SEISMO-TECTONIC CHARTS IN THE GULF OF CALIFORNIA

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1. Introduction.

The Gulf of California is the southernmost boundary between the Pacific and North American plates. The Gulf of California represents a unique tectonic environment since it is neither a typical back-arc basin nor is it a simple marginal extensional basin (Saunders et al., 1982). In the Gulf region a series of young, rifted basins have formed as a result of *en echelon* spreading centers that are connected by long-offset transform faults of up to 200 km in length. The Gulf has been described as a leaky plate boundary (Schubert and Garfunkel, 1984) because of the small separations between the transform faults, but both the Guaymas and Farallon basins should be considered more than just simple leaks along a major offset transform fault. Not surprisingly, the major seismic activity associated with the plate motion is characterized by moderate events (magnitude < 7.0) along the transform faults.

The Gulf can be viewed as consisting of three distinct tectonic regions: (1) the northern portion of the Gulf is an area of continental crust that joins the San Andreas fault system of southern California; (2) the central to southern Gulf is a transition zone of continental and oceanic crust; and (3) the southernmost portion at the mouth of the Gulf consists mostly of oceanic crust. The transition from continental- to oceanic-type crustal structure can be observed in the cross-section profile of P wave velocities derived from a refraction survey along the Gulf axis by Phillips (1964). The tectonic development of this region is known at the mouth of the Gulf and further south based on seafloor magnetic anomaly correlations. However, in the northern and central Gulf low amplitude magnetic anomalies can not be correlated because the thick sedimentary deposits obscure or preclude the formation of magnetic anomalies (Lawver and Hawkins, 1978). Accordingly the tectonic evolution of the Gulf is still based on conjecture.

In the project " A Seismo-Tectonic and Seismic Slip Characterization of the Ocean-Continent Transition in the Gulf of California" funded by NASA (NAG 5-1041), we have been studying the tectonic process in this region. To help comprehend seismo-tectonic activity in this region, we have compiled all the available data bearing on the regional tectonics including seismological data. We have digitized the bathymetry and the plate boundary in the Gulf as well as the faults and topography of the surrounding region. The seismological data include a seismicity map for teleseismically observed events (magnitude > 4.7) and focal mechanism solutions for events (magnitude ≥ 5.5) which occurred between 1964 to September 1989 in the Gulf of California.

2. Data Base

Bathymetry

The bathymetric chart produced by the Direccion General de Oceanografia Naval and the Continental Margins Group of the University of Oregon (CONMAR) (1987) served as the basemap for our data compilation (Figure 1). From this chart we digitized the coastlines of the Baja peninsula and mainland Mexico. The bathymetric contours (200m interval) within the Gulf of California and immediately to the west and south of the peninsula were also digitized from this chart. To complete the data set further offshore in the Pacific Ocean, we added the 1000m bathymetric contour from the General Bathymetric Chart of the Oceans (GEBCO) series (Mammerickx and Smith, 1982).

Geologic faults

The fault lineaments shown in Figure 1 (in red) represent two types of faults. The first type of faults (light red lines) is based on geological mapping and does not necessarily imply any current displacement or activity. For the Mexican mainland, we digitized geologic charts from the Direccion General de Geografia del Territorio Nacional (1981) from which we also digitized the border between Mexico and the United States. The source for the Baja peninsula was a series of charts by Gastil et al. (1971). We used U.S. Geological Survey charts as sources for California (Jennings et al., 1975), Arizona (Wilson et al., 1969), New Mexico (Dane and Bachman, 1965) and Texas (Darton et al., 1937). The second type of faults (heavy red lines) represents historically-active faults. The chart by Jennings et al. (1975) served as a source for the lineaments in California. The source for this type of faults in Mexico was Ricardo Fernandez and Francisco Suarez-Vidal of CICESE.

Topography

Figure 1 shows the topography (green) of the regions surrounding the Gulf of California. The topographic contours (at 1000m intervals) for the Baja peninsula and the Mexican mainland were digitized from a chart series from the Direccion General de Geografia (1982). The topographic contours for the United States were digitized from the GEBCO chart series (Mammerickx and Smith, 1982).

