Jour. Korean Earth Science Society, v. 21, no. 3, p. 315−322, June 2000

Thermoelastic Aspects of the San Andreas Faults under Very Low Strength

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낮은 강도를 갖는 산 안드레아 단층의 열탄성 특성

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Abstract: In this study, the data used for the models were a set of 56 geologic estimates of long-term fault slip rates. The best models were those in which mantle drag was convergent on the Transverse Ranges in the San Andreas fault system, and faults had a low friction (μ= 0.3). It is clearly important to decide whether these cases of low strength are local anomalies or whether they are representative. Furthermore, it would be helpful to determine fault strength in as many tectonic settings as possible. Analysis of data was considered by unsuspected sources of pore pressure, or even to question the relevance of the friction law. To contribute to the solution of this problem, three attempts were tried to apply finite element method that would permit computational experiments with different hypothesized fault rheologies. The computed model has an assumed rheology and plate tectonic boundary conditions, and produces predictions of present surface velocity, strain rate, and stress. The results of model will be acceptably close to reality in its predictions of mean fault slip rates, stress directions and geodetic data. This study suggests some implications of the thermoelastic characteristics to interpret the relationship with very low strength of San Andreas fault system.

Key word: slip rate, friction law, rheology, geodetic, thermoelastic

요 약: 본 연구는 장기간에 걸쳐 산 안드레아 단층계 내에서 56개 지점의 단층이동률에 대한 지질학적인 측정자료를 기준으로 모델을 설정하였다. 모델은 산안드레아 단층을 중심으로 한 수렴대에서 낮은 마찰(μ=0.3)을 갖는 단층군에 대해 최적의 결과를 보여주고 있다. 저강도를 갖는 단층에 대해 국지적인 이상값이나 대표값을 결정하는 것은 분명히 중요한 의미를 갖는다. 더욱이 이러한 연구는 지구조적인 체계에서의 단층의 강도를 결정하는 데 도움이 될 것으로 보인다. 예상치 못한 원인에 의한 공극압력이나 마찰법칙의 적절성에 대한 의문을 고려하지 않을 수 없을 것이다. 이러한 문제를 해결하기 위해서, 다른 가설하에서 단층의 유체학적인 모의 실험이 가능한 유한요소법을 적용하기 위해 세 가지의 단층분석 모델을 시도하였다. 계산된 모델은 추정된 유체역학적 특성과 판구조경계 조건을 만족하며, 현재의 지진파 표면속도, 변형률과 강도의 예측값을 나타내고 있다. 모델 연구의 결과는 평균 단층이동률, 강도의 방향과 측지학적인 자료의 예측값 범위 내에서 실제 측정치에 접근하고 있음을 보여준다. 본 연구는 저강도를 갖는 산 안드레아 단층계에서의 상호관련성을 해석하기 위한 열탄성 특성의 적용 결과를 잘 제시하고 있다.

주요어: 이동률, 마찰법칙, 유체학, 측지학적, 열탄성

Introduction

The studies related to the strength or weakness of faults may have started with Hubbert and Rubey(1959), who showed the impossibility of explaining large overthrusts with conventional theory. By the previous studies, there are restricted in local solutions showing much lower stress.

In California, Henyey(1968) searched unsuccessfully for a heat flow anomaly along the San Andreas fault area(Fig.1) and concluded that its mean shear stress must be less than 20 MPa (Henyey and Wasserburg, 1971; Lachenbruch and Sass, 1980). Mount and Suppe(1987) complied stress direction data along the

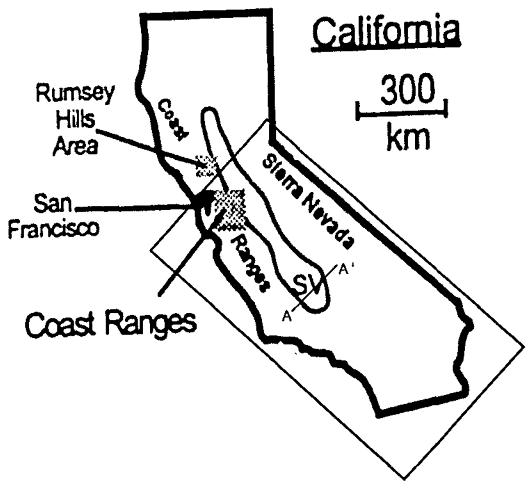

Fig. 1. Study area and location map.

