JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. B4, PAGES 6421–6430, APRIL 10, 1995

Patterns of seismic release in the southern California region

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Abstract. Southern California experiences earthquakes on the San Andreas system of vertical right-lateral predominantly strike-slip faults and on a second system of faults that includes thrusts, oblique-slip, left-lateral, and other faults. Pattern recognition and cluster analysis are used to analyze the catalog of earthquakes with magnitudes ≥5.5 from 1915 to 1994. We use pattern recognition to find a suite of traits that would characterize each of these two systems and distinguish them from each other. Both pattern recognition and cluster analysis show that epochs of seismic release occur in which one or the other system is the predominant form of earthquake activity. For the past 2 decades the second system has been the active one. Small changes in the direction of plate movements could account for this phenomenon. Seismic release on the San Andreas system is preceded by episodes of activity in the Great Basin or in the Gulf of California. Presumably, these episodes would represent extension in the former region and spreading and slip on transform faults in the latter.

Introduction

California's San Andreas fault and its system of subparallel faults are generally recognized as the modern plate boundary between the Pacific and North American plates. Right-lateral, strike-slip faulting on the San Andreas (SA) fault system is a major source of California earthquakes (SA earthquakes), including some with magnitudes exceeding 8. The magnitude 6.7 Northridge earthquake that occurred on January 17, 1994, is the most recent in a series of earthquakes near Los Angeles with non-San Andreas (NSA) attributes, in this case a reverse fault mechanism. If one defines a category of earthquakes (NSA earthquakes) with non-San Andreas characteristics having significant reverse or oblique-slip faulting, left-lateral faulting, or faulting with large obliquity to the strike of the San Andreas system, then an interesting trend is discerned from a cursory examination of the southern California catalog of earthquakes with magnitudes reported as greater than 5.5 on any magnitude scale and with unambiguous classification. For the California region between the latitudes of Parkfield and northern Baja California more than twice as many SA as NSA earthquakes occurred from 1915 to 1970. During this period the bent segment of the San Andreas fault has been quiet, and SA earthquakes occurred primarily on the San Andreas system of faults north and south of the bent segment. From 1971 to 1994, twice as many NSA as SA earthquakes occurred. In this paper we apply the methods of pattern recognition and a form of multivariate data analysis called cluster analysis to discern traits that characterize SA and NSA events. We then offer hypotheses that might explain these traits.

Computers have been programmed to analyze data and then reproduce classical scientific discoveries. The motivation for these studies was to understand how humans formulate scientific theories [*Simon*, 1992]. Computers have also been used to advance new hypotheses that explain complex data. For example, *Press and Briggs* [1975] used pattern recognition to analyze data and formulate an hypothesis relating the Chandler Wobble to other geophysical phenomena. For this paper we choose an older recognition algorithm because it was designed specifically for application to geological data [*Bongard et al.*, 1966; *Bongard*, 1970]. *Keilis-Borok et al.* [1988] have extended the older recognition algorithm and used it as a new approach to earthquake prediction. In addition, we have used a more recently developed cluster analysis algorithm as an alternate approach to analyzing the data [*Murtagh and Heck*, 1987].

We agree with others [*Oreskes et al.*, 1994] who urge caution in interpreting the results of numerical models in the earth sciences and ascribing significance to hypotheses formulated by procedures such as ours, based on incomplete access to natural phenomena. The results are nonunique and may have little relation to the physical world. However, they have heuristic value and may even ring true. On occasion, as in the case of this paper, the hypotheses can be tested against reality over a period of years.

Earthquake Catalog

In our approach, data for the pattern recognition and cluster analysis programs are drawn from a catalog of earthquakes in the southern California region with magnitudes ≥5.5, with aftershocks removed (Table 1 and Figure 1). Each earthquake has been placed in the SA, NSA, or questionable category. Although we have relied heavily on surface fault rupture and aftershock distribution to determine fault type, some judgment has necessarily been exercised in assigning a fault plane to an earthquake for which only a focal mechanism exists. In a few cases, even in the absence of a focal mechanism, the local geological environment points persuasively to a particular fault type, such as

