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Nonvolcanic Tremor Evolution and the San Simeon and Parkfield, California, Earthquakes

Robert M. Nadeau and Aurélie Guilhem

Nonvolcanic tremors occur adjacent to locked faults and may be closely related to the generation of earthquakes. Monitoring of the San Andreas Fault in the Parkfield, California, region revealed that after two strong earthquakes, tremor activity increased in a nearly dormant tremor zone, increased and became periodic in a previously active zone, and has remained elevated and periodic for over 4 years. Static shear- and Coulomb-stress increases of 6 to 14 kilopascals from these two earthquakes are coincident with sudden increases in tremor rates. The persistent changes in tremor suggest that stress is now accumulating more rapidly beneath this part of the San Andreas Fault, which ruptured in the moment magnitude 7.8 Ft. Tejon earthquake of 1857.

Nonvolcanic tremors (long-duration seismic events with no clear P or S waves) have generally been observed in transition zones between freely slipping and locked faults (1–8). In many of these locations, tremor activity increased with detectable transient fault zone deformation (slow-slip events) (2, 8–10) or with dynamic stress changes produced by solid-earth and ocean tides and the surface waves of teleseismic (distant) earthquakes (11–16). These spatial and temporal associations suggest that tremor activity is closely related to the processes responsible for generating earthquakes. To investigate this possible relation, we analyzed tremor activity in the Parkfield region of California between 27 July 2001 and 21 February 2009. During this period, this region experienced two strong earthquakes: the moment magnitude 6.5 San Simeon earthquake in 2003 (17) and the Mw 6.0 Parkfield earthquake in 2004 (18) (Fig. 1).

Borehole seismometer data from the High Resolution Seismic Network (HRSN) at Parkfield, California, recorded continuously at 20 Hz were used to detect 2198 tremors (12,547 min of cumulative activity) during our study period (19) (Fig. 2A). The tremor events lasted from 3 to nearly 21 min. Substantial activity also occurred below our detection threshold (19). Between 3 and 8 Hz, the average seismic energy released during the tremors was typically equivalent to an ~Mw 0.5 earthquake, and energies ranged over 1.5 Mw units among tremors not coincident with earthquakes. The frequency content of the tremors (based on 250-Hz sampled data) was also typically above background levels, between 1 and 15 Hz.

Continuous data from five seismographic networks (76 stations, fig. S1) were combined to locate the tremors by means of envelope cross-correlation techniques and a migrating grid search location program (19) (Fig. 1). Consistent with previous spatially or temporally limited studies (3, 12, 14, 20), ~90% of the tremors were concentrated in a zone adjacent to the locked Cholame segment of the San Andreas Fault (SAF). An additional 5 to 10% were located ~65 km to the northwest along the SAF in the vicinity of Monarch Peak near Lonoak, California. Tremors in both zones occurred at depths between ~15 and 30 km: below the seismogenic zone (the upper ~15 km of Earth’s crust, where most earthquakes occur) in the ductile lower crust and at or above the Mohorovicic discontinuity in this part of California.

A sudden increase in and subsequent decay of tremor activity (aftertremors) began immediately after the 2003 San Simeon and 2004 Parkfield earthquakes (Fig. 2A and fig. S2). Cumulatively, there was 140 min of tremor activity in the 45 days preceding the San Simeon event and 312 min of activity in the 45 days after that earthquake. An even larger increase in activity followed the Parkfield event: 850 min in the 45 days after Parkfield. In addition, approximately 3 weeks before the Parkfield earthquake, an unusually strong episode of activity (foretremor) lasting ~5 days also occurred (19) (Fig. 2A and fig. S2). During the 5-day episode, we detected 164 min of tremor, representing an over 10-fold rate increase as compared to the 45-day pre–San Simeon period. The peak daily activity during the episode was 82 min. The largest daily peak before the foreshock episode was 43 min, occurring 98 days after the San Simeon earthquake.

The decay of tremor activity after the Parkfield event continued until mid-2006, when annual activity rates had decreased to 150% of the rate for the year preceding the San Simeon earthquake. Since mid-2006, annual rates have generally increased, reaching ~181% of the pre–San Simeon level during the final year of our analysis (Fig. 2A).

Our data also show that zones relatively devoid of detectable tremor can transition into a state of long-term elevated activity as a result of perturbations from a nearby moderately strong earthquake. For example, before the Parkfield earthquake, tremor activity in the Monarch Peak tremor zone (Fig. 1) was low (14 tremors in ~3.2 years) (Fig. 2B). However, beginning ~10 days after the Parkfield event, activity in this zone increased substantially and has continued at an elevated rate (98 tremors in ~4.4 years) (Fig. 2B). The 10-day delay may reflect anelastic redistribution of stress in the ductile lower crust.