Plate Boundary

We incorporated the detailed bathymetric data within the Gulf, the geologic faults, and the locations of earthquake epicenters from the International Seismological Center (ISC) and National Earthquake Information Center (NEIC) catalogues (see *Seismicity* below) onto a single chart in order to determine the location of the Pacific-North America plate boundary. Shown as a series of long transform faults and short ridge segments along the length of the Gulf, the plate boundary extends northward to the Salton Sea (at approximately 33°N) and southward to the Rivera Fracture Zone (at 20°S). Because of the complicated tectonics north of the Salton Sea, we have tentatively located (dashed line) the northern portion of the Pacific-North America plate boundary along the San Andreas Fault. The geologic faults and earthquake epicenters in this area, however, suggest a more diffuse plate boundary than the one we have drawn (see *Tectonic Background* below).

3. Tectonic Background, Plate Boundary and Plate Motion

The plate tectonic history of the Northeast Pacific and western North America is reviewed by Atwater (1989). Eastward dipping subduction occurred along the western margin of North America through the Late Mesozoic and well into the Cenozoic. The present day triple junction between the Gorda plate remnant of the Farallon plate, the Pacific Plate and the California plate (that part of North America west of the Basin and Range extensional province) is located where the Mendocino transform fault intersects coastal North America at 40°N. The triple junction first formed with the subduction of the Pacific-Farallon spreading center at ~29 Ma, just after Anomaly 10 time. The timing is evidenced by Anomaly 10 as the oldest identified anomaly adjacent to the continental margin south of the Mendocino Fracture Zone. The collision first occurred at about 32°N in a present day framework, or ~29-30°N in a reconstructed framework with the Gulf of California closed. Between the time of collision and 20 Ma, the initial northern triple junction which consisted of the Pioneer transform fault, the trench to the north, and the Pacific-North American transform fault to the south, migrated northward. By 20 Ma the Pioneer transform fault was inactive and the northern triple junction consisted of the Mendocino transform fault and the other two components mentioned above. While the northern triple junction has persisted to the present, it has steadily migrated northward such that the Mendocino transform fault now intersects North America at ~40°N. The southern triple junction, initially nearly coincident with the northern one, migrated southward at virtually the same rate as the Pacific plate migrated northward with respect to the North American plate. In consequence, the southern triple junction, which consisted of the Pacific-Farallon spreading center, the Pacific-North American transform fault and the "Middle America" trench, remained virtually stationary at 30°N in a reconstructed framework until 12.5 Ma or just prior to Anomaly 5A time. The region between the two triple junctions spanned the present day continental borderland off Southern California and undoubtedly contributed to the complexity of the region.

The Pacific-Farallon spreading along the Baja California margin, ceased at Anomaly 5A time (~12.5 Ma), leaving a series of abandoned spreading centers (Atwater, 1989). The northernmost fragment of Anomaly 5A is found at about 30.5°N and supports the idea that as the northern triple junction migrated northward, the southern one remained fairly stable at ~30°N, southwest of Ensenada.

Anomaly 5B (~15 Ma) is mapped from the tip of the Peninsula to about 27.5°N where the Shirley Fracture Zone intersects the continental margin, much like the Pioneer Fracture Zone did to the north at 29 Ma ago. Anomaly 5B trends sub-parallel to the continental margin. Apparently when the Pacific-Cocos spreading center was initially subducted at a present day latitude of 27.5°N, there was so little oceanic crust between the spreading center and the trench that it was difficult for the very young crust to be subducted beneath the central and southern section of the Baja California Peninsula (Atwater, 1989) so spreading stopped both to the north between 27.5°N and 30°N and to the south to the vicinity of the present day tip of the Baja California Peninsula. At ~12.5 Ma ago, the Pacific-Cocos spreading center near the mouth of the Gulf became reoriented with spreading on the Mathematician Ridge. Between 12.5 Ma and 5.5 Ma when seafloor spreading began in the Gulf, North America-Pacific plate motion probably took place along the Tosco-Abreojos Fault along the Pacific margin of the Peninsula (Spencer and Normark, 1979). As early as 1972 (Karig and Jensky, 1972), it was suggested that a proto-Gulf existed as a shallow marine sea. Normal faulting that may be as old as 10 to 12 million years has been identified in many places in the Gulf (Gastil et al., 1971; Stock and Hodges, 1989).