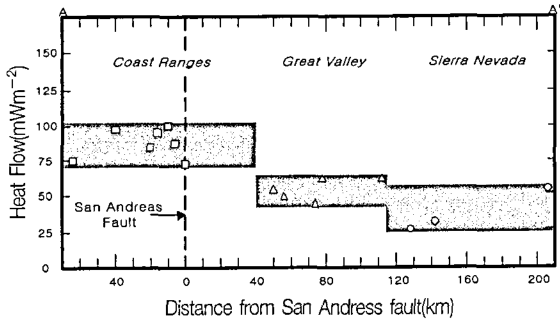

Fig. 2. Heat flow distribution of major faults diagramed from San Andreas faults and its vicinity.

same fault and showed that the nearly orthogonal relation requires very low friction($\mu \leq 0.1$). These results suggest that the standard model often predicts stresses which are too high by an order of magnitude.

In this study, the data used for the models was a set of 56 geologic estimates of long-term fault slip rates. The best models were those in which mantle drag was convergent on the Transverse Ranges, and faults had a low friction (μ=0.3).

In most cases, faults were forced through to a connection with other faults, even where the actual intersection is obscured by Quaternary sediments. It is important to do this if the intention is to perform numerical experiments with faults much weaker than intervening blocks.

The heat flow distribution which this paper was assumed is shown in Figure 2; it was contoured from references listed in Bird and Baumgardner(1984), plus northern California values obtained from Lachenbruch and Sass(1980). To approximately represent the three dimensional structure of California, each node of the grid was assigned values of elevation, heat flow, and crustal thickness; at other point, these values were interpolated using the quadratic nodal functions. Crustal thickness is actually quite controversial, and we selected the map of Mooney and Weaver(1989) partly because of its simplicity and lack of short wavelength features which(if incorrect) might bias the behavior of particular faults.

It is clearly important to decide whether these cases of low strength are local anomalies or whether they are representative. Furthermore, it would be helpful to determine fault strength in as many tectonic settings as possible. We might be forced to consider unsuspected sources of pore pressure, or even to question the relevance of the friction law(Han, 1991; Williams, 1995; Hickman *et al.*, 1995; Han and Keehm, 1997). To contribute to the solution of this problem, three attempts of data were tried to apply finite element method that would permit computational experiments with different hypothesized fault rheologies. Every computed model has an assumed rheology and plate tectonic boundary conditions, and produces predictions of present surface velocity, strain rate, and stress. The hope is that out of a suite of models, one will be acceptably close to reality in its predictions of mean fault slip rates, stress directions and geodetic data. The results of study would permit conclusions about the strength of the corresponding real faults.

The computed codes based on assumptions and approximations are suggested in the previous paper(Park and Han, 2000). The relationship between surface heat flow and seismic activity was derived by changing the parameters. The simulation is discussed in detail by Park and Han(2000), compared to the results of analysis of seismic hazard estimation in the study area.

In this paper, some implications of the thermoelastic characteristics are evaluated to interpret the relationship with very low strength of San Andreas fault system.

Rheologic Models

The base model is one in which the entire crust shares a common rheology, both in faults and in the blocks. This common rheology includes both a frictional and dislocation creep part, with the "brittle and ductile" transition between them depending upon temperature and strain rate. In the frictional part, the base coefficient of friction is 0.85, the Biot coefficient is 1, and the pore pressure(P_p) is assumed hydrostatic. Each computed model makes three kinds of testable predictions: long term average slip rates of faults, principal directions of stress, and relative velocities of geodetic benchmarks.

