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Reflection and scattering of Stoneley guided waves at the tips of fluid-filled fractures

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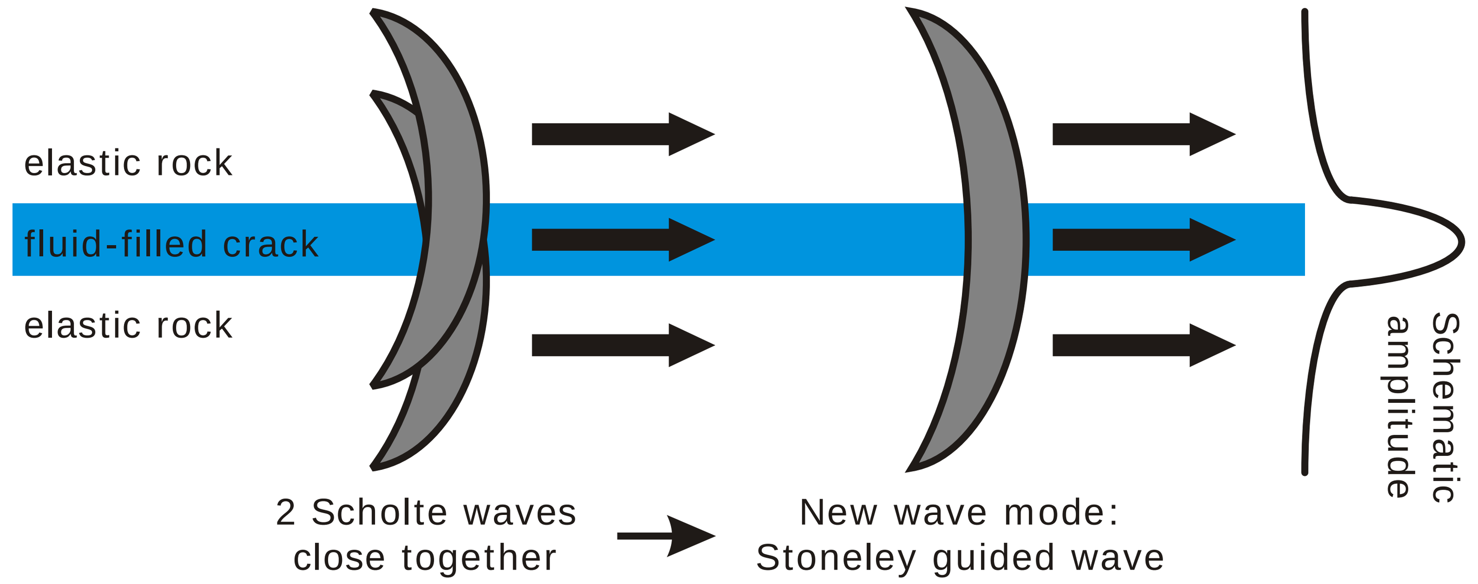
I) Abstract