As spreading reoriented on the Mathematician Ridge to more northwest-southeast it seems to have also propagated northeastward towards the present-day mouth of the Gulf of California. As the Mendocino triple junction continued to migrate northwards and with some changes in the pole of rotation for the Pacific plate, the Pacific-North America plate motion along the Tosco-Abreojos Fault became more difficult to sustain. Eventually that plate motion began to be taken up in the Gulf of California. Initially the motion produced the opening of the Pescadero, Farallon, Carmen and Guaymas basins. Some of the major plate motion may have then been translated back across the Peninsula to the Continental Borderland region off Southern California.

In the central Gulf of California, south of 28°N, Pacific-North America plate motion can be assumed to be confined to the extensional basins and transform faults of the Gulf. South of the tip of the Baja California Peninsula, organized seafloor spreading is not indicative of Pacific-North America plate motion since a third plate, the Rivera Plate is involved. Larson (1972) based his Pacific-North America plate motion on the identification of marine magnetic anomalies south of the Tamayo transform fault. It is now evident that the magnetic anomalies formed south of the Tamayo transform fault are not indicative of Pacific-North America plate motion but instead represent Pacific-Rivera plate motion. Both the Nuvel-1 model (DeMets et al., 1990) and RM2 plate circuit model of Minster and Jordan (1978, with the removal of Larson's anomalies from the mouth of the Gulf of California) give plate motion along the Pacific-North America boundary of about 48 mm/a. Based on seismicity, the Middle America Trench appears to extend to the Tres Marias Islands, which mark the eastern end of the Tamayo fracture zone. The Trans-Mexican volcanic zone, which heads east from the region of the Tres Marias Islands, may be an additional plate boundary but is not pertinent to the question of Pacific-North America plate motion.

Within the Gulf of California, the Pescadero Basin, just north of the Tamayo Fracture Zone, the Farallon Basin, the Carmen Basin and the Guaymas Basin appear to have resulted from simple transform motion between the North American and Pacific plates. Early seismic refraction data (Phillips, 1964) seemed to indicate that the crust at the mouth of the Gulf can be considered to be normal oceanic crust, and that the crust thickens to the north, with the crust in the northern Gulf of California being as much as 25 km thick. Within the limitations of the data, the crust in the Guaymas Basin may be thicker than the crust at the south end of the Gulf (9.5 km as opposed to ~5 km at the mouth).

If the Gulf of California has opened at 48 mm/a for the last 5.5 My then about 260 km of oceanic crust might be expected in the Gulf of California. Morphologically, there appears to be around 250 km of offset between the northwest and southeast rifted margins of the Guaymas Basin. The depression in the northeast Guaymas trough, where evidence of hydrothermal activity was observed (Lonsdale and Lawver, 1980), was mapped and a clear junction between the trough as the site of crustal extension and its bounding transform fault was mapped by Lawver and Williams (1979, see their Figure 2b). The lack of continental seismicity to the west of the Guaymas Basin and along the western margin of the State of Baja California Sur (south of 28°N) leads us to suppose that all of the Pacific-North America plate motion is presently occurring along the northern Guaymas Basin transform fault. Just to the north of 28°N, the trend of the northern Guaymas Basin transform fault changes its general strike (Figure 1).