For testing the predictions of long term average slip rates, we used geologic data concerning large offsets(>40 m on long faults, >5 m on short faults) in order to average over several seismic cycles. More recent data and data from northern California are listed in Table 1. The scalar measure of misfit that the value was adopted is the root mean square (RMS) prediction error, $\varepsilon_{geologic}$, in $mmyr^{-1}$.

Directions of principal stresses were obtained from the compilation of Zoback and Zoback (1989) as detailed on the "Geophysics of North America". To quantify the model, it was computed by a variation diagram, which is a graph of the variance of the differences in stress direction between all possible pairs of data versus the distance between them. From the intercept value of this variation diagram, we estimate that the dataset contains errors with standard deviation of 17 degrees. Calculated relative velocities between pairs of points are not immediately comparable to geodetic results, because most geodetic data were obtained over short time periods during which there were no large earthquakes. Thus, model velocities are discontinuous across faults, while most geodetic profiles are continuous. We take the rate of slip on these dislocation patches to be the opposite of the model long-term average slip rate, so that the fault becomes temporarily locked in the upper crust. Then, the sum of the far field elastic displacements from these dislocations (Mansinha and Smylie, 1971) is a vector field of velocity corrections due to temporary fault locking. This vector field is added to the original long term average velocity predictions before scoring the model.

Heat Flow Data

For the strength of rocks and rheology of the crust, the factors are very sensitively related to crustal temperatures. The factor of the most important uses of heat flow is to estimate crustal temperatures, which can provide constraints on the thermal models for the earthquake(Figure 2.). For example, it is generally thought that the base of the seismogenic layer corresponds to the frictional stability transition from unstable to stable sliding which occurs for typical crustal rocks at temperatures in the 300 ℃-450 ℃ range(Henyey and Wasserburg, 1971; Blanpied *et al.*, 1995; Sass, 1997). We can use the relation derived by Lachenbruch and Sass(1980),

$$q(z)=[(q_o-bA_o)z+b^2A_o(1-e^{-z/b})]/k$$

which accommodates an exponential decrease of radiogenic heat production with depth. The heat production(Ao) of the earth surface was taken as 1.5 μWm^{-3} and the logarithmic decrement(b) was taken as 10km. Thermal conductivity(k) was assumed constant at 2.5 $Wm^{-1o}K^{-1}$. Surface heat flows(q_o) for the Central Coast Ranges and San Andreas region were assumed as 83 and 74-95 mWm^{-2}, respectively in Figure 3. The resultant geotherms have temperatures in the range

Table 1. Geologic slip rates modified from Park and Han(2000).

Fault	Slip *	Rate(mmyr^{-1})	References
Calaveras	RL	3±?	Sarna-Wojcicki *et al.*(1986)
Coast Ranges	RL	20±?	Paul Segall(1995)
E. CA shear zone	RL	6-12	Dokka and Travis(1990a)
W. Great Valley	RL	31±1	Paul Segall(1995)
Hayward	RL	7-10	Lienkaemper *et al.*(1989)
Panamint Valley	RL	1.6-3.2	Zhang *et al.*(1990)
Panamint Valley	RV	≤4.7	Zhang *et al.*(1990)
Rodgers Creek	RL	≥2.1	Budding *et al.*(1991)
N. San Andreas	RL	10-30	Cummings(1968)
N. San Andreas	RL	≤25	Prentice(1989)
N. San Andreas	RL	≥7.5	Ward and Page(1989)
N. San Andreas	RL	39±3	Paul Segall(1995)
S. San Andreas	RL	13-28	Prentice *et al.*(1986)
S. San Andreas	RL	14-25	Harden and Matti(1989)
San Cayetano	RV	5.2-13.8	Yeats and Huftile(1990)
San Jacinto	RL	6-14	Prentice *et al.*(1986)
San Jacinto	RL	≥7	Rockwell *et al.*(1990)
Santa Cruz Island	RV	1.27-2.5	Pinter and Sorlien(1991)

*The asterisk symbol corresponds to slip component directions: RL=right-lateral, RV=relative-vertical(which is less than true dip-slip).