Paper number 95JB00316.
0148-0227/95/95JB-00316$05.00

Table 1. Earthquakes in the Southern California Region, $M \geq 5.5$, 1915–1994

Earthquake	Type	Date	Magnitude	Area	References
A	?	June 23, 1915	5.5	Imperial Valley	*Hanks et al.* [1975] and *Anderson and Bodin* [1987]
1	SA	Nov. 21, 1915	6.6	Volcano Lake	*Doser* [1994]
B	?	Oct. 23, 1916	6	Tejon Pass	*Branner* [1917] and *Hanks et al.* [1975]
2	SA	April 21, 1918	6.8	San Jacinto Valley	*Doser* [1992a]
3	SA	March 10, 1922	6.0	Parkfield	*Tsai and Aki* [1969] and *Bakun and McEvilly* [1984]
4	SA	July 23, 1923	6.2	San Bernardino	*Doser* [1992a] and *Hanks and Kanamori* [1979]
5	NSA	June 29, 1925	6.8	Santa Barbara	*Hanks and Kanamori* [1979]
6	NSA	Nov. 4, 1927	6.8	Point Arguello	*Helmberger et al.* [1992]
7	SA	March 11, 1933	6.4	Long Beach	*Hanks and Kanamori* [1979] and *Hauksson and Gross* [1991]
8	SA	June 7, 1934	6.0	Parkfield	*Tsai and Aki* [1969], *Bakun and McEvilly* [1984], and *Hutton and Jones* [1993]
9	SA	Dec. 30, 1934	6.5	Laguna Salada	*Doser* [1994]
10	SA	Dec. 31, 1934	7.0	Colorado River delta	*Doser* [1994]
C	?	Feb. 24, 1935	6.0	Laguna Salada	*Hileman et al.* [1973]
11	SA	March 25, 1937	5.6	Buck Ridge	*Doser* [1990] and *Hutton and Jones* [1993]
12	SA	May 19, 1940	6.9	El Centro	*Ellsworth* [1990]
D	?	Dec. 7, 1940	6.0	Colorado River delta	*Hileman et al.* [1973]
13	NSA	July 1, 1941	6.0	Santa Barbara	*Hanks and Kanamori* [1979] and *Hutton and Jones* [1993]
14	SA	Oct. 21, 1942	6.6	Borrego Valley	*Hanks and Kanamori* [1979] and *Doser* [1990]
E	?	Aug. 15, 1945	5.7	Borrego Valley	*Hutton and Jones* [1993]
15	NSA	March 15, 1946	6.0	Walker Pass	*Hanks and Kanamori* [1979] and *Hileman et al.* [1973]
F	?	July 18, 1946	5.5	Amboy	*Hutton and Jones* [1993]
16	NSA	April 10, 1947	6.5	Manix	*Richter* [1947], *Hanks and Kanamori* [1979], and *Doser* [1990]
17	SA	Dec. 4, 1948	6.0	Desert Hot Springs	*Nicholson* [1987] and *Williams et al.* [1990]
18	NSA	May 2, 1949	5.8	Pinto Mountains	*Hutton and Jones* [1993]
G	?	July 29, 1950	5.5	Calipatria	*Hutton and Jones* [1993]
19	SA	Jan. 24, 1951	5.8	Superstition Hills	*Allen et al.* [1965] and *Hutton and Jones* [1993]
H	?	Dec. 26, 1951	5.9	San Clemente Island	*Hileman et al.* [1973]
20	NSA	July 21, 1952	7.5	Kern County	*Buwalda and St. Amand* [1955] and *Hanks and Kanamori* [1979] and *Stein and Thatcher* [1981]
I	?	June 14, 1953	5.5	Superstition Hills	*Hutton and Jones* [1993]
J	?	Feb. 1, 1954	5.6	Colorado River delta	*Doser* [1990]
21	SA	March 19, 1954	6.4	Arroyo Salada	*Hanks and Kanamori* [1979] and *Doser* [1990]
K	?	Oct. 17, 1954	6.3	Baja California	*Thatcher* [1972]
L	?	Oct. 24, 1954	6.0	El Alamo	*Doser* [1992b, 1994] and *Thatcher* [1972]
M	?	Nov. 12, 1954	6.3	El Alamo	*Doser* [1992b, 1994] and *Thatcher* [1972]
22	SA	Feb. 9, 1956	6.7	San Miguel	*Shor and Roberts* [1958] and *Doser* [1992b]
N	?	Dec. 1, 1958	5.8	Laguna Salada	*Hileman et al.* [1973]
23	SA	June 28, 1966	5.6	Parkfield	*Brown et al.* [1967] and *Bakun and McEvilly* [1984]
24	SA	Aug. 7, 1966	6.4	El Golfo	*Ebel et al.* [1978]
25	SA	April 9, 1968	6.5	Borrego Mountain	*Clark* [1972] and *Hanks and Kanamori* [1979]
26	SA	April 28, 1969	5.8	Coyote Mountain	*Thatcher and Hamilton* [1973], *Petersen et al.* [1991], and *Hutton and Jones* [1993]
27	NSA	Feb. 9, 1971	6.6	San Fernando	*Whitcomb et al.* [1973], *Hanks and Kanamori* [1979], and *Heaton* [1982]
28	NSA	Feb. 21, 1973	6.0	Point Mugu	*Ellsworth et al.* [1973]
29	NSA	Aug. 13, 1978	6.0	Santa Barbara	*Corbett and Johnson* [1982]
30	SA	Oct. 15, 1979	6.4	Imperial Valley	*Sharp et al.* [1982] and *Hartzell and Heaton* [1983]
31	SA	Feb. 25, 1980	5.5	Horse Canyon	*Hutton and Jones* [1993]
32	SA	June 9, 1980	6.4	Victoria	*Nakanishi and Kanamori* [1984]
33	NSA	April 26, 1981	5.7	Westmorland	*Hutton and Johnson* [1981]
34	SA	Sept. 4, 1981	5.5	Santa Barbara Island	*Corbett and Piper* [1981] and *Hutton and Jones* [1993]
35	NSA	May 2, 1983	6.4	Coalinga	*Stein and Ekström* [1992]
36	NSA	Aug. 4, 1985	6.1	Kettleman Hills	*Ekström et al.* [1992]
37	SA	July 8, 1986	5.6	North Palm Springs	*Jones et al.* [1986], *Nicholson* [1987], and *Williams et al.* [1990]
38	NSA	Oct. 1, 1987	5.9	Whittier Narrows	*Hauksson et al.* [1988]
39	NSA	Nov. 24, 1987	6.2	Elmore Ranch	*Magistrale et al.* [1989] and *Sharp et al.* [1989]
40	SA	Nov. 24, 1987	6.6	Superstition Hills	*Magistrale et al.* [1989] and *Sharp et al.* [1989]
O	?	Jan. 25, 1988	5.6	San Miguel	
41	NSA	June 28, 1991	5.6	Sierra Madre	*Dreger and Helmberger* [1992]
42	SA	April 22, 1992	6.1	Joshua Tree	*Sieh et al.* [1993]
43	SA	June 28, 1992	7.5	Landers	*Sieh et al.* [1993]
44	NSA	June 28, 1992	6.6	Big Bear	*Sieh et al.* [1993]
45	NSA	July 11, 1992	5.7	Garlock	
46	NSA	Jan. 17, 1994	6.7	Northridge	*Hall* [1994]

SA is San Andreas type, NSA is non-San Andreas type, and question mark is unknown. Magnitudes are M_W if available, otherwise M_L. Aftershocks are omitted.

