission generated during the shear of the sample. These signals are carefully
51 scrutinized in order to investigate the temporal timing of the sliding characteristics and of the
52 TLS emission.

53

54 **Results:**

55 Figure 1 (B, C, D), presents three different stages of a friction experiment representative of the
56 stable, intermediate and unstable frictional regimes. The unstable regime is characterized by
57 cycles of long stress increase followed by sudden drops of the friction force, associated with
58 the stick-slip behavior of the slider (stage 1, Fig. 1B). The jumps of the slider produce short
59 duration and high amplitude acoustic signals. In this stage of stick-slip, no TLS is recorded.
60 The salt slider follows an evolution from an unstable stick-slip behavior to more and more
61 stable behavior with accumulated displacement [Voisin *et al.*, 2007]. Figure 1C presents a
62 second experiment (under the same conditions) where the sample has accumulated 3.3 mm of
63 displacement and for which the slider interface has become more mature (stage 2). In this
64 condition, the stick-slip behavior changes and smoothens. The slider still obeys a stick-slip
65 behavior, but is creeping before and after the jump. Interestingly, the associated acoustic
66 emission presents two types of signals: i) a tremor like signal with long duration and low
67 amplitude followed by ii) a strong impulsive and short duration event, signature of the jump.
68 Finally, Figure 1D presents an experiment in the stable regime, characterized by smooth
69 oscillations of the frictional force around a mean value, which corresponds to smooth
70 variations of the sliding velocity of the slider [Voisin *et al.*, 2007]. During this stable regime,
71 the acoustic emission is composed exclusively of noise and TLS. Those TLS are identical to
72 those presented in Figure 1C in terms of frequency content, duration and amplitude,

73 suggesting their common physical origin. These results show that TLS in friction experiments
74 are related to regimes of stable slip (Fig 1D) or simultaneous creep and stick-slip (Fig 1C).
75 Note however, that the high level of experimental noise impairs to exclude definitively the
76 existence of TLS at other time than the slip events.

77

78 Figure 2 presents 4 typical examples out of the 46 TLS extracted from a friction experiment
79 (see Figure S1 for an exhaustive presentation of the TLS). For each case, the TLS slowly
80 emerges from the background noise, keeping a low waxing and waning amplitude. Some
81 bursts or peaks in the signal occur randomly, creating some variability in the TLS. The
82 maximum amplitude of TLS is always relatively small, in the range $\pm 5.10^{-7}$ m.s⁻¹. The
83 apparent duration of a TLS is variable, with 90% of the records in the range 8-20
84 milliseconds. We compared the Fourier power spectrum of the acoustic events recorded
85 during the experiments against the Fourier spectrum of background noise (Fig. 3). The
86 acoustic event associated with a stick-slip event (see Fig. 1B for the time plot) presents a
87 highly energetic spectrum with a few peaks between 10^4 and 10^5 Hertz. Conversely, the TLS
88 spectrum is hardly above the noise spectrum in this same frequency range, confirming the low
89 S/N ratio of these signals. Anyway, we can observe two peaks of energy at 48 and 57 kHz.
90 The strong resonance inherent to the experimental set-up and the limited bandwidth of the
91 sensor whose response is flat in the 10-60 kHz range probably alter the shape of the TLS
92 spectrum. Nonetheless, most of the energy of the TLS apparently lies in the range 40-60 kHz.
93 Such a frequency range corresponds to a wavelength of a few centimeters and indicates
94 vibrations of the whole NaCl sample, and impairs the description of the microstructural
95 process(es) at work during the emission of the TLS.

96

97 A continuous record of the acoustic emission together with the frictional force at a 500 kHz
98 sampling frequency allows for a precise timing of the TLS with respect to the onset of slip
99 acceleration. Doing such a careful analysis for all the recorded TLS we observe a systematic
100 correlation between the onset of slip acceleration of the interface and the generation of TLS.
101 Figure 2 exemplifies this behavior where the acceleration of slip (top plot) is associated with a
102 burst of acoustic emissions (bottom plot) for the 4 selected slip events. There is a clear
103 temporal correlation between the occurrence of TLS and the beginning of slip acceleration
104 that starts when the shear stress equals the static resistance and the maximum level of
105 dilatancy sustained by the slider is reached. The relation between shear stress level, dilatancy
106 and tremor like signals might explain why the TLS progressively vanish while the slider is

107 still accelerating. We might infer from the experiments that the sliding of the interface is
108 associated with a change in the contacts population resulting from the mass redistribution at
109 the interface and leading to the generation of a TLS right before the drop in friction.