After the Parkfield earthquake, persistent episodes of quasiperiodic tremor emerged along the SAF that are reminiscent of episodic tremor observed in some subduction zones (2A) (2, 9). However, unlike many subduction zone tremors, where the recurrence of dominant episodes is typically 6 months or longer and is accompanied by relatively low-amplitude inter-episode activity, the SAF episodes show progressively increasing recurrence intervals ranging from ~50 days (in 2005) to ~100 days (in 2008) and are accompanied by more energetic inter-episode activity (Fig. 2A). The SAF episodes have also typically concentrated in a zone adjacent to the locked Cholame segment of the San Andreas Fault (SAF). An additional 5 to 10% were located ~65 km to the northwest along the SAF in the vicinity of Monarch Peak near Lonoak, California. Tremors in both zones occurred at depths between ~15 and 30 km: below the seismogenic zone (the upper ~15 km of Earth’s crust, where most earthquakes occur) in the ductile lower crust and at or above the Mohorovicic discontinuity in this part of California.

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Fig. 1. Study region with 1250 well-located tremors (black dots). Thirty-kilometer-square boxes (black) define the Monarch Peak (MP) and Cholame tremor zones. Color contours give regional shear-stress change at 20 km depth from the Parkfield earthquake (green segment) along the SAF. The thrust-type San Simeon earthquake rupture is represented by the gray rectangle and line with triangles labeled SS. The currently locked Cholame segment is ~63 km long (solid portion of the arrow) and is believed capable of rupturing on its own in ~Mw 7 earthquake. The gray lines within the Cholame box bound the west quadrant, where quasiperiodic episodes predominate. The white star indicates the epicenter and the gray stars the foreshocks of the 1857 Ft. Tejon earthquake (30, 31).
occurred as bursts of activity lasting ~3 to 10 days rather than 1 to 7 weeks, as is more common in subduction zones. These differences may, in part, be related to the tectonic environment or the much smaller dimensions of the SAF tremor zones.

The episodic tremors are not ubiquitous throughout the central part of the SAF. Rather, they seem to have been most persistent and regular in the western quadrant of the Cholame tremor zone, which is bounded by the SAF to the northeast and by the seismic-aseismic transition into the locked Cholame segment to the southeast (Figs. 1 and 2, B to D, and figs. S3 and S4). This localization of tremor behavior suggests that there are differences in the process generating tremor in different subregions of the SAF. It also supports the argument that tremor in the Cholame zone is distributed both normal to and along strike of the SAF at depth (figs. S3 to S5). Tremors in the Cholame zone are also spatially clustered, and >55% of the tremors are separated by ≤2 km from at least four other tremors and, in some cases, from as many as 35 other events. Precise relative locations of Cholame tremor activity with waveforms similar to those of a low-frequency earthquake showed that during a 24-hour period, the similar tremor formed a deep, near-linear, SAF-parallel structure within the Cholame zone at a depth of ~26 km (20). Taken together, the fault-normal distribution, clustering, and near-linear fault-parallel alignment of at least some tremor suggest that the SAF may broaden into several distinct subparallel zones as it extends into the ductile lower crust.

Static Coulomb- and shear-stress changes from the 2003 San Simeon and 2004 Parkfield earthquakes on planes aligned along the SAF at a depth of 20 km (19) (Fig. 1 and fig. S6) are small in the Cholame and Monarch Peak tremor zones (table S1), but both stress types increase with increases in tremor rates in the two zones. In the Cholame zone, modeled shear- and Coulomb-stress changes associated with the San Simeon earthquake are ~6 to 8 kPa, whereas those associated with the Parkfield event are ~9 to 14 kPa (table S1). In the Monarch Peak zone, shear- and Coulomb-stress changes from the San Simeon event, which failed to stimulate tremor, were negative (~4 to ~9 kPa); however, stress changes from the Parkfield earthquake were positive (~6 to 9 kPa) and correspond to the postseismic activation in tremor activity in this zone (Fig. 2B).

Static normal-stress changes from the earthquakes do not clearly correspond to the tremor rate changes in either zone (fig. S6 and table S1). This lack of correlation suggests that either normal-stress change did not play an important role in stimulating tremor or that other circumstances (such as the generally low change in normal stress as compared to that in shear stress, or offsetting signs of shear and normal stress; table S1) masked the effects of normal stress on tremor stimulation.

The static earthquake stress changes that stimulated the SAF tremors are roughly an order of magnitude smaller than those typically reported for the triggering of earthquakes (21). This suggests that tremors are a more sensitive indicator of stress changes than are earthquakes. The small stress changes that stimulated the SAF tremor (~0.01 MPa or 1-to-10th of atmospheric pressure) are consistent with stress changes produced by solid-earth or ocean tides or the passage of surface waves from large teleseismic events that have stimulated tremor in subduction zones (13–15).

The periodic tremor and persistent elevated activity after the 2004 Parkfield earthquake (Fig. 2, A and B) are not consistent with expectations of exponentially decaying postseismic stress after an earthquake (22, 23). It appears, therefore, that in the deep tremor zones, the SAF may have transitioned into a new state of stress and/or deformation. Models of faulting imply that step-like stress perturbations from nearby earthquakes or pore pressure changes during episodic fluid release could cause deformation styles to transition between steady-state, transient, and quasiperiodic (7). For such mechanisms to apply to the SAF, deep slow-slip events must be occurring and fluid pressures must be high in the tremor zones. Although deep slow slip associated with the SAF tremors has not been detected, slow-slip events with moment release equivalents as large as ~Mw 3 could occur in the tremor zones without being detected (24).