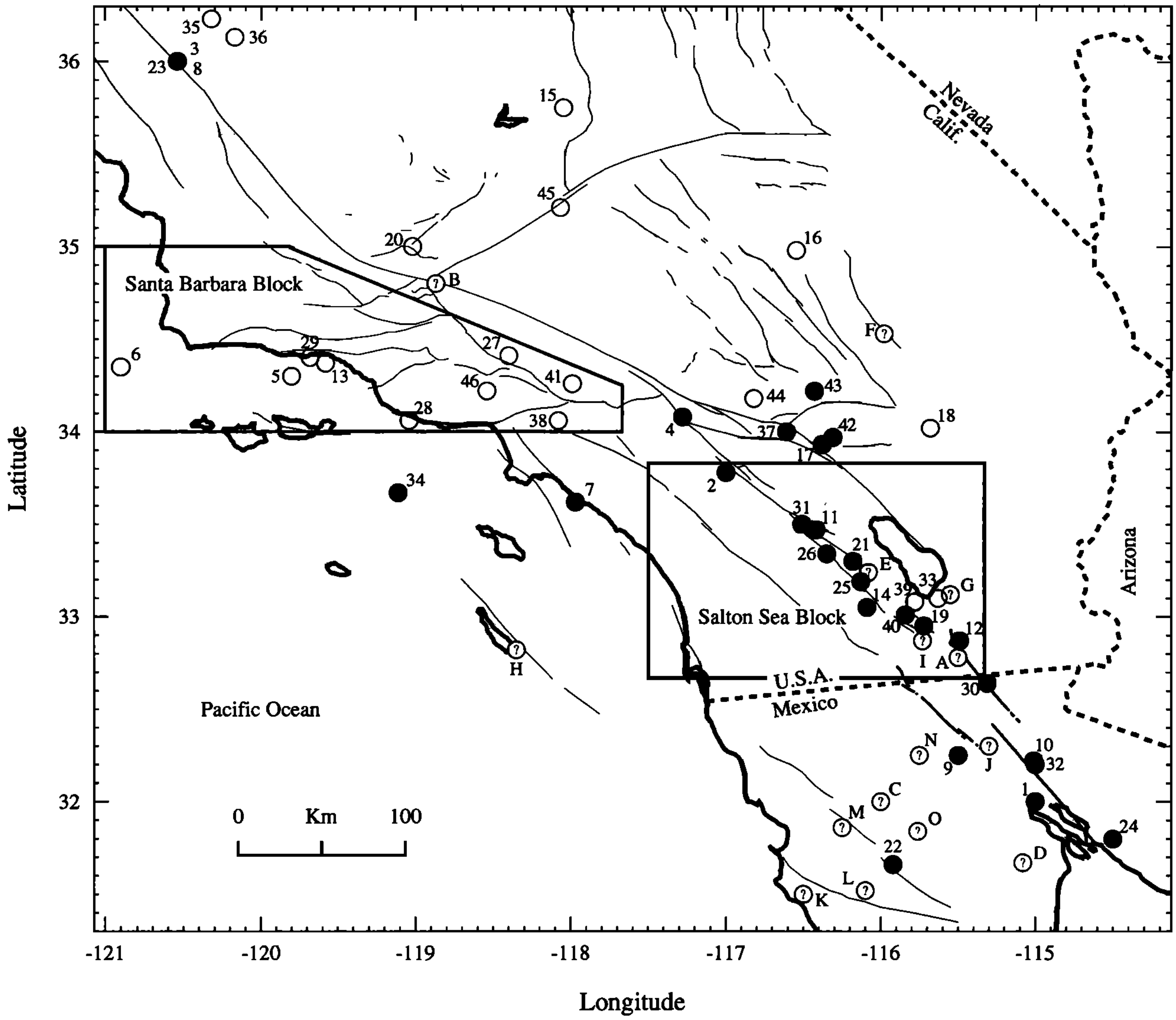

Figure 1. Earthquakes of $M \geq 5.5$ in the southern California region, 1915–1994. Solid circles are San Andreas type (SA), open circles are non-San Andreas type (NSA), and question marks are of unknown type. Numbers (SA or NSA type) and letters (unknown type) refer to Table 1. References pertain to magnitudes, locations, and source mechanisms. Note that events 17, 37, 42, and 43 were initially categorized as SA, as portrayed here, but were later changed to NSA (see text). Known faults are shown as fine lines.

the Santa Barbara events of 1925 and 1941, which were in close proximity to the demonstrably NSA earthquake of 1978. We have tried carefully to be unbiased in such assignments; thus 15 out of the 61 total events remain in the questionable category.

Petersen et al. [1991] have pointed out that particularly within the San Jacinto fault zone, block rotations may lead to left-lateral displacements on conjugate faults perpendicular to the regional northwest trending, right-lateral faults. Apparent examples of this phenomenon, as indicated by aftershock trends, are illustrated by earthquakes 33 and 39 (Figure 1 and Table 1). Because of their northeast fault strikes these earthquakes are herein classified as NSA, despite the fact that they may be caused by a stress system very close to that of their SA-type counterparts. Indeed, during the Elmore Ranch–Superstition Hills earthquake sequence of 1987 (events 39 and 40), two intersecting perpendicular faults ruptured within 12 hours of one another, with opposing senses of strike-slip displacement.