Table 2. Geologic net slips of San Andreas Faults System modified from Park and Han(2000).

Fault	Net slip(km)	References
North San Andreas	295	Dickinson *et al.*(1972)
South San Andreas	225	Ehlert and Ehlig(1977)
San Gregorio-Hosgri	115	Graham and Dickinson(1978)
Garlock	64	Davis and Burchfiel(1973)
Hayward-Rodgers Crk	44	Sarna-Wojcicki(1986)
Elsinoire-Whitter	40	Crowell and Syvester(1979)
Morales	25	Segall P.(1995)
San Jacinto	24	Sharp(1967)
Calico	9	Dokka(1983)
Hunter Mountain	9	Burchfiel *et al.*(1987)
Santa Monica	8	Lamar(1961)
Rose canyon	4	Kennedy(1975)
Newport-Inglewood	3	Yeats(1973)
Santa Suanna	3	Barnhart and Slosson(1973)
Palos Verdes	2	Yeats *et al.*(1990)
W. Great Valley	2	Segall P.(1995)

310℃-450℃ at depth range of 10~15 km, consistent with a possible brittle-ductile transition at the depth. At the depth of 10 km projected for a deep research well along the San Andreas faults (Hickman *et al.*, 1995) the predicted temperatures are also in 300 ℃, which corresponds to the onset of ductility in quartz rich rocks. It should be emphasized that the geotherms are subject to substantial uncertainty on the thermal conductivity that increases with depth.

Seismic Hazard Evaluation

Results of models may be useful for improving estimates of long-term seismic hazard, by contributing new limits on the long-term average slip rate of each fault in Table 2. Of course, it is necessary to give priority to actual geodetic and geologic data, and to only use computer models where data are absent or ambiguous. Also, it is necessary to consider the full range of rates displayed in a set of models (all those with reasonably good values) in order to avoid giving a misleading impression of precision.

Following this concepts, we have constructed Table 3, in which all available data are summarized and tentative conclusions offered. Geologic slip rates are represented from Table 1. Where multiple studies

Table 3. Depth to brittle-ductile transition.

Fault/Area	Heat Flow(mWm^{-2})	Deepest Events	410°C Depth	Model
San Jacinto	61	19	17.5	(20.9)
Elsinore	65	21	16.3 (19.1)	
W. Trans. Ranges	69	15	15.3 (16.0)	
San Andreas(Central Area)	73	12	14.3	(15.9)
San Andreas(Basin and Range)	74	14	14.1	(17.2)
San Andreas(Coastal Ranges)	80	10	13.0	(15.6)
Hayward	83	11	12.5	(15.8)
N. San Andreas	86	12	12.0	(15.6)
Rodgers Creek	90	12	11.4	(13.2)
Coso Range	96	9	10.7	(13.0)
Imperial Valley	130	12	7.8	(11.2)
Geysers	130	4	7.8	(9.0)

Numbers in parentheses are data sets modified from Bird(1989) as a result of experiments

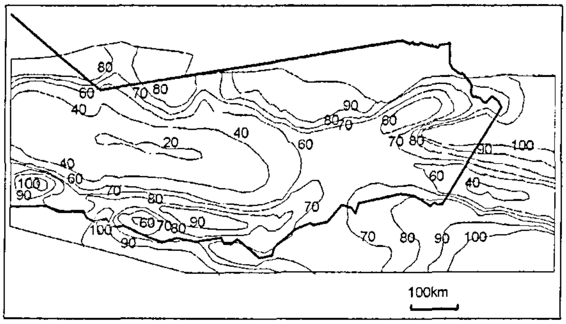

Fig. 3. Heat flow profile of the study area. The contour interval is 10 mWm^{-2}, labeled in milliwaters per square meters. Data was reproduced from Park and Han(2000).

gave overlapping rate windows, the common central segment is quoted. Geodetic rates are all derived from laser geodimeter trilateration data of Lisowski *et al.* (1991) or Savage *et al.* (1990). The assignments of equivalent slip rates to individual fault are our own subjective estimates. The column "Good Models" gives the range of rates found among the 30 models from data set which had global prediction errors of 4 mmyr^{-1} or less. The column "Best Model" gives the rate from the model marked as parentheses in Table 4. In combining the different kinds of limits, the highest weight is given to geodetic data, the geologic data are ranked second, and the models are considered the weakest.