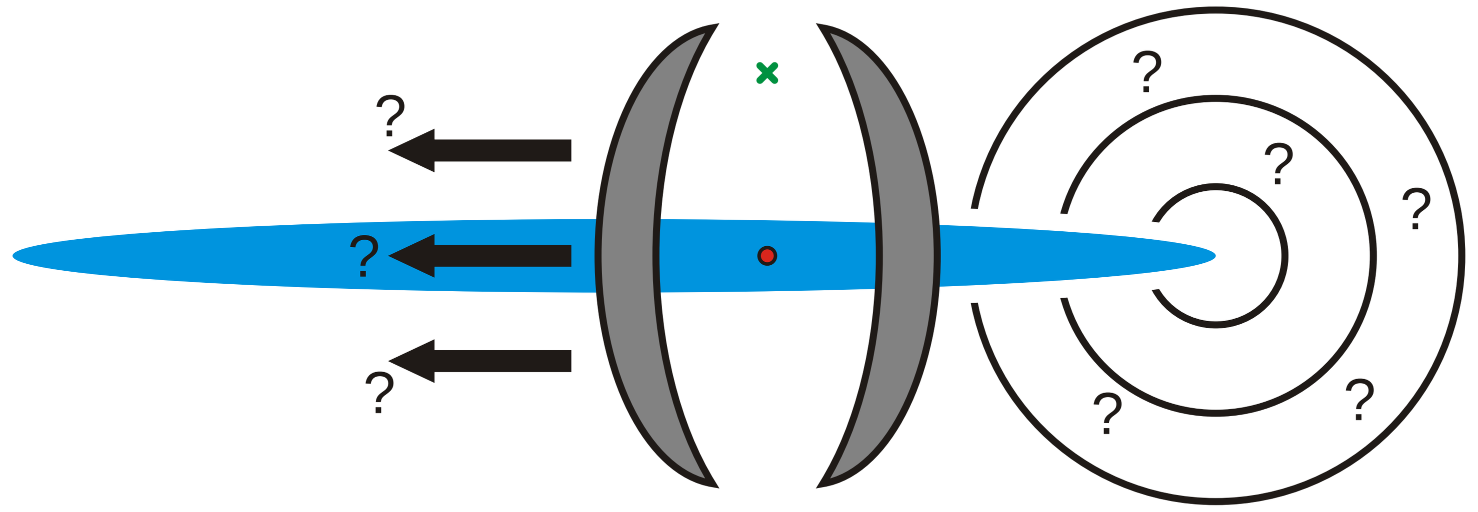
Reflection and scattering of Stoneley guided waves (SGWs) at the tip of a crack filled with a viscous fluid is studied numerically in two dimensions using the finite element method. The surrounding rock is fully elastic and the fluid filling the crack is elastic in its bulk deformation behavior and viscous in its shear deformation behavior. The crack geometry, especially the crack tip, is resolved in detail by the unstructured finite element mesh. At the tip of the crack the SGW is reflected. The amplitude ratio between reflected and incident SGW is calculated from numerical simulations, which provide values between 43% and close to 100%, depending on the type of fluid filling the crack (water, oil or hydrocarbon gas), the crack geometry (elliptical or rectangular) and the presence of a small gas cap at the crack tip. The interference of incident and reflected SGWs leads to a node (zero amplitude) at the tip of the crack. At other positions along the crack this interference increases the amplitude. However, the exponential amplitude decay away from the crack makes the SGW difficult to detect at a relatively short distance away from the crack. The part of the SGW that is not reflected is scattered at the crack tip and emitted into the surrounding elastic rock as body waves. For fully saturated cracks the radiation pattern of these elastic body waves points in every direction from the crack tip. The emitted body waves may allow detecting SGW-related resonant signals at distances away from the crack where the amplitude of the SGW itself is too small to be detected.

II) What are SGWs?

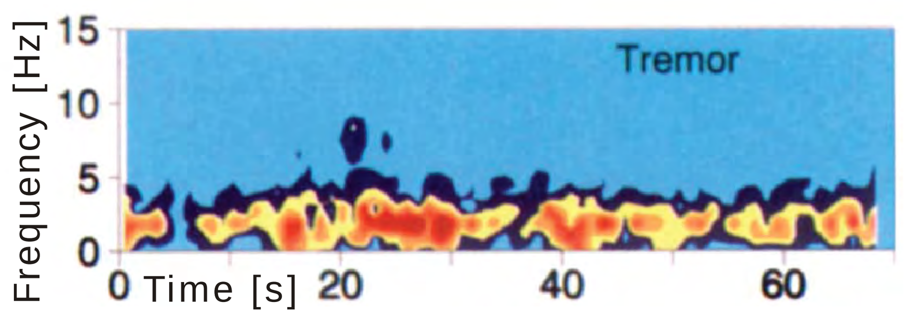


- Scholte wave: Interface wave between solid and fluid
- Interference between two Scholte waves propagating very close together leads to a new wave mode: The Stoneley guided wave
- Properties:
  - Bound to a fracture
  - Strongly dispersive (V_{SGW}=0 for f=0)
  - Attenuating for viscous fluids, not attenuating for inviscid fluids
- Ferrazzini and Aki, JGR (1987); Korneev, Geophysics (2008)

III) Why are SGWs interesting?



- SGWs can exhibit a resonance frequency when propagating back and forth along a finite crack.
- Used for explaining low-frequency volcanic tremor
- This study focusses on the reflection process.