Pattern Recognition Algorithm

We use pattern recognition to find a suite of traits that would characterize the SA and NSA systems and distinguish them from each other. Only a brief conceptual description of the algorithm we employ to find these traits is given here because it has been described in great detail elsewhere [*Briggs et al.*, 1977]. The data we examine to find traits derive from a series of heuristic questions which are posed and whose answers might characterize the two systems of earthquakes. The questions are selected on the basis of being answerable by available data for the period covered by the

Table 2. Questions Used

Question Number	Question
1	SA earthquake 0–3 years before?
2	SA earthquake 0–3 years after?
3	NSA earthquake 0–3 years before?
4	NSA earthquake 0–2 years after?
5	earthquake occurs 1971–1994?
6	earthquake occurs within 100 km of bent segment of San Andreas fault?
7	two or more earthquakes, $M \geq 6.0$, in Great Basin in prior 0–4 years?
8	three or more earthquakes, $M \geq 4.5$, in Santa Barbara Block within 2 years?
9	five or more earthquakes, $M \geq 4.5$, in Salton Sea Block within 2 years?
10	five or more events in Gulf of California in prior 0–12 years?

catalog and are heuristic in that they explore different possibilities that make reasonable geophysical sense. In this study the choice of questions reflects our interest in the time relationships of SA and NSA earthquake occurrences and in the possibility of relationships in seismicity extending to adjacent regions. Many trial questions have been posed and eliminated either because data are lacking or a cursory scan reveals that the they are not discriminatory between the two systems of earthquakes. If the questions involve specific parameters such as time intervals, numbers of earthquakes, or distances, the actual values used are assigned after a preliminary survey to find the best discriminants between SA and NSA events.

We are particularly interested in patterns of answers revealed by the recognition algorithm that were not discernable in the cursory scan, that is, combinations of questions whose answers link up and provide insights in addition to those provided by the individual questions. The questions (Table 2) are answered yes/no or 1/0 in binary code. If a question is unanswerable for a specific earthquake because of a lack of data (e.g., an earthquake whose mechanism is uncertain or a question which is otherwise unanswerable because of the time limits of the catalog), the answer 2 is assigned. In this manner each of m earthquakes is characterized by a string of digits, the answers to the n questions. The $m \times n$ array of earthquakes and answers constitute a matrix of zeros, ones, and twos for SA events and another for NSA events (Tables 3 and 4). These answer matrices are then examined to see if certain patterns emerge which are particularly characteristic of one system and not the other. In the algorithm a trait is a particular pattern that is found to occur more frequently in one than the other. The pattern can involve a combination of answers to questions taken three at a time, two at a time, or one at a time (triplet, doublet, or singlet traits, respectively). For example, a doublet trait that characterizes NSA earthquakes may state that such earthquakes tend to occur after 1971 and are further characterized by small earthquake inactivity in the southern California region surrounding the Salton Sea, where the SA system of faults is a principal tectonic feature. This might suggest the hypothesis that the years following 1971 represent an epoch in which the seismic release is predominantly NSA, one in which the San Andreas fault system becomes relatively quiet. In a sense, a trait mimics the way a scientist might combine multiple observations and merge them into a hypothesis.

For the answer matrices in Tables 3 and 4 there are 1160 possible traits. Of these, 15 traits which are particularly characteristic of the SA system are selected by the algorithm. Similarly, 23 NSA traits are found by the procedures followed. The traits are found at more than half the earthquakes in the system they characterize, and most occurred at least 3 times as much in that category than in the other and never less than twice as much. The use of the digit 2 where data are not available to answer a question allows a degree of "fuzzy logic" in that it is considered as both a 0 and 1 answer in the analysis.

In a sense we have used pattern recognition as an hypothesis selector and have checked 1160 possible combinations of answers to see if novel and reasonable hypotheses can explain the few traits that emerge. An alternative way of looking at the procedure is to think of the computer asking the investigator about a singlet, doublet, or triplet trait: "Have you thought of this combination of phenomena and its meaning?"

In a procedure such as this there are concerns about the uniqueness of the results. It may be possible to discriminate by chance between SA and NSA events even if the questions posed were answered on the basis of false data. In a control experiment we used the bootstrap method [*Press et al.*, 1992] to test against this possibility. One thousand spurious

Table 3. Answer Matrix of San Andreas Type Events

	Question									
Earthquake	1	2	3	4	5	6	7	8	9	10
1	2	1	2	2	0	0	1	2	2	2
2	1	0	2	0	0	1	1	2	2	2
3	0	1	0	0	0	0	1	2	2	2
4	1	0	0	1	0	1	0	2	2	2
7	0	1	0	2	0	1	1	1	1	1
8	1	1	0	2	0	0	1	1	1	1
9	1	1	0	2	0	0	1	1	1	1
10	1	1	0	2	0	0	1	1	1	1
11	1	1	2	0	0	0	1	1	1	1
12	1	1	0	1	0	0	0	0	1	1
14	1	2	1	0	0	0	1	1	1	1
19	0	1	1	1	0	0	0	0	1	1
21	1	1	1	2	0	0	1	0	1	1
22	1	2	2	2	0	0	1	1	1	1
23	0	1	0	0	0	0	1	0	0	1
24	1	1	0	0	0	0	1	0	0	1
25	1	1	0	0	0	0	1	0	1	0
26	1	0	0	1	0	0	1	0	1	0
30	0	1	1	1	1	0	0	1	0	1
31	1	1	1	1	1	1	0	0	0	1
32	1	1	1	1	1	0	0	0	0	1
34	1	0	1	1	1	0	0	0	0	1
40	0	2	1	2	1	0	1	1	0	0

Binary code is 1 for yes, 0 for no, and 2 for uncertain.

SA and NSA answer matrices were synthesized by randomly mixing the questions and answers in the real answer matrices. In this way, synthetic answer matrices were generated with roughly the same underlying distribution of answers as the real data but which have no other basis in reality. Each of the synthetic matrices was analyzed by our program. Only 0.1% yielded 10 or more discriminatory traits compared to the 38 traits that resulted from the real answers. This gives us good reason to believe that our results were not obtained by chance and implies that the traits found with real data may carry real physical information, although this cannot be proved.