Given these conservative rules, it is not surprising that these models add little to our knowledge of the intensively studied San Andreas Fault system(Figure 4.). What we can add is some limits for minor

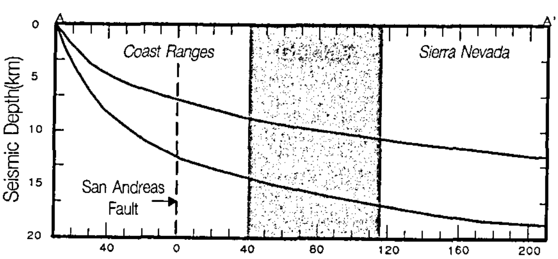

Fig. 4. Data sets seismic depth estimated from San Andreas Faults and its vicinity.

branches: the Caneros fault of northern California probably does not exceed 6.6 mmyr^{-1}, and the San Juan-White rock-Morales system of the southern Coast Ranges probably moves no more than 9 mmyr^{-1}.

These models are most useful in suggesting estimates for offshore and coastal faults which are difficult to access, for thrust faults which typically 'bury their evidence', and for faults in less active areas which have been given low priority in modeling of studies. For example, these models present the controversy over the Hosgri fault, where Hamilton and Willingham(1977) inferred only 2-4 mmyr^{-1} from geologic evidence, while Humphreyes *et al.*(1984) argued for 16-19.

In this study, the result never show the rates over 3 mmyr^{-1} on the San Gregorio-Carmel Canyon-Hosgri system in these models, so the lower rate is probably appropriate for seismic hazard evaluation (regardless of which is the correct mean rate for Pliocene-Quaternary time). In the southern California borderland, the result of this study confirms that the shoreline cutting Newport-Inglewood-Rose canyon-Vallecitos and Palos-Verdes-Coronado Bank systems are moving at no more than a few millimeters per year. One surprising result here is that the slip on the outer Santa Barbara Island-San Diego Trough-Agua Blanca system increases northwestward, from about 2 mmyr^{-1} in Baja California to as much as 19 mmyr^{-1} at the intersection with the Santa Barbara Channel structures. However, this result is not unique, as we have other good models where this system moves very slowly. Perhaps GPS observations at Santa Barbara and San Clemente islands can be used to resolve this problem.

It is important to estimate the slip rates of the thrust faults along the southern margin of the Transverse Ranges because of the high population densities in the priority of study area. Geodetic data are still inconclusive, and geologic rates must usually be treated as lower limits because of the tendency of thrusts to spray over a broad zone. It was ominous when Bird and Rosenstock (1984) used rigid block kinematics to infer slip rates of 7-15 $mmyr^{-1}$ along this zone. Weldon and Humphreys (1986) showed an alternative kinematic model with slower thrusting, but did not resolve the new problems that this would create in the borderland. In this study, we find rates that are about half compared with the results of Bird and Rosenstock' s, but still indicative of real hazard. The Cucamonga fault slips at about 7 $mmyr^{-1}$ and the Sierra Madre fault rate is 3-6 $mmyr^{-1}$. Along the southwest branch of this system (Santa Monica and Malibu Coast faults) the model rates are scattered, from under 1 to over 18 $mmyr^{-1}$; however, since there is geologic constraint showing slow motion(≤ 1.1 $mmyr^{-1}$) on the Santa Monica fault, this probably applies to the whole branch. On the northwest branch (Sierra Madre-San Fernando-Santa Susanna-San Cayetano-Red Mountain-Santa Barbara Channel faults) the models suggest an upper limit of 7 $mmyr^{-1}$ for the San Fernando fault and an upper limit of 3 $mmyr^{-1}$ for the Santa Barbara Channel fault. The fact that fastest slipping models just match the lower geologic rate limit (9 $mmyr^{-1}$) on the central Red Mountain-San Cayetano fault segment suggests that these models may be the results closest to reality.

