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Seismicity and fault geometry of the San Andreas fault around Parkfield, California and their implications

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ABSTRACT

Fault geometry is a consequence of tectonic evolution, and it provides important information on potential seismic hazards. We investigated fault geometry and its properties in Parkfield, California on the basis of local seismicity and seismic velocity residuals refined by an adaptive-velocity hypocentral-parameter inversion method. The station correction terms from the hypocentral-parameter inversion present characteristic seismic velocity changes around the fault, suggesting low seismic velocities in the region east of the fault and high seismic velocities in the region to the west. Large seismic velocity anomalies are observed at shallow depths along the whole fault zone. At depths of 3–8 km, seismic velocity anomalies are small in the central fault zone, but are large in the northern and southern fault zones. At depths >8 km, low seismic velocities are observed in the northern fault zone. High seismicity is observed in the Southwest Fracture Zone, which has developed beside the creeping segment of the San Andreas fault. The vertical distribution of seismicity suggests that the fault has spiral geometry, dipping NE in the northern region, nearly vertical in the central region, and SW in the southern region. The rapid twisting of the fault plane occurs in a short distance of approximately 50 km. The seismic velocity anomalies and fault geometry suggest location-dependent piecewise faulting, which may cause the periodic M6 events in the Parkfield region.

1. Introduction

Fault structure and geometry are useful indicators of fault mechanics and seismic behavior. Seismic reflection and refraction studies have been found to be useful for investigation of fault properties (Louie et al., 1988; Fuis et al., 2001; Catchings et al., 2002; Lutter et al., 2004; Hole et al., 2006; Zhao et al., 2010). Low-velocity fault zones have been well mapped in seismic tomography studies (Eberhart-Phillips and Michael, 1993; Shapiro et al., 2005; Thurber et al., 2006). The utility of geophysical explorations has been demonstrated for studies of local fault structure (Griscom and Jachens, 1990; Unsworth et al., 1997; McPhee et al., 2004; Le Pichon et al., 2005; Fialko, 2006; Wdowinski et al., 2007). Detailed fault structure can be imaged well by combining methods based on multiple approaches (Unsworth et al., 1997; Fuis et al., 2012).

Drilling may be the most direct method to study fault-zone properties. However, it is applicable only in limited situations (Zoback et al., 2010). Fault-zone head waves and guided waves are influenced by fault-zone properties, which enable us to infer the physical properties of the medium (Ben-Zion and Malin, 1991; Hough et al., 1994; Korneev et al., 2003; Lewis et al., 2007; Zhao and Peng, 2008; Zhao et al., 2010). The spatial distribution of seismicity may be useful as an indirect method for making inference regarding fault geometry (Eberhart-Phillips and Michael, 1993; Thurber et al., 2006).

Accurate determination of event locations may be essential for the elucidation of fault geometry using seismicity. A number of hypocentral-inversion methods including HYPO71 (Lee and Lahr, 1975; Lee, 1990), HYPOINVERSE (Klein, 1978, 2002), HYPOELLIPSE (Lahr, 1980), VELEST (Kissling et al., 1994), HYPOSAT (Schweitzer, 1997), and HYPODD (Waldhauser and Ellsworth, 2000) have been proposed. In particular, a double-difference location technique (e.g., HYPODD) has been determined found to be useful for clustered events (Waldhauser et al., 2004). However, the hypocentral parameters obtained using such methods are highly influenced by the accuracy of the implemented velocity models (Kim et al., 2014). This feature makes it difficult to apply such 1-D velocity-model-based methods to seismicity in regions with complex velocity structures.

Fault zone structures are naturally complex, and they are poorly represented by 1-D velocity models (Kim et al., 2014). Attempts have been made to perform hypocentral-parameter inversions based on 3-D velocity models (e.g., Thurber et al., 2006). However, fine-scale structures can be represented only limitedly even with 3-D velocity models. An inversion based on adaptive velocity models may be desirable for correct determination of hypocentral parameters of events in complex-

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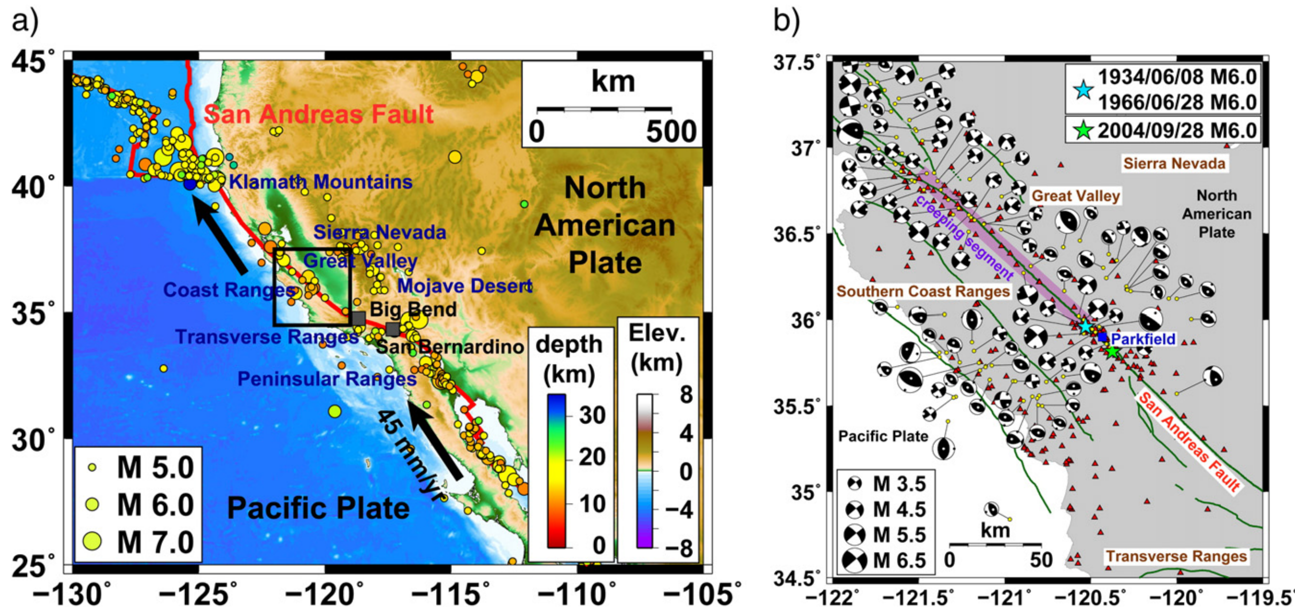