110 However, if slip acceleration is a necessary condition, it is not the only one to be met to emit a
111 TLS. It is interesting to remark that TLS are not recorded at the beginning of the experiment,
112 during the stick-slip stage (Fig. 1B). The interface has to accumulate some amount of slip
113 before to emit TLS. This might be related to the restructuration of the sliding interface and the
114 development of the striations parallel to the sliding direction [Voisin *et al.*, 2007; Voisin *et al.*,
115 2008]. A third condition has to be met, related to the state of stress and/or the peak dilatancy
116 of the slider. TLS are not recorded randomly. During stage 2 (Fig. 1C), TLS are recorded only
117 during the last smooth oscillation before the stick-slip, that is when the interface is close to
118 failure. During stage 3 (Fig. 1D), TLS are recorded at each slip acceleration that occurs when
119 the shear stress is at a maximum and starts to decrease gently. In both cases, the TLS occur at
120 the maximum of the shear stress and also at the maximum of dilatancy bore by the slider.

121

122 **Discussion and Conclusions:**

123 TLS recorded in these experiments are related solely to the frictional process occurring along
124 the contact interface. Because of the limited wavelength of the sensors used in this study, we
125 are not able to characterize the processes at the origin of the TLS. Consequently, there is no
126 simple possibility to derive a scaling between TLS and natural seismic tremors. Nonetheless,
127 if we assume that the same process could produce seismic tremors in the nature as suggested
128 by the coincidence of tremors with slow-slip events or by the fast migrations of tremors
129 [Brown *et al.*, 2009; Ghosh *et al.*, 2009a; Ide *et al.*, 2007; Kao *et al.*, 2007; La Rocca *et al.*,
130 2009; Larmat *et al.*, 2009], we can use the laboratory results to shed some light on the natural
131 system of slow slip, seismic tremors and triggering.

132 Result 1: This friction experiment conducted with a deformable interface exhibits a large
133 variety of frictional behavior associated with different amounts of cumulative slip. These
134 behaviors are themselves accompanied by different acoustic signals, impulsive events and
135 TLS. A comparable variety of behaviors is observed on natural fault segments exhibiting in
136 time and space different frictional behaviors: seismic, aseismic, creeping, associated with
137 seismic events or seismic tremors.

138 Result 2: the TLS are emitted when the shear stress and/or the dilatancy are at maximum. A
139 large and growing number of observations emphasize the link between stress changes and
140 seismic tremors. Maybe the clearest evidence is the triggering of seismic tremor by large

141 transient shear stresses [Rubinstein *et al.*, 2007], dilatational stresses [Miyazawa and Mori,
142 2006], or the tidal modulation of tremor rate [Rubinstein *et al.*, 2008]. Such conveniently
143 orientated stress waves temporarily increase the stress level on a given sliding interface or
144 increase the dilatancy, inducing slip and tremor triggering like in the laboratory experiments.
145 Another evidence might be found in silent or slow slip events that are often associated with
146 seismic tremors in episodic tremor and slip events, described for the first time in Cascadia
147 [Dragert *et al.*, 2001]. Tremors are sometimes found to migrate along strike, in agreement
148 with the slow slip propagation [Obara and Sekine, 2009; Shelly *et al.*, 2007a]. Lead by the
149 laboratory results, we propose that the temporary increase of stress induced by the rupture
150 front propagation itself can trigger seismic tremors in zones where the stress state is close to
151 its maximum. The present understanding of rupture propagation relies on a friction law, either
152 slip-dependent or rate-and-state dependent, that defines a breaking-down zone governing the
153 stress drop preceded by a short stress increase [Ida, 1975; Rubin, 2008; Voisin *et al.*, 2002].
154 Assuming that a similar breaking down process occurs for slow slip event, the small stress
155 increase associated with the rupture tip would be able to trigger seismic tremors, according to
156 our experimental results.

157 Result 3: TLS occur when the slider accelerates. Seismic tremors appear as a local
158 recollection of the unstable frictional behavior occurring during the slippage of aseismic slow
159 events down dip subduction zones [Shelly *et al.*, 2007a]. At a large scale, a slow slip event
160 can be considered as an acceleration of slip on the interface during a few months, thus a
161 possible source for seismic tremors. The slip complexity derived from inversion imposes slip
162 rate variations and thus local accelerations that would be able to trigger seismic tremors.