On land Gastil et al. (1971) show the first observed fault traces sub-parallel to the northern Guaymas Basin transform fault at about 28°10'N. It is probable that some of the Pacific-North America plate motion is distributed throughout the State of Baja California on the western side of the Gulf as well as being translated into the Basin and Range Province at the north end of the Gulf. We indicate that the plate motion changes trend since the small extensional center in the Salsipuedes Basin does not lie along strike of the northern Guaymas Basin transform fault. High heat flow was measured in the Ballenas Channel and may possibly be indicative of recent extension between Isla Angel de la Guardia and the mainland (Lawver, 1975). North of the island the major plate boundary was drawn based on bathymetry but the seismicity does not follow the bathymetry. The Southern California Batholith actually extends into the northern part of the State of Baja California and its southern end may be along strike of the transform boundary between the Ballenas Channel and the Delfin Basin. In the northern Gulf of California there is clearly not enough room to reconstruct the plates by simple closure of the Delfin Basin. We assume that north of 28°N the Pacific-North America plate motion is distributed over a very wide zone. Some of the major plate motion may in fact connect the seafloor spreading in the Guaymas Basin by motion along the San Miguel, Vallecitos, Rose Canyon and Newport-Ingelwood faults, with motion along the continental margin of California.

The northern Gulf of California has opened as a result of seafloor spreading or continental extension but sediments from the Colorado River have poured into the region as rapidly as the crust has subsided, leaving the region fairly shallow. Consequently it is difficult to use morphology to decipher the present-day plate boundary. As can be seen in Figure 1, a fair amount of seismic release has occurred between the Consag Rock/Wagner Basin region of the northern Gulf of California and Cerro Prieto, a geothermal power plant which may be on top of a zone of crustal extension. Some seismicity and observed fault scarps connect the activity at Cerro Prieto into the Elsinore Fault of Southern California. In fact though, there is additional motion along the Imperial Fault, which seems to connect to the Black Butte, Red Hills region of the southeastern Salton Sea. Even so, the vast majority of the large earthquakes that occur in this region seem to be occurring on the San Jacinto Fault. North of the Transverse Range in the Carraizo Plains region of central California, the North America-Pacific plate boundary (with the exception of the extensional component of motion in the Basin and Range) seems to be narrowly defined by motion along the San Andreas Fault (with the exception of the Coalinga Earthquake). The Pacific-North America plate motion then bifurcates into the San Andreas and Hayward/Calaveras Faults south of San Jose. The Hayward/Calaveras Fault further splays into a number of faults including the Green Valley Fault on the east in the Livermore Valley region. In northern California we know the plate motion is distributed because the triple junction is moving northward and motion that once was taken up exclusively along the San Andreas Fault is stepping eastward as the triple junction moves northward. In the northern Gulf of California the answer is not so simple.

The secret to understanding the neo-tectonics of the Gulf of California lies in understanding the tectonic evolution of western North America for the last 29 million years. The Pacific-Farallon spreading center intersected North America at about 30°N in a present day framework and produced a disruption in the continental margin of North America that developed into the Continental Borderland off Southern California. As the Mendocino triple junction migrated northward over time, the Pacific-North American plate boundary underwent a continual realignment. At 5.5 Ma, the Pacific-Farallon (now Cocos) spreading center propagated into the Gulf of California region and the Baja California Terrane was produced. It is now moving northward. At first some of the northward motion was taken up with some trans-Peninsular faulting across the northern part of Baja California as evidenced by the present-day motion on the San Miguel and Vallecitos faults as well as the normal faults mapped by Stock and Hodges (1989). As the Mendocino triple junction continues to migrate northward the present day San Andreas Fault no longer lies on a small circle of rotation about the Pacific-North American pole of rotation. Consequently the major plate motion is stepping eastward as evidenced by the Hayward-Calaveras, the Green Valley and other faults in Northern California.

4. Seismic Activity and Focal Mechanism Solutions.

Seismicity Map

The locations of the earthquake epicenters shown in Figure 1 were taken from the ISC catalogue (from 1964 through 1981) and from the NEIC catalogue (from 1982 through September, 1989). Earthquakes with a body magnitude (m_b) greater than or equal to 5.5 are shown as stars within circles. Earthquakes with m_b less than 5.5 but with a surface magnitude (M_s) greater than or equal to 5.5 are shown as stars only. Earthquakes with both m_b and M_s less than 5.5 are shown simply as X's.