Cluster Analysis

We have used pattern recognition to analyze the 46 × 10 array of earthquakes and answers. Another approach is to examine the same data using cluster analysis [*Murtagh and Heck*, 1987]. This is an automatic procedure for grouping a set of objects according to their mutual similarity and thereby revealing fundamental features and interrelationships which may be present. Cluster analysis is used today in biology, astronomy, and other fields to find natural groupings of objects such as plant species or stars based on attributes of the individual objects. This is a more formal procedure than pattern recognition and should provide a check of any categorization or grouping of earthquakes revealed by that method.

In this application each of the 46 earthquakes is treated as a vector in a hyperspace of 10 dimensions with each dimension represented by an answer to one of the 10 questions. Thus the components of the 10-dimensional vector have values of 0 or 1 or the intermediate value 0.5 in those cases where the answer is unknown. The clustering algorithm groups the 46 earthquakes (vectors) into clusters depending on the Euclidean distances of the vectors from each other. It seeks groups with maximum homogeneity within the cluster and maximum separation or isolation among the clusters. In this manner a hierarchy of groups and subgroups is established proceeding from large separations to smaller ones. Unlike the pattern recognition method, no prior knowledge of the earthquakes as SA or NSA was assumed in applying cluster analysis. The methods also differ in that pattern recognition looks for combinations of answers taken one, two, or three at a time that have significance because of their frequency of occurrence in one system and not the other, whereas cluster analysis classifies each earthquake by the relative position of a 10-dimensional vector whose components are the answers to all 10 questions.

Questionnaire

Ten questions were selected from a larger number that were tested in trial exercises to find those that show the potential to discriminate between the SA and NSA groups. Question 7 was selected to see if a neighboring seismic region (in this case the Great Basin) was influenced by or exerted influence on the timing and mechanisms of seismic release in southern California. The Great Basin itself is characterized by active extensional tectonics with earthquakes showing normal and strike-slip faulting.

Similarly, question 10 was included to ascertain the influence of activity in the Gulf of California, which is a system of active transform faults offset by small centers of spreading as indicated by earthquake distributions and mechanisms, submarine geology, and volcanism. Including gulf events in the preceding 0–12 years reflects the large range of distances between epicenters in the gulf and the southern California region and the slow rate of propagation of strain waves emanating from earthquakes (roughly tens to hundreds of kilometers per year, as reported by others [*Mogi*, 1968; *Rydelek and Sacks*, 1988]). Although it might be argued that the Gulf of California should be considered as a geologic extension of southern California and therefore included in the same province, we were persuaded that the larger number of centers of spreading and the evolution of oceanic depths and oceanic crust warranted separate treatment of the gulf for the purposes of this study.

We do not believe that individual earthquakes in the Gulf of California or in the Great Basin can change the local stress field or by themselves act as triggers of earthquakes in southern California. The distances are too large for the extent of the faults. Rather, we view these earthquakes as indicators of episodes of regional activity, such as slip on transform faults or spreading in the gulf, or extension in the Great Basin.

Two regions, more localized in extent, were defined by their geological structures and seismic mechanisms to be prototypical of San Andreas earthquakes and non-San Andreas (thrust fault) earthquakes, as shown in Figure 1. We call these the Salton Sea Block and the Santa Barbara Block, respectively. Earthquakes with magnitudes ≥4.5 (aftershocks excepted) were counted for each of these blocks in obtaining the answers to questions 8 and 9. The purpose of these questions was to see if smaller SA or NSA earthquakes mirror patterns that characterize larger events.

Question 6 is used to see if the change in trend of the San Andreas fault between Tejon Pass and San Bernardino (the

Table 4. Answer Matrix of Non-San Andreas Type Events

	Question									
Earthquake	1	2	3	4	5	6	7	8	9	10
5	1	0	0	1	0	1	0	2	2	2
6	0	0	1	0	0	0	0	2	2	0
13	1	1	2	0	0	1	1	0	1	1
15	2	2	2	1	0	0	0	1	0	0
16	2	2	1	1	0	0	0	1	0	0
17	2	1	1	1	0	0	0	1	0	0
18	0	1	1	2	0	0	0	1	1	1
20	1	1	1	2	0	1	0	0	1	1
27	1	0	0	1	1	1	0	0	0	0
28	0	0	1	0	1	1	0	1	0	0
29	0	1	0	0	1	1	0	1	0	1
33	1	1	1	1	1	0	0	0	0	1
35	1	0	1	1	1	0	0	0	0	0
36	0	1	1	1	1	0	0	0	0	0
37	0	1	1	1	1	1	1	1	0	0
38	0	1	1	1	1	1	1	1	0	0
39	0	1	1	2	1	0	1	1	0	0
41	2	0	2	1	1	1	0	1	0	0
42	0	2	1	1	1	0	0	1	0	0
43	0	2	1	1	1	1	0	1	0	0
44	0	2	1	1	1	1	0	1	0	0
45	0	2	1	1	1	1	0	1	0	0
46	0	2	1	2	1	1	0	2	2	0

Binary code is 1 for yes, 0 for no, and 2 for uncertain.

Big Bend) plays a role as a discriminant. The distance 100 km was selected because the effect of a weak fault would extend out a distance equal to the fault's vertical extent (presumably the thickness of the lithosphere) [*Zoback et al.*, 1987]. This distance also contains almost all of the earthquakes, reverse faults, and folds adjacent to the bent segment of the San Andreas.

Question 5 was formulated in two ways. In the first the catalog was divided into two equal halves, 1915–1954 and 1955–1994, to see if the mechanisms of seismic release differed over these epochs. They did, but even better discrimination was found when the intervals were partitioned 1915–1970 and 1971–1994. The major thrust earthquakes San Fernando (1971) and Northridge (1994) punctuate the period 1971–1994. Results for the latter partition are presented here, although the principal conclusions are unchanged if the first formulation is used.