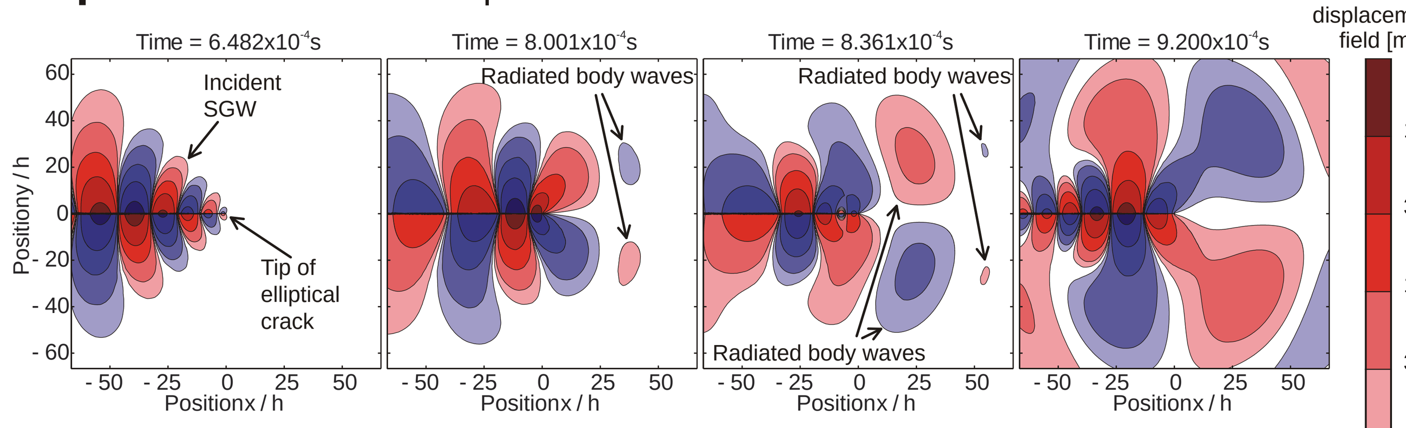


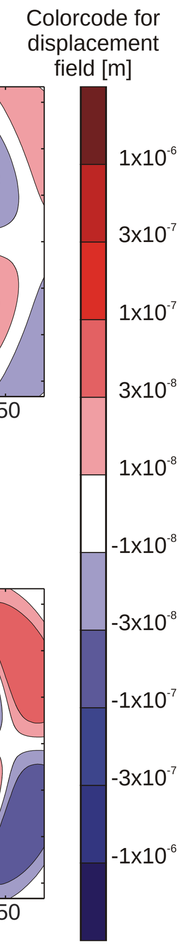
Chouet, Nature (1996):
Volcanic tremor, Mt. Redoubt, Alaska
Continuous narrow-band seismic signal

IV) Radiation pattern

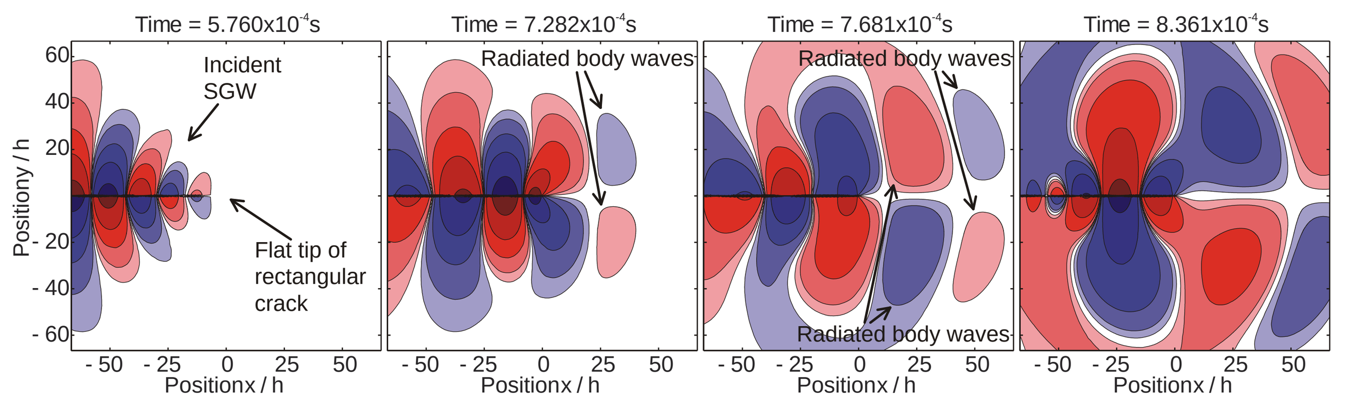
Finite element simulations of SGWs reflecting at the tip of water-filled cracks. Vertical displacement is displayed. Crack thickness : Wave length = 1 : 100

