JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. B6, PAGES 11,217-11,237, JUNE 10, 2001

Estimating source parameters from deformation data, with an application to the March 1997 earthquake swarm off the Izu Peninsula, Japan

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Abstract. We have applied two Monte Carlo optimization techniques, simulated annealing and random cost, to the inversion of deformation data for fault and magma chamber geometry. These techniques involve an element of randomness that permits them to escape local minima and ultimately converge to the global minimum of misfit space. We have tested the Monte Carlo algorithms on two synthetic data sets. We have also compared them to one another in terms of their efficiency and reliability. We have applied the bootstrap method to estimate confidence intervals for the source parameters, including the correlations inherent in the data. Additionally, we present methods that use the information from the bootstrapping procedure to visualize the correlations between the different model parameters. We have applied these techniques to GPS, tilt, and leveling data from the March 1997 earthquake swarm off of the Izu Peninsula, Japan. Using the two Monte Carlo algorithms, we have inferred two sources, a dike and a fault, that fit the deformation data and the patterns of seismicity and that are consistent with the regional stress field.

1. Introduction

The increasingly widespread use of space geodesy has resulted in numerous, high-quality surface deformation data sets. For example, a large continuous GPS network of nearly 1000 stations covers most of Japan [*Kato et al.,* 1998], and a network of more than 250 stations is under construction in the greater Los Angeles area [*Bock et al.,* 1997]. Many geologically active areas such as Kilauea volcano and Long Valley caldera also have regional continuous GPS networks [*Owen et al.,* 2000; *Dixon et al.,* 1997]. Survey mode GPS data spanning more than a decade exist in many areas around the globe. Interferometric synthetic aperture radar (INSAR) promises even more deformation data with potentially worldwide spatial extent [*Massonet and Feigl,* 1998]. These geodetic data can provide important constraints on fault geometry and slip distribution. For this reason, we have developed robust and nearly automatic methods for rigorously inverting surface deformation fields for source type and geometry.

Many past attempts to infer source geometry from deformation fields have used elasticity theory and a trial-and-error approach to find geologically plausible deformation models that fit the major features of the observed deformation field [e.g., *Okada and Yamamoto,* 1991; *Owen et al.,* 1995]. Other workers have systematically searched through a large set of feasible models, comparing the predictions to the data and choosing the model that minimizes the misfit [e.g., *Ward and Barrientos* 1986; *Marshall et al.,* 1991]. Derivative-based searching algorithms have also been used; for example, *Árnadóttir et al.* [1992] used a quasi-Newton method to invert for the fault plane of the 1989 Loma Prieta earthquake. Finally, we have applied the inversion methods discussed below to the source geometry estimation problem. See, for example, *Murray et al.* [1996], *Jònsson et al.* [1999], *Freymueller et al.* [1999], or *Aoki et al.* [1999]. The aims of this paper are (1) to evaluate, using synthetic data sets, a variety of inversion methods for robustness and efficiency, (2) to develop techniques for assigning meaningful uncertainties to the estimated source parameters, and (3) to apply the inversion methods to the deformation from the March 1997 Izu Peninsula earthquake swarm. The study of the Izu swarm is included here both for pedagogical reasons and as an expansion on our previous work [*Aoki et al.,* 1999].

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Paper number 2000JB900399.
0148-0227/01/2000JB900399$09.00

2. Theory

2.1. Earth and Source Models

Estimating source geometry from geodetic data requires a forward model of how the crust responds to various kinds