All of these computations will be conducted before indicating the active movement that the new fault segments revealed. The range of slip rates that we calculated for the Pipes Canyon fault (0.2-2.1 $mmyr^{-1}$) may be of interest to help place these events in context. Apparently, major events on these faults should have long recurrence times, and the fact that these segments now appear to be more active than the adjacent San Andreas fault is only an artifact of the short instrumental record.

Discussion and Conclusion

1. The best value of the model is about fault friction coefficients of 0.17, among models which have no shear tractions on the mantle. The activity of so many faults of diverse trends in California is proof of strong strength contrast between faults and the intervening

Table 4. Results of slip rate estimates for major faults in San Andreas area.

Fault	Geologic Rate	Geologic Rate	Good Models	Best Model	This study
Agua Blanca	2.4~5.0	·	0.2~1.3	0.7	≅ 2.4
Elsinore	0.8~9.0	8.0~16.0	0.4~18.0	7.5	8.0~9.0
Hayward	7.0~10.0	·	0.1~22.0	14.7	7.0~10.0
Hogri	2.0~19.0	·	0.2~3.1	2.1	2.0~(3.1)
Central Mojave group	6.0~12.0	5.4~10.0	0.1~ 3.4	2.8	6.0~10.0
Newport-Inglewood	0.4~0.8	·	0~0.2	0.0	≅0.4
San Andreas(Mecca)	21.0~35.0	18.0~22.0	3.5~38.0	14.1	21.0~22.0
San Andreas(San Gorgonio)	13.0~28.0	12.0~20.0	0.4~36.0	4.4	13.0~20.0
San Andreas(San Bernardino)	≤29.0	·	5.6~39.0	11.1	(5.6)~29.0
San Andreas(Pearblossom)	35.0~60.0	18.0~30.0	16.0~33.0	22.0	18.0~30.0
San Andreas(Elkhorn Hills)	31.0~37.0	25.0~30.0	15.0~36.0	22.9	25.0~30.0
San Andreas(Paekfield)	32.0~59.0	16.0~40.0	24.0~38.0	29.2	32.0~(38.0)
San Andreas(San Francisco)	10.0~38.0	16.0~24.0	8.3~46.0	18.1	16.0~24.0
San Andreas(Tomales Bay)	≤25.0	·	5.2~38.0	15.1	(5.2)~25.0
San Jacinto	13.3~14.0	11.0~15.0	0.2~30.0	16.2	13.3~14.0
Santa Monica	0.8~1.1	·	0.3~18.0	10.8	0.8~1.1
Sierra Nevada	0.3~1.5	·	0.1~6.9	0.9	0.3~1.5

Numbers in parentheses are conclusions which depend on computer models, all figures in $mmyr^{-1}$

blocks.

2. The mean temperature of the brittle or ductile transition in San Andreas tectonics, California is the range of 350-410℃. Models of this study can approximate the observed variations in the maximum depth of seismicity without resorting to lateral variations in the creep rheology of the lower crust; known variations in heat flow and strain rate are sufficient explanation.

3. The upper mantle lithosphere of plate at California is converging on a downwelling zone along the Transverse Ranges, and shear tractions from the mantle are necessary in a good model of current tectonics. The magnitude of these tractions is about 8-14 MPa in the Transverse Ranges area, and less elsewhere. The inclusion of mantle drag in these models does not affect the conclusion that, if all faults have the same friction, that friction is low at 0.25-0.17.

The results of study suggest that the ranges of fault slip rates predicted by the best models from experiments sets like ours may be useful in assessing heat flow and long-term seismic hazard evaluation, particularly for thrust faults and inaccessible faults of the coastline and borderland.

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2000년 4월 10일 원고 접수
2000년 6월 10일 원고 채택