Elliptical crack: Low-amplitude radiation in all directions

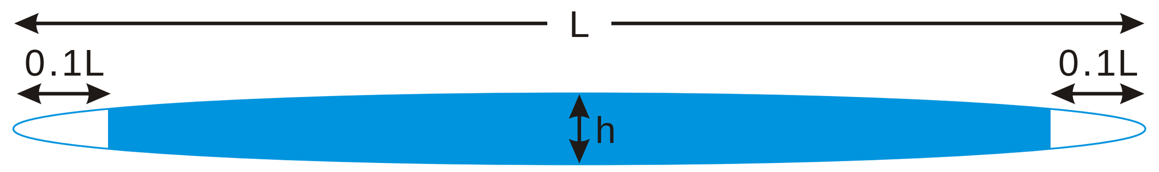




Rectangular crack: High-amplitude radiation in all directions

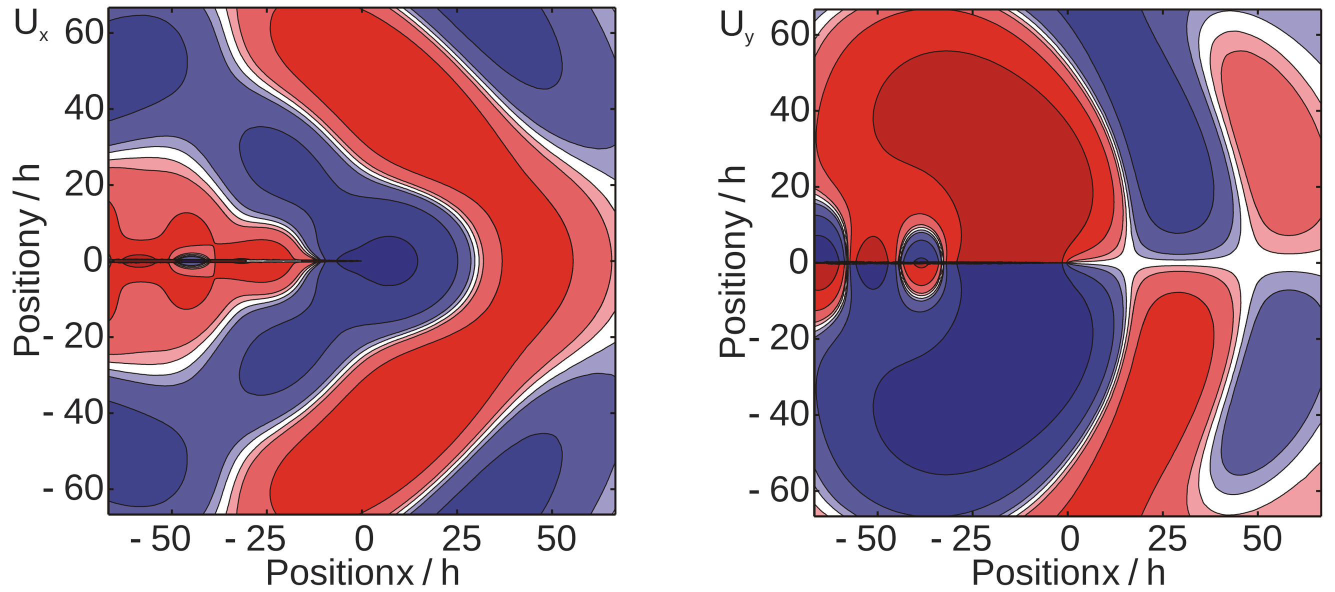


V) Partial saturation



Model for a partially oil-filled crack. A small gas-cap is present at the tip where the SGW reflects. The aspect ratio of the crack is L:h=333:1

Horizontal and vertical displacement at one point in time of a finite element simulation of a SGW reflecting at the tip of a partially oil-filled crack (Model above). Colorcode as before. The radiation is predominantly forward directed.