Little variation is noted in the spatial seismicity pattern along the entire plate boundary. However, when Tajima and Tralli (1990) examined the accumulated seismic moment release in this region using the catalogues of Harvard CMT solutions (Dwiewonski et al, 1981; Dwiewonski and Woodhouse, 1983), they noted several episodic moment releases (Note: CMT catalogues include events with magnitudes of about 5 and greater during the period from 1977 to September 1989). These episodes are associated with the Imperial Valley, CA, earthquake (Ms=6.9) in 1979, the Superstition Hills, CA, earthquake (Ms=6.6) in 1987, and the Guaymas Basin earthquake (Ms=7.0), Gulf of California, in 1988. The total seismic moment release is 4.66 x 10^{26} dyne-cm. When Tajima and Tralli (1990) investigated the variation of accumulated seismic moment release along the plate boundary by dividing the Gulf region into three sections (roughly corresponding to the southern, central and northern parts of the Gulf), they noted substantial spatial variations. The northern section indicates two significant steps in accumulated moment release which are associated with the Imperial Valley and Superstitions Hills events. On the other hand, the moment release in the southern section is very gradual with no major steps noted during this period. The gradual moment release pattern in the central gulf section is similar to that in the southern region until the 1988 Guaymas Basin earthquake.

Tajima and Tralli (1990) also checked the moment release over a longer time period using both ISC and NEIC seismicity catalogues, which include smaller events (magnitude ≥ 4.7) listed consistently starting around 1969 to estimate. In this case surface wave magnitudes were converted to seismic moments using the expression given by Hanks and Kanamori (1979):

$$\log M_o = 1.5\, M_w + 16.1 \quad (1)$$

where M_w is a moment magnitude. They assumed $M_w \sim M_s$ for moderate events. When surface wave magnitudes were not available, Tajima and Tralli (1990) used the body wave magnitude, m_b, and assumed that $m_b \sim M_s$ in the magnitude range < 6.5 (Heaton et al., 1986). The total accumulated seismic moment release in the entire Gulf is thus 1.78 x 10^{27} dyne-cm for the period from 1969 to September 1989. The general patterns are essentially similar to those obtained using the CMT catalogues, but the total moment released in each section was greater even during the period from 1977 to September 1989. In the southern Gulf there was an episodic moment release associated with a swarm of several major events in 1969. After this, the moment release was very gradual. In the central Gulf the predominant moment release between 1971 and 1975 occurred as a few minor episodes followed by a period of gradual moment release until the 1988 Guaymas Basin earthquake. In the northern Gulf, the majority of the seismic moment was released during a few episodic periods. Based on this, it is suggested that seismic slip varies both spatially and temporally along the Pacific and North America plate boundary in the Gulf.

Focal Mechanisms

Figure 2 shows the best double couple focal mechanisms that include first-motion focal mechanism solutions determined or constrained during forward modelings in this study, the results of body waveform inversion (Goff et al., 1987) or CMT solutions (provided by the Harvard group). This figure suggests that strike-slip focal mechanisms are dominant along this plate boundary; 23 events show strike-slip mechanisms with northwest-southeast trending faults. Because of the northwest-southeast trend of the transform faults and the geometry of the Pacific- and North American plate motion in the Gulf of California, the northwest-southeast striking nodal planes with right-lateral motion are the probable fault planes for the strike-slip solutions. Among the strike-slip solutions, three events (i.e. the 7-5-64, 8-17-69, 11-21-77 events) show fault dips substantially shallower than the others. For these events, there were few stations found in the western and southern quadrants of the focal hemisphere; therefore the constraint of the fault dip is poor. Two events near Wagner Basin and one off Pescadero Basin show normal faulting. The 4-4-69 event which occurred to the west of the plate boundary in the southern Gulf shows a well-constrained normal faulting solution, and our first-motion solution is consistent with that of Molnar (1973) and the body wave moment tensor solution of Goff et al. (1987). One well-constrained thrust-type focal mechanism is found along the Tres Marias Escarpment, on the Rivera-North American plate boundary. Our solution has compression directed east-west with some component of left-lateral strike-slip motion as well. This is consistent with the slip vectors for the two plates.