163 Result 4: TLS are emitted only when enough slip is accumulated and the interface has
164 developed a striation [Voisin *et al.*, 2007]. It is the case down-dip the subduction zones, where
165 seismic tremors were first recorded. The recent discovery of the control of tremor migration
166 by preferred directions linked to striation of the subduction plane [Ide, 2010] together with
167 our experimental observations suggest that the striation is a necessary condition to emit
168 seismic tremors and to control the tremor migration [Ide, 2010]. Large cumulative slips are
169 also observed along some large continental strike slip faults. The relation between seismic
170 tremors and seismic events in continental context remains open. If most of the seismic
171 tremors and seismic events occur in different areas, the brittle crust for the latter, and the
172 deeper ductile crust for the former, in very rare cases they do occur beneath the same location.
173 It is the case with the Cholame area, a segment of the San Andreas Fault at the north tip of the
174 great 1857 Fort Tejon earthquake rupture. Tremor activity was detected just before and after

175 the 2004 M6 Parkfield earthquake, at the depth where the earthquake rupture nucleated, at the
 176 transition between the stable sliding layer and the seismogenic layer [Nadeau and Guilhem,
 177 2009] . Our experiment reported in Figure 1C shows that the same interface can generate
 178 tremors and seismic events. We observe that the TLS emission occurs systematically before
 179 the slip event. Because of the complete stress release in our experiment, the TLS rapidly stops
 180 after a few milliseconds. This is to be compared to the Cholame segment, where the “fore-
 181 tremor” activity was proposed before to the Parkfield earthquake of 2004. A recent study
 182 [Bouchon et al, Observation of Tremors Before a Large Earthquake, Science, in revision] also
 183 reports LFEs and tremors located in the hypocentral area before the large 1999 Izmit
 184 earthquake. We thus can imagine that the tremors would be generated by some creep
 185 acceleration eventually leading to the seismic event [Shelly, 2009]. If so, seismic tremors
 186 occurring at the base of the brittle crust might be seen as potential signature of the nucleation
 187 of seismic events.

188

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281

281 **Figure Captions:**

282

283 **Fig. 1:** (A) Sketch of the experimental block-slider system (details in supplementary
 284 material). (B, C, D) Frictional behavior of a salt/glass interface (top plots: recorded shear
 285 force divided by normal load, noted F/W) and associated acoustic emission records (bottom
 286 plots). (B) Typical stick-slip regime characterized by sudden shear stress drops separated by
 287 periods of stress accumulation. The acoustic emission is formed of large impulsive events,
 288 sometimes preceded and followed by smaller impulsive events. (C) The frictional behavior is
 289 more complex than previously. If the sudden jumps still occur, they are preceded by smooth
 290 oscillations of growing amplitude. This behavior is at the limit between stable and unstable
 291 behaviors. It arises with the cumulative displacement of the slider (here 3.3 mm; about 120
 292 cycles) that modifies the properties of the salt interface. The associated acoustic emission
 293 presents a complex signal formed by a TLS with long duration (10 to 20 ms) and low
 294 amplitude followed by a strong impulsive and short duration event that represents the
 295 signature of the jump. (D) The frictional force remains more or less constant with small
 296 variations around a mean value (see insert): this is the stable regime obtained after 8mm
 297 (about 150 cycles) of cumulative slip. The associated acoustic emission is formed of a TLS
 298 with low amplitude and long duration, emitted at each slip acceleration, when the shear stress
 299 and the dilatancy are at maximum.

300

301 **Fig. 2:** Examples of TLS and the associated slip acceleration evolution. We present here 4
 302 examples out of the 46 windows containing TLS. All TLS share some common features:
 303 progressive emergence from the background noise, very low amplitude, and rather long
 304 duration of 10-20 ms. Here and there, some bursts of energy create a variability of the TLS.
 305 Associated with the time traces of the TLS, we represent the shear stress evolution in a
 306 manner that mimics the slip acceleration. The high sampling rate of both force and acoustic
 307 emission and the short instrumental response of a millisecond allow for a precise comparison
 308 between acceleration of slip (top plot) and acoustic record (bottom plot). For each event A B
 309 C D, an arrow points to the beginning of slip acceleration determined by visual inspection.
 310 We note the strong correlation between the onset of slip acceleration and the emission of the
 311 TLS. The maximum of the TLS is reached after a few milliseconds. Note all TLS do occur at
 312 the beginning of the acceleration, and are thus associated with change of slip properties of the
 313 frictional interface.

314

315 **Fig. 3:** Fourier spectrums of the acoustic signature of a jump (blue curve), TLS (red curve),
316 and noise (black curve) computed from 20 ms time windows. The low frequency range of the
317 signals recorded below 10 kHz is not presented on the figure because it is dominated by
318 experimental noise (motor) and associated with the movement of the slider as a block. The
319 noise spectrum is computed from the mean of different time windows. The spectrum of a
320 jump is highly energetic between 10 kHz and 100 kHz. By contrast the spectrum of the TLS is
321 close to the noise level and presents only two clear peaks of energy at 48 and 57 kHz, not
322 present in the power spectrum of the jump signal.