VI) Reflection

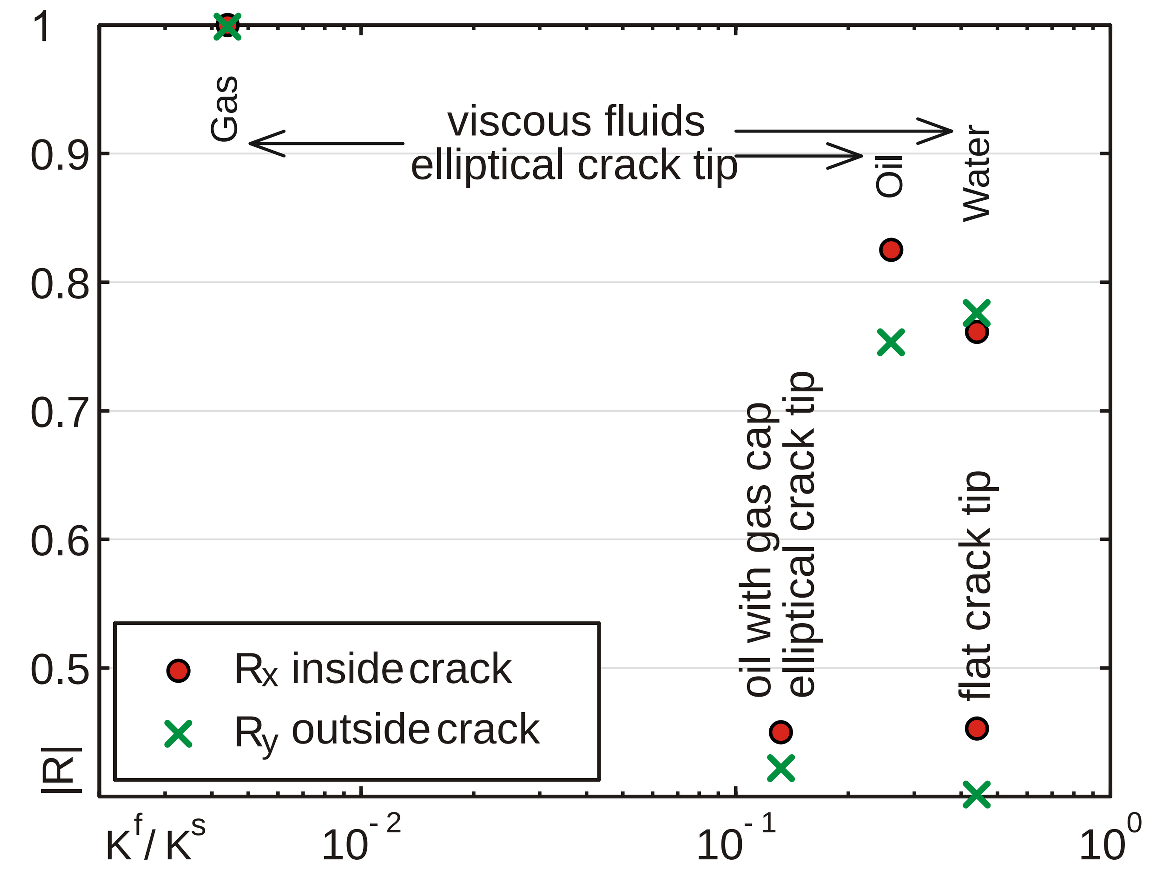
Amplitude ratio |R| between reflected and incident SGWs. During numerical simulations incident and reflected SGW amplitudes are measured at indicated virtual receivers. The horizontal axis is the normalized bulk modulus of the fluid filling the crack.