5. Discussions and Summary.

Using our seismicity database, Tajima and Tralli (1990) assessed the seismic slip along the plate boundary as follows: the accumulated seismic moment release estimated in the southern Gulf from the seismicity catalogues is 2.7×10^{26} dyne-cm. If an oceanic rigidity of 5×10^{11} dyne/cm^2 and a crustal thickness (~ fault width) of 5 km are assumed, then the total seismic slip obtained is 17.4 cm. On the other hand, the total tectonic slip during this study period from the NUVEL-1 (DeMets et al., 1990) relative plate velocity is 102 cm (common to each section). The ratio of seismic slip to tectonic slip is 17.1%. If we use 10 km for the fault width, based on the maximum source depth in this area (Goff et al., 1987; Zemlicka and Tajima, 1990), the seismic slip and, accordingly, the seismic to tectonic slip ratio are reduced in half. The total seismic moment release is 6.86×10^{26} dyne-cm. However, since this region is an oceanic to continental transition zone, the crustal thickness and rigidity should also vary. If we use oceanic parameters, 10 km for the fault width and 5×10^{11} dyne/cm^2 for moment, the seismic slip estimate and its ratio to tectonic slip are 22.1 cm and 21.7%, respectively. For continental parameters, 15 km for the fault width and 3×10^{11} dyne/cm^2 for moment, the estimated seismic slip rate is 24.6 cm with a 24.1% ratio of seismic to tectonic slip. Finally, the accumulated moment release in the northern gulf is 8.22×10^{26} dyne-cm. The crustal thickness in the northern gulf section may be over 30 km, but source depths for major events are shallower than 15 km (Goff ., 1987; Zemlicka and Tajima, 1990) and therefore we use this smaller value. The estimated seismic slip is 29.5 cm, which is 29% of the tectonic slip. Overall, the seismic slip ratio is less than 30% in the entire gulf but appears to increase slightly from south to north. This discrepancy between the estimated seismic slip and the tectonic slip based on the NUVEL-1 (DeMets et al., 1990) global plate motion model is addressed as a significant tectonic feature in the Gulf region (Tajima and Tralli, 1990).

Zemlicka and Tajima (1990) examined effects of water phases on the P waveforms using the forward modeling approach of Wiens (1987) and modeled the source processes with simple short source-time functions for some events. Goff et al. (1987) had modeled the source processes of these events with relatively long lasting source time functions and less control of focal parameters, probably because they attempted to account for the later complex phase arrivals (e.g., water phases) as source signals. In the forward modeling, the focal parameters have also been revised. Accordingly the slip vectors inferred from the earthquakes are slightly different from that suggested by Goff et al. (1987). However, due to the presence of a substantial ambiguity in fault plane determination and of a certain range of slip angles allowed for an existing fault under the same tectonic stress condition (Tajima and Celerier, 1989), we do not extract any definite conclusion out of this.

Further, if seismicity affects the relative plate motion, direct geodetic measurements across the Gulf similarly may be expected to vary given plate boundary complexities (Tajima and Tralli, 1990). Thus, the charts compiled in this project provide a good database for seismo-tectonic study in the Gulf of California, which is an unique tectonic transition zone.