Questions 1–4 were posed to see if earthquakes in one category or the other occur in subepochs of certain duration; the values selected for the number of years preceding or following an earthquake were found by preliminary scans to find those which show the best promise of being discriminants.

To answer the questions, we have used the earthquake regional catalogs compiled for the Decade of North American Geology [*Engdahl and Rinehart*, 1991]. To fill gaps, we have also used the catalogs of the U.S. Geological Survey, the California Institute of Technology, and the International Seismological Summary.

Characteristic Traits for SA and NSA Events

Tables 5 and 6 show all the characteristic traits for SA and NSA events, respectively. All of the traits suggest interesting concepts worthy of consideration. In particular, we call attention to the following traits:

1. The San Andreas system is the primary mechanism of seismic release in the years 1915–1970, and NSA events predominate in the period 1971–1994 (SA trait 6 and NSA trait 12). The durations of these periods, which we call San Andreas and non-San Andreas epochs, are uncertain because of the limits set by the beginning and end of our catalog. Epochal changes in alternating cycles of 20–30 years in global seismic release between strike-slip and thrust earthquakes have been reported by *Romanowicz* [1993]. A. M. Dziewonski (personal communication, 1994) has observed spatio-temporal changes in seismic release from thrust to strike slip in the Fiji Plateau and the adjacent subduction regions. Both studies postulate slowly propagating strain waves as the agent of change. Their explanations would also apply to the results of this paper. Presumably, a distant event such as a major episode of subduction or midocean ridge spreading is the source of strain waves which arrive years later to influence interactions in the plate boundary zones where these changes in earthquake regimes occur.

2. Activity (extension?) in the Great Basin precedes a typical SA event by 0–4 years (SA trait 13). This was evidenced by a yes answer to question 7 for 16 out of 23 SA events and only four out of 23 NSA events, as can be seen in Tables 3 and 4. Independently, activity in the Gulf of California precedes typical SA earthquakes by 0–12 years (SA trait 15). In this case, question 10 was answered yes for 16 out of 19 SA events, with four answers uncertain; only five out of 22 NSA events received a yes answer, with one answer uncertain. These adjacent regions tend to be quiet in the periods before typical NSA earthquakes (NSA traits 14 and 23).

3. There is a tendency for clustering to occur, suggesting subepochs for each group. A SA earthquake is typically preceded by a similar event within 3 years (SA trait 1) and prior to 1971 tends to be followed by a similar event within 3 years (SA trait 3). Similarly, a NSA event is preceded and followed by NSA events within 3 years or 2 years, respectively, but is not preceded by a SA event (NSA traits 3 and 1).

4. During the San Andreas epoch the Salton Sea Block (Figure 1) was active within 2 years of a SA earthquake (SA

Table 5. Characteristic San Andreas Type Traits

	Question									
Trait	1	2	3	4	5	6	7	8	9	10
1	1	·	·	·	·	·	·	·	·	·
2	1	·	·	·	·	·	·	·	·	1
3	·	1	·	·	0	·	·	·	·	·
4	·	1	·	·	·	0	·	·	·	·
5	·	1	·	·	·	·	·	·	·	1
6	·	·	·	·	0	·	·	·	·	·
7	·	·	·	·	0	0	·	·	·	·
8	·	·	·	·	0	·	1	·	·	·
9	·	·	·	·	0	·	·	·	1	·
10	·	·	·	·	0	·	·	·	·	1
11	·	·	·	·	·	0	1	·	·	·
12	·	·	·	·	·	0	·	·	·	1
13	·	·	·	·	·	·	1	·	·	·
14	·	·	·	·	·	·	·	·	1	·
15	·	·	·	·	·	·	·	·	·	1

Binary code is 1 for yes and 0 for no.

Table 6. Characteristic Non-San Andreas Type Traits

	Question									
Trait	1	2	3	4	5	6	7	8	9	10
1	0	·	·	·	·	·	·	·	·	·
2	0	·	1	·	·	·	·	·	·	·
3	·	·	1	1	·	·	·	·	·	·
4	·	·	1	·	·	·	0	·	·	·
5	·	·	1	·	·	·	·	·	0	·
6	·	·	1	·	·	·	·	·	0	0
7	·	·	1	·	·	·	·	·	·	0
8	·	·	·	1	·	·	0	·	·	·
9	·	·	·	1	·	·	·	·	0	·
10	·	·	·	1	·	·	·	·	0	0
11	·	·	·	1	·	·	·	·	·	0
12	·	·	·	·	1	·	·	·	·	·
13	·	·	·	·	1	·	·	·	0	·
14	·	·	·	·	·	·	0	·	·	·
15	·	·	·	·	·	·	0	·	0	·
16	·	·	·	·	·	·	0	·	0	0
17	·	·	·	·	·	·	0	·	·	0
18	·	·	·	·	·	·	·	1	0	·
19	·	·	·	·	·	·	·	1	0	0
20	·	·	·	·	·	·	·	1	·	0
21	·	·	·	·	·	·	·	·	0	·
22	·	·	·	·	·	·	·	·	0	0
23	·	·	·	·	·	·	·	·	·	0

Binary code is 1 for yes and 0 for no.

traits 9 and 14). This block tends to be quiet within 2 years of a NSA earthquake (NSA traits 13 and 21).

5. Within 2 years of a NSA earthquake the Santa Barbara Block was active and the Salton Sea Block was quiet (NSA trait 18).

6. NSA traits 8 and 10 are examples of doublet and triplet traits, respectively. They report that NSA events tend to be followed by NSA events within 2 years and occur when the Great Basin, the Gulf of California, and the Salton Sea Block have been quiet.

7. The zero answers to question 6 among several SA traits verify what is well known that large earthquakes on the San Andreas system of faults have mostly occurred on such faults as the San Jacinto, Cerro Prieto, Imperial, and others well to the south of the Big Bend, which has not ruptured since 1857.