Reflection depends on:

- Crack geometry
- Fluid filling the crack
- Full or partial saturation

Generally:

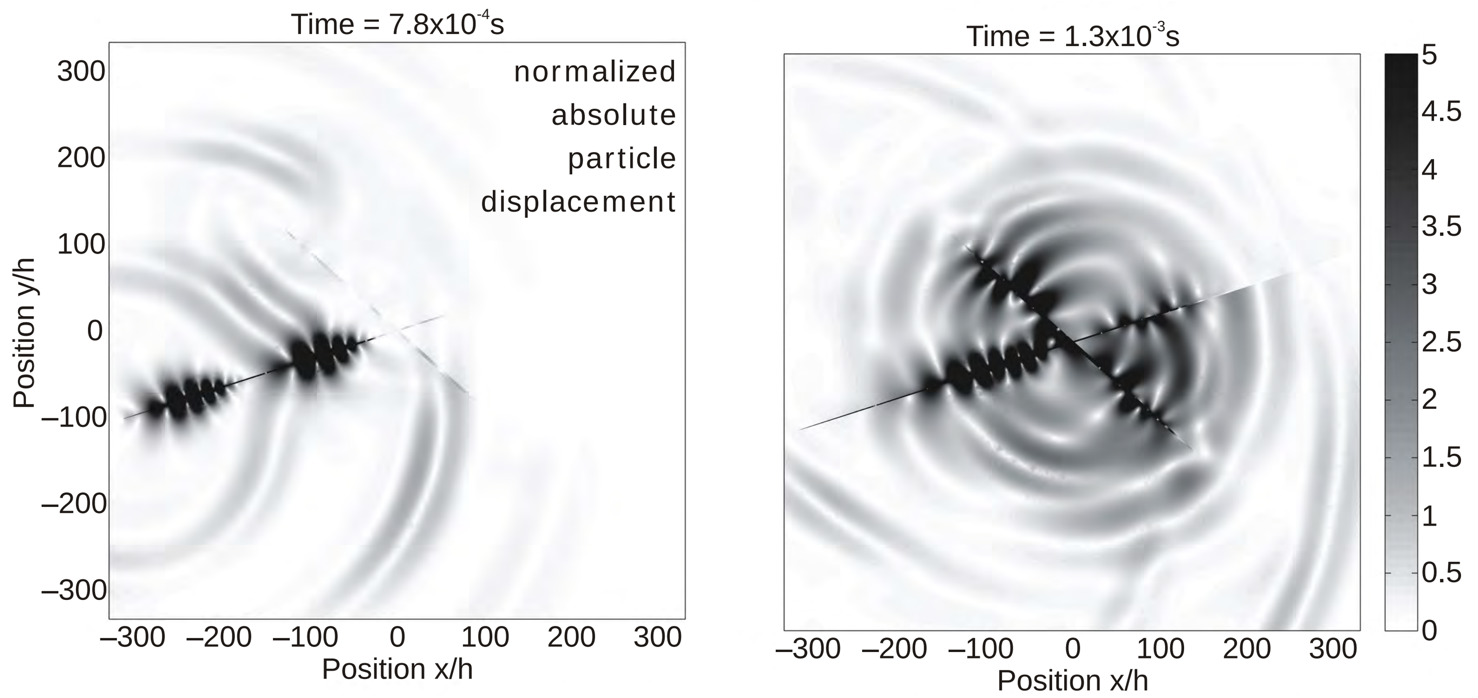
- |R| relatively high



VII) Intersecting cracks

Propagation of a SGW along a crack that is intersected by a second crack. At the intersection point, a part of the SGW propagates straight ahead while a significant part makes a sharp turn and propagates along the second crack. Also, body waves are emitted into the surrounding medium from the intersection point.

Displayed is the normalized absolute displacement at two points in time.



VIII) Summary & conclusions

Summary of results:

- SGWs reflect at the tip of a fracture.
- Reflection depends on crack geometry, fluid filling the crack and the presence of heterogeneities inside the crack.
- Non-reflected part is scattered at the crack tip and radiated as body waves.
- Radiation points in every direction for fully saturated cracks while it is dominantly forward directed if a small gas cap is present at the crack tip.

Conclusions:

- The relatively strong reflection of SGWs at the crack tip enables them to fall into resonance when propagating back and forth many times along a crack.
- The emission of body waves makes the detection of SGW-related resonance signals possible even at distances away from the crack where the SGW itself is too weak to be detected.

References:

Chouet, B.A., 1996: Long-period volcano seismicity: Its source and use in eruption forecasting, Nature 380, 309-316
Ferrazzini, V. and Aki, K., 1987: Slow waves trapped in a fluid-filled infinite crack: Implications for volcanic tremor, JGR 92, 9215-9223
Korneev, V., 2008: Slow waves in fractures filled with viscous fluid, Geophysics 73, N1-N7, doi: 10.1190/1.2802174