Fig. 1. (a) Tectonic setting around the western North American plate. The study region is marked with a black box. Major events with magnitudes greater than or equal to 5 are presented (circles). (b) Enlarged map of the study region around Parkfield with the focal mechanism solutions of major earthquakes (Ekström et al., 2012). Major geological structures are denoted. Stations (triangles) are distributed densely around the faults. The epicenters of periodic M6 events are marked (stars).

velocity regions (Lees and Malin, 1990; Michelini and McEvilly, 1991; Eberhart-Phillips and Michael, 1993; Thurber et al., 2003, 2004, 2006; Lin et al., 2010).

Seismicity is naturally associated with faulting. Microearthquakes may occur in local branches around a major fault, resulting in a complex distribution of seismicity. Seismicity of several or more years is expected to present the dominant seismic activity in the fault system. Seismicity is useful to constrain fault geometry, which provides important information for assessing potential seismic hazards. In this study, we investigate the seismicity around the San Andreas fault (SAF) in central California. The hypocentral parameters of the earthquakes are determined using a hypocentral-parameter inversion method based on an adaptive-velocity-model-updating scheme. The inverted hypocenters are compared with those obtained using other conventional methods. The fault dips and the geometry along the fault trace are investigated using the vertical distribution of seismicity.

2. Geology and tectonics

The San Andreas fault (SAF) is an approximately 1100-km-long right-lateral strike-slip fault that forms a plate boundary between the Pacific and North American plates along the west coast of the US (Catchings et al., 2002; Fig. 1). The locking segments of the SAF are separated by a 175-km-long creeping segment in central California (Harris and Segall, 1987; Nadeau and McEvilly, 2004). The fault naturally divides the basements of the Pacific and North American plates. The southwestern basement is formed of Salinian granite overlain by Quaternary and Tertiary sediments (Dibblee, 1980; Unsworth et al., 1997). The northeastern basement contains a melange of metamorphosed accretionary prism overlain by Tertiary and Holocene sediments.

The slip rates on the locked segment in northern California are 13–22 mm/yr, and those on the locked segment in southern California are 12–22 mm/yr (Geist and Andrews, 2000; Behr et al., 2010). In contrast,

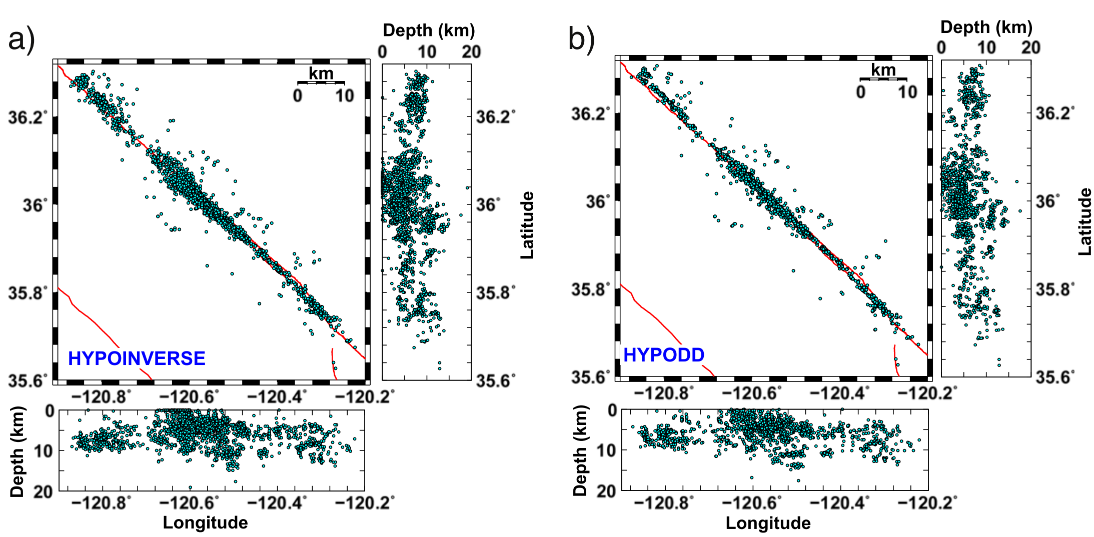

Fig. 2. Event epicenters and focal depths determined by (a) HYPOINVERSE and (b) HYPODD. The epicenters from HYPOINVERSE are diffused around the fault trace, whereas those from HYPODD are clustered along the fault trace. Most focal depths are less than 15 km.