8. NSA subepochs of a few years duration can occur in the SA epoch and vice versa (neither SA trait 1 nor NSA trait 3 show an entry for question 5 which would assign a SA or NSA epoch).

Reclassification of Four Events

Four events were considered ambiguous with respect to classification as SA or NSA and were grouped initially with SA as indicated in Table 1. These were the Desert Hot Springs earthquake of 1948, the North Palm Springs earthquake of 1986, and the Landers and Joshua Tree earthquakes of 1992. All of these events occurred in an area where the strike and dip of the San Andreas fault are changing rapidly and progressively as the fault approaches the Big Bend from the southeast. The first two earthquakes occurred on moderately dipping faults with significant components of thrust displacement, and the latter two earthquakes occurred with right-lateral strike slip along faults in the east California shear zone, at a significant angle to the strike of the nearby San Andreas fault. All four events showed many more NSA than SA traits in the computer runs, comparable to earthquakes which were clearly NSA. In the case of Landers and Joshua Tree, all of the NSA traits and none of the SA traits occurred. These four events were reclassified as NSA in deriving the traits described above. This change yielded many more traits. However, traits on which some major conclusions of this paper are based emerge even without the reclassification: SA and NSA epochs, SA events preceded by activity in the Great Basin and Gulf, and inactivity of the Salton Sea Block during NSA activity.

One can make a case on geological grounds alone for the classification of these four events as NSA, independent of the computer indications. However, the pronounced associations of NSA traits with the Landers and Joshua Tree events warrants some speculation, and we offer the following possibilities: (1) The strength of the Landers and related faults in the eastern California shear zone differ from those on the SA system, and they are responding to regional stress in a different manner than the response of the SA system, for example, in the recurrence of activity. (2) Others [e.g., *Sauber*, 1988] propose that Landers and related faults are kinematically related to Great Basin tectonics rather than the San Andreas system. (3) Reclassification carries no physical significance and is simply a statement that an occasional "contrarian" event falls in the epoch of the other system. (4) Landers and related faults represent an incipient new plate boundary between the Pacific and North American plates replacing the San Andreas system as proposed by *Nur et al.* [1993]. The interval covered by our study just happened to "catch" an event in this long-term process.

Classification by Cluster Analysis

Figure 2 shows the results in the form of a dendrogram depicting the four clusters with the largest separation, the separation decreasing with increasing cluster number. Thus the separation between clusters 1 and 2 is the largest, and that between 3 and 4 is the smallest of the four clusters. Cluster 1 and its subgroups 3 and 4 includes all of the earthquakes that occurred from 1915 to 1973, and cluster 2 includes all earthquakes from 1978 to 1994. In the first period, SA events are predominant (19 SA and 9 NSA in Table 1). In the second period, NSA events outnumber SA events, even more so if Landers and Joshua are labeled uncertain (6 SA and 10 NSA) or reclassified as NSA (6 SA and 12 NSA). This automatic bifurcation of the catalog by cluster analysis, the highest in the hierarchy of separation, is close to the result from pattern analysis (SA trait 6 and NSA trait 12), which divided the catalog into SA and NSA epochs of seismic release, and over similar time periods. Since the methods differ, this may be viewed as additional support for the conclusions reached about distinct epochs of SA and NSA seismic release even though both procedures analyze the same answer matrices.

However, the cluster algorithm provides an additional insight. Cluster 3 and its subgroup 4 branch from cluster 1 (Figure 2). They are made up of earthquakes 15–28 which occurred over the time period 1946–1973 when 8 SA and 6 NSA events occurred. It is reasonable to view this period of mixed events as a transition in which the seismic release changes from an SA epoch (cluster 1, earthquakes 1–14 from

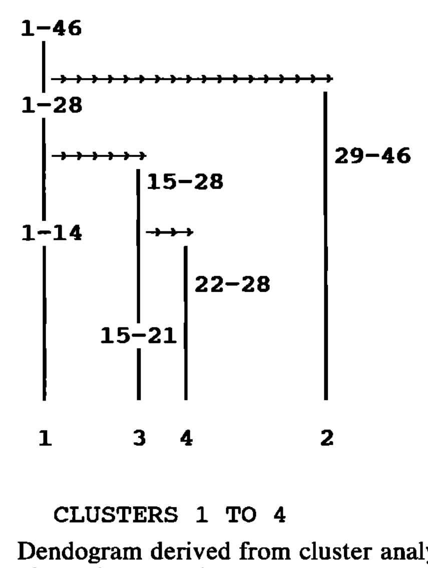

Figure 2. Dendogram derived from cluster analysis showing the top four clusters with the most separation in the hierarchy of clusters. Cluster 1 represents a SA epoch and includes earthquakes with catalog numbers 1–14 over the period 1915–1942. Cluster 2 is a NSA epoch made up of earthquakes 29–46 over the period 1978–1994. Cluster 3 and its subbranch 4 cover the period 1946–1973 during which a mixture of the two types occurred (earthquakes 15–28). It is interpreted as a transition period between the two epochs.

1915 to 1942, 11 SA and 3 NSA events) to the current NSA epoch (cluster 2).

Hypotheses That Derive From the Characteristic Traits

With the disclaimers mentioned earlier we speculate on the meaning of the characteristic traits. Several independent lines of evidence indicate that the faults of the San Andreas system are weak. A consequence is that the principal horizontal stress in the Pacific plate, which is oblique to the trend of the San Andreas a few hundred kilometers distant, becomes the fault-normal stress within about 100 km of the fault. This accounts for basin compression and thrust faults with strikes subparallel to the San Andreas and within about 100 km of it [*Zoback and Zoback*, 1991].