The lack of correlation between normal-stress and tremor rate changes from the San Simeon and Parkfield earthquakes may imply that effective normal stress is low and pore fluid pressure is high in the SAF zones. Recent studies of stimulation of tremor in the SAF by teleseismic events (14) and solid-earth tides (16) support this by showing that tremor rates correlate predominantly with variations in shear stress, even though normal-stress variations in some cases exceed shear-stress variations by roughly an order of magnitude (16). In subduction zones, the dehydration of subducting oceanic crust elevates fluid pressure (4). Although subduction no longer occurs along the SAF, two strong magnetic anomalies at Monarch Peak and Cholame (25) suggest that serpentinite bodies are present at depth, and these could be fluid sources (26) in the tremor zones. Alternatively, deep mantle-derived fluids might also play a role (27).

Because changes in SAF tremor activity have persisted for years beyond the last major quake in 2004, they could be signaling a shift in the process of deformation and stress accumulation beneath this portion of the SAF. The northwest tremor zone near Monarch Peak is an area of the SAF with anomalous structural complexity and low surface fault-creep rates (28). Two foreshocks (~Mw 6.1 and ~Mw 5.6) occurred in this area within 2 hours of the 1857 Mw 7.8 Ft. Tejon earthquake (29–31). Faulting from the 1857 event appears to have propagated from the Monarch Peak area southeastward along the SAF for ~350 km.
through Parkfield and the Cholame tremor zone (31) (Fig. 1). The rupture zone of the great 1857 event is composed of multiple fault segments (32), including the Cholame segment immediately southeast of the Cholame tremor zone. This segment is now fully locked. Its estimated mean recurrence time is between 85 and 142 years (32), and it last ruptured as part of the great 1857 event.

References and Notes
19. Materials and methods are available as supporting material on Science Online.

Evolution of the Turtle Body Plan by the Folding and Creation of New Muscle Connections
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The turtle shell offers a fascinating case study of vertebrate evolution, based on the modification of a common body plan. The carapace is formed from ribs, which encapsulate the scapula; this stands in contrast to the typical amniote body plan and serves as a key to understanding turtle evolution. Comparative analyses of musculoskeletal development between the Chinese soft-shelled turtle and other amniotes revealed that initial turtle development conforms to the amniote pattern; however, during embryogenesis, lateral rib growth results in a shift of elements. In addition, some limb muscles establish new turtle-specific attachments associated with carapace formation. We propose that the evolutionary origin of the turtle body plan results from heterotopy based on folding and novel connectivities.

Turtles are characterized by their shell, and there have been various opinions as to the evolutionary origin of their unique body plan (1–8). One possible scenario suggests that acquisition of the osteoderms, the dermal skeletal elements, predated the bony shell (6), but other studies have emphasized the importance of more fundamental anatomical changes, especially those associated with the pectoral region, as the decisive factor in turtle evolution (1–5). The dorsal part of the turtle shell, or carapace, is derived from the ribs, and the scapula is found beneath the carapace, in contrast to the pattern of other amniotes in which the scapula is outside the rib cage (Fig. 1, A to E). Concomitant with the positional change of skeletal elements, the muscles connecting the trunk and scapula, the serratus anterior (AS) and levator scapulae–rhomboid muscle complex (LSR), also showed aberrant positions and connections in the adult turtle (Fig. 1, D and E, and fig. S1). This unusual topography led to the opinion that the turtle shell represents an evolutionary novelty (1–5). At first glance, this evolutionary shift cannot be resolved by gradual changes of shape and size while maintaining the basic architecture of the body, because an intermediate state is impossible. Thus, it was proposed that turtle evolution represents a radical, saltatory evolutionary change (1–5). This change has been ascribed to a developmental shift in the ribs, not of the scapula (7, 8). However, the embryonic anatomy of the musculoskeletal system has not been analyzed sufficiently to identify the origin of the turtle-specific body plan.

To understand the developmental changes underlying the origin of the turtle Bauplan, we compared the development patterns in embryos of the Chinese soft-shelled turtle (Pelodiscus sinensis) and two other amniotes, the chicken (Gallus gallus) and the mouse (Mus musculus); three to four embryos were examined for each species and stage. As a specialized group of archosaurs, in which turtles are also included (9), avians have undergone specialization during evolution (SOM Text 1 and table S1); however, they are expected to exhibit an unaltered developmental pattern reflecting ancestral developmental programs that may have been lost or altered in turtles. Mammals, on the other hand, belong to synapsids, a lineage that diverged before archosaurs (9). Thus, the common developmental features shared by chicken and mouse are expected to represent the primitive state of amniotes. We focused on postorganogenetic periods of the embryos when the anatomical variations are thought to be becoming apparent (10), and the observations were based on comparative embryological methods.

We used Sox9 expression as the marker for the skeletal precursor in the late pharyngula stage