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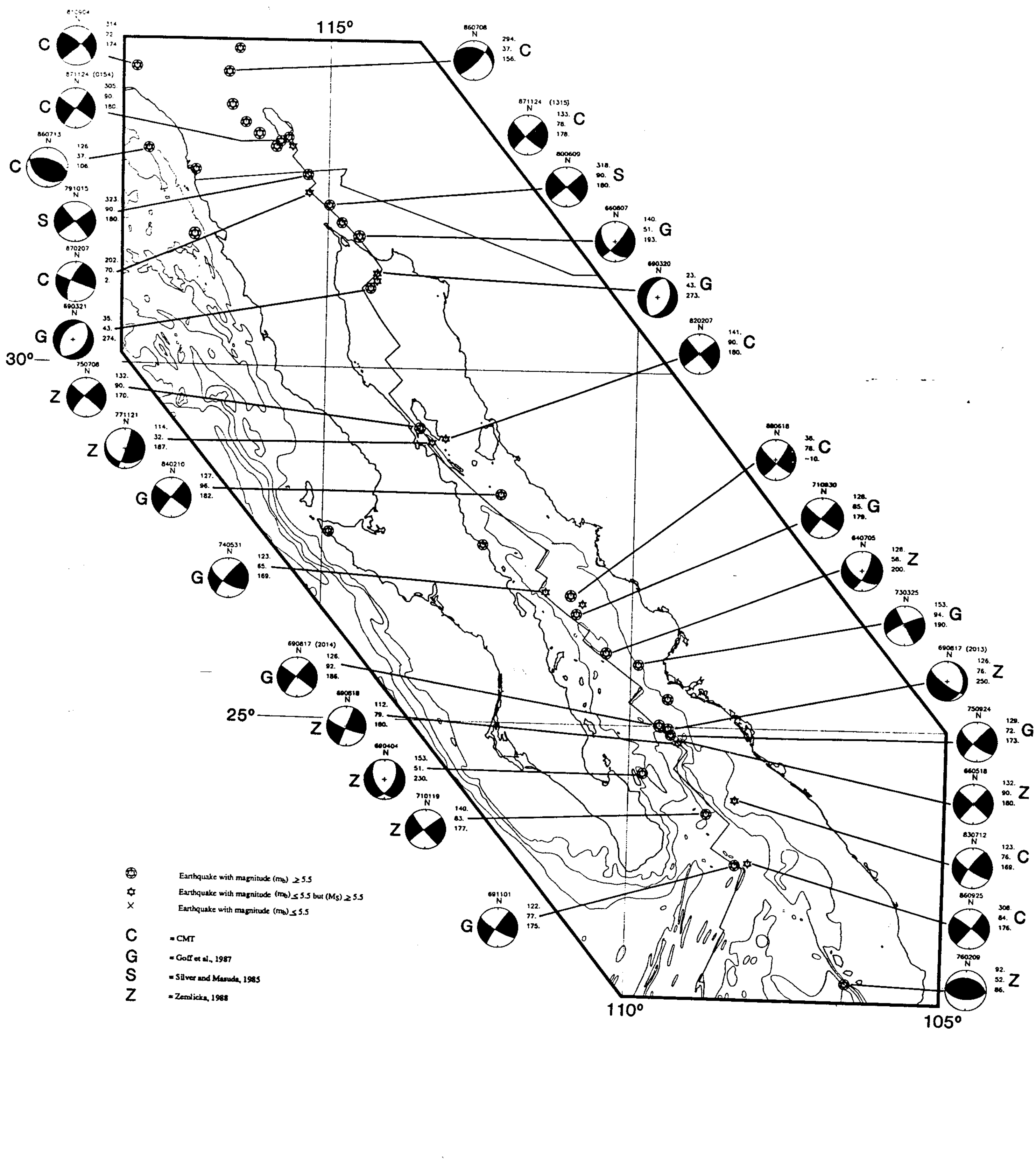
115°
110°
105°
30°
25°
Earthquake with magnitude (mb) ≥ 5.5
Earthquake with magnitude (mb) ≤ 5.5 but (Ms) ≥ 5.5
Earthquake with magnitude (mb) ≤ 5.5
C = CMT
G = Goff et al., 1987
S = Silver and Masuda, 1985
Z = Zemlicka, 1988

Fig. 2