The magnitude of the fault-normal stress is sensitive to the angle between the direction of principal horizontal stress of the Pacific plate and the strike of the San Andreas (obliquity). It diminishes from the maximum principal horizontal stress and approaches least horizontal compression as the obliquity decreases below 45° [*Zoback and Zoback*, 1991]. We speculate with Zoback and Zoback that small changes in the direction of plate motion can change the obliquity of the principal stress to the trend of the San Andreas fault system and increase or decrease the magnitude of the fault-normal stress. An increase in the fault-normal stress will increase frictional locking of the system of San Andreas faults and tend to activate NSA earthquakes, particularly those on thrust faults within 100 km of San Andreas system faults. This characterizes the current NSA epoch, which began with the San Fernando earthquake of 1971, or shortly thereafter according to cluster analysis. Alternatively, small changes in plate motion direction that decrease the obliquity of the principal horizontal stress to SA faults would decrease the fault-normal stress and shift the mechanism of seismic release to earthquakes on the San Andreas fault system. This concept applies less to the Big Bend segment of the San Andreas than to the faults in the SA system to the north and south because the segment strikes more westerly, and therefore the obliquity and the fault normal compressive stress is larger. SA earthquakes removed from the Big Bend make up the principal SA events in our catalog since the Big Bend has been relatively inactive since the beginning of our catalog in 1915. They occur on faults for which the obliquities are smaller than is the case for the Big Bend. Such faults would be more sensitive to changes in plate motion direction. This seems to be the case for the period covered in this study. It is relevant that a change in mechanism from thrust events to strike-slip events was correlated with measured strain changes from compression to extension in a local segment of the San Andreas fault [*Sauber et al.*, 1983].

The premonitory episodes of transform slip and spreading in the Gulf of California and extension in the Great Basin support the hypothesis that action at a distance can affect the seismicity of southern California, a concept recognized by Keilis-Borok and his colleagues in their approach to earthquake prediction [*Gelfand et al.*, 1976]. This distant activity may be the cause of the changes in the direction or magnitude of plate motion. Alternatively, they may be an earlier manifestation of such changes which subsequently initiate SA or NSA epochs or subepochs for southern California.

An earthquake in the magnitude 6 range has been predicted for Parkfield, which has been heavily instrumented to observe the event. It has not yet occurred. If the preceding discussion bears any semblance to reality, it is not likely to occur until activity picks up in the Great Basin or the Gulf of California.

The Landers earthquake also invites speculation because of the extraordinary number of triggered earthquakes to distances of 1200 km. Many of the triggered events lie in a directivity lobe of more intense shear waves which radiated from the propagating rupture. There also seems to be a correlation of triggering with the occurrence of nearby subsurface magmatic reservoirs. Some investigators have connected the two phenomena in explaining the triggered events [*Hill et al.*, 1993; *Linde et al.*, 1994]. They propose that intense shear waves released bubbles or otherwise changed local stress patterns in the fluid reservoirs which triggered earthquakes. However, several sites of triggering lie well outside the lobe, and earthquakes with magnitudes comparable to that of Landers, and closer to some of the sites, apparently did not trigger earthquakes there. If the concept suggested by the results of this paper that the nature of seismic release over a region can be influenced by activity well beyond the region rather than by local changes in the stress field, then it occurs to us that a large region encompassing Landers and the sites of triggered events was primed for earthquakes to occur by a strain wave which traversed the region. Landers was the first and largest event. It would have been easier for seismic waves emanating from Landers to stimulate triggering under these circumstances.

None of these speculations can be proved on the basis of the data we have analyzed. However, they predict phenomena that can be checked in time. In a few years, arrays of Global Positioning System instruments will be installed at permanent sites and should be able to detect the slowly moving strain waves that take months or years to traverse a region and signal plate motion changes. It would then be possible to see if such changes affect the mechanism of seismic release. Over some period of time it will also be possible to check if heightened seismicity in the Great Basin or the Gulf of California precedes activity on the San Andreas system of southern California.

Conclusions

An examination of a catalog of southern California earthquakes using pattern recognition and cluster analysis leads to the hypothesis that seismic release in this region occurs in epochs in which the earthquakes are predominantly SA or NSA. Both methods indicate that southern California is currently in a NSA epoch in which earthquakes on reverse faults predominate. The recent Northridge earthquake is an example, and the epoch may have been initiated in 1971 when the San Fernando earthquake occurred or shortly thereafter. The prior years, extending to at least the beginning of the catalog in 1915, define an epoch of SA release. Cluster analysis further suggests that a transition between the SA and NSA epochs occurred in the years 1946–1973 in which the earthquake were a mix of the two types.

The pattern recognition algorithm also finds traits that characterize the SA and NSA systems. These traits can be explained by the following additional hypotheses. Earthquakes in southern California occur within a larger system that includes at least the Great Basin and the Gulf of

California. Episodes of activity in these adjacent regions signal subsequent release of the SA type. In the absence of activity in these adjacent regions, SA release is reduced, and NSA release occurs more frequently.

We propose that small changes in the direction of relative motion between the Pacific and North American plates along the transform plate boundary in California may activate either the SA or NSA systems of faults. These changes could be caused by activity in the Great Basin or the Gulf of Baja California. Alternatively, the entire system discussed here could reflect more distant events which introduce small fluctuations in plate motion direction in this region by occasional arrivals of slowly traveling strain waves.

Acknowledgments. We thank Bernard Minster, Mark Zoback, V. I. Keilis-Borok, Barbara Romanowicz, and Selwyn Sacks for their helpful advice. Reviewers Albert Hsui, Lucy Jones, and an anonymous reviewer made valuable suggestions which helped us improve the paper. Lucy Jones provided us with the aftershock free catalog of southern California earthquakes. F.P. is grateful for support as a Fairchild Scholar at Caltech. Contribution 5511 Division of Geological and Planetary Sciences, California Institute of Technology.

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(Received August 5, 1994; revised December 20, 1994; accepted January 26, 1995.)