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Block versus continuum deformation in the Western United States

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Abstract

The relative role of block versus continuum deformation of continental lithosphere is a current subject of debate. Continuous deformation is suggested by distributed seismicity at continental plate margins and by cumulative seismic moment sums which yield slip estimates that are less than estimates from plate motion studies. In contrast, block models are favored by geologic studies of displacement in places like Asia. A problem in this debate is a lack of data from which unequivocal conclusions may be reached. In this paper we apply the techniques of study used in regions such as the Alpine–Himalayan belt to an area with a wealth of instrumental data—the Western United States.

By comparing plate rates to seismic moment release rates and assuming a typical seismogenic layer thickness of 15 km it appears that since 1850 about 60% of the Pacific–North America motion across the plate boundary in California and Nevada has occurred seismically and 40% aseismically. The San Francisco Bay area shows similar partitioning between seismic and aseismic deformation, and it can be shown that within the seismogenic depth range aseismic deformation is concentrated near the surface and at depth. In some cases this deformation can be located on creeping surface faults, but elsewhere it is spread over a several kilometer wide zone adjacent to the fault. These superficial creeping deformation zones may be responsible for the palaeomagnetic rotations that have been ascribed elsewhere to the surface expression of continuum deformation in the lithosphere.

Our results support the dominant role of non-continuum deformation processes with the implication that deformation localization by strain softening must occur in the lower crust and probably the upper mantle. Our conclusions apply only to the regions where the data are good, and even within the Western United States (i.e., the Basin and Range) deformation styles remain poorly resolved. Nonetheless, we maintain that block motion is the deformation style of choice for those continental regions where the data are best.

1. Introduction

Since the last century earth scientists have debated whether deformation is widely spread in a continuous fashion throughout large volumes of rock or is restricted to a few large faults that bound undeforming blocks. Plate tectonics unequivocally demonstrated block motion at large scales, and this debate appeared to be settled. However, clear evidence that deformation occurs along narrow plate boundaries is found only in oceanic regions. Whether continental lithosphere deforms as a series of blocks or as a continuum is now in question [1–4].

A number of arguments appear to support the continuum view. Continental rocks are typically

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deformed both at plate margins and in plate interiors, whereas deformation of ocean rocks outside subduction zones is unusual. Paleomagnetic rotations of near-surface continental rocks suggest distributed zones of deformation as well as block rotation in California and New Zealand [5–7]. Recorded seismicity in oceanic regions is restricted to narrow zones with little evidence of deformation in the interiors of plates, whereas for continental deformation zones seismicity is more diffuse. In continental regions deformation rates determined from seismic moment have often been found to be smaller than those determined geodetically or from plate tectonics [1,8–10], and it has been suggested that the balance of the deformation is accommodated either as distributed creep [11,3] or accommodated on many small (and sometimes aseismic) faults [12–15].

Continuum views have been backed by theoretical arguments concerning the physics of lithospheric processes [16,11,3]. Estimates of lithospheric viscosities made in conjunction with typical deformation rates for active mountain belts imply substantial stresses over depth ranges of many tens of kilometers. This is much greater than the seismogenic depth range of 15–20 km considered, on the basis of seismicity, to deform in a brittle fashion [17]. It has consequently been argued that the brittle crust does not determine deformation patterns, but responds passively to displacements and rotations of the underlying material [2,3]. On this basis, models of mountain building which use averaged crust and mantle viscosities and include buoyancy effects have been developed which are broadly consistent with the overall distribution of topography of features such as the Himalayas [3].

Recent geological studies reveal a different picture. In the Himalayas and other parts of Asia, strike-slip fault zones having widths of 10–20 km have undergone displacements of hundreds of kilometers and have apparently persisted for 10–15 Ma or more [18–21]. Deformation at active mountain fronts is also localized when compared to vast areas such as parts of Tibet or the Tarim depression, which exhibit minimal deformation [22]. Consequently, plate models based on fault slip data that require kinematic consistency for the relative slip between moving blocks can explain the deformation of Asia over the last 1 Ma [19,22]. Conceptually similar models, but lacking such robust information on fault slip rates, have also been used to explain the recent geologic evolution of parts of the Mediterranean [23–26].

Theoretical models to explain block motion depend on the belief that strain softening processes are important and extend into the lower crust and possibly the mantle [23,27]. Unfortunately, numerical or mechanical models that employ material properties that give rise to such behavior are less tractable than those that employ simpler materials, and, in general, systems where the conditions at a given time depend on a memory of past history are commonly chaotic or at least numerically unstable [28]. Thus, exercises that are possible with the simpler rheologies used for continuum models, such as attempting to trace the evolution of the Himalayas from first collision to the present, are currently impossible.

Care must be exercised when taking sides in the continuum–non-continuum debate. De Sitter [29] remarked that, in many cases, the only difference between faulting and folding was the scale at which the observer was looking. When averaged over large regions and for long time periods, distributed deformation of continental crust is undeniable. On the other hand, persistent localized deformation does occur in continental environments over geologic time periods, and in the most brittle parts of the crust block motion is certainly occurring when small enough scales are resolved. Implicit in the debate, however, are more detailed questions. These include (1) to what degree does the seismogenic upper crust deform only seismically?, (2) are paleomagnetic rotations representative of deep processes in a deforming zone?, and (3) is deep deformation diffuse or do strain-weakening processes cause localization in the lower crust and upper mantle?

In most parts of the world data do not yet exist to address the foregoing questions. However, in the Western United States, and the San Francisco Bay area in particular, data do exist, although for only a part of the seismic cycle. Naturally, conclusions from such a limited area need not apply generally, but nonetheless it behooves us to take notice of the way in which such a well studied region operates.

2. Deformation of the Western United States

Since no well-defined spreading ridges separate the North American from the Pacific plates north of the Gulf of California, relative motion cannot be determined directly. However, self-consistent models for the motions of all major plates constrain the rate of Pacific–North America relative motion to be 48 mm/yr [30]. Recent VLBI results are consistent with the average plate tectonic rate and suggest that about 9 mm/yr is accommodated across the Basin and Range, a value that is consistent with seismologic and geologic data [31,32]. Although the direction of displacement across the Basin and Range remains in dispute, correction for this relatively small value gives a relative motion of 39 mm/yr at an azimuth of N30°W ± 2° between the Sierra Nevada mountains and the Pacific Plate at the latitude of San Francisco Bay.

Like other regions of continental deformation, seismicity in California and Nevada extends over a zone hundreds of kilometers wide, suggesting that the deformation is widespread (Fig. 1). The locations of $M > 5.5$ earthquakes since 1850 [33], however, are not random across this broad zone of deformation. Most of the large earthquakes have occurred on the San Andreas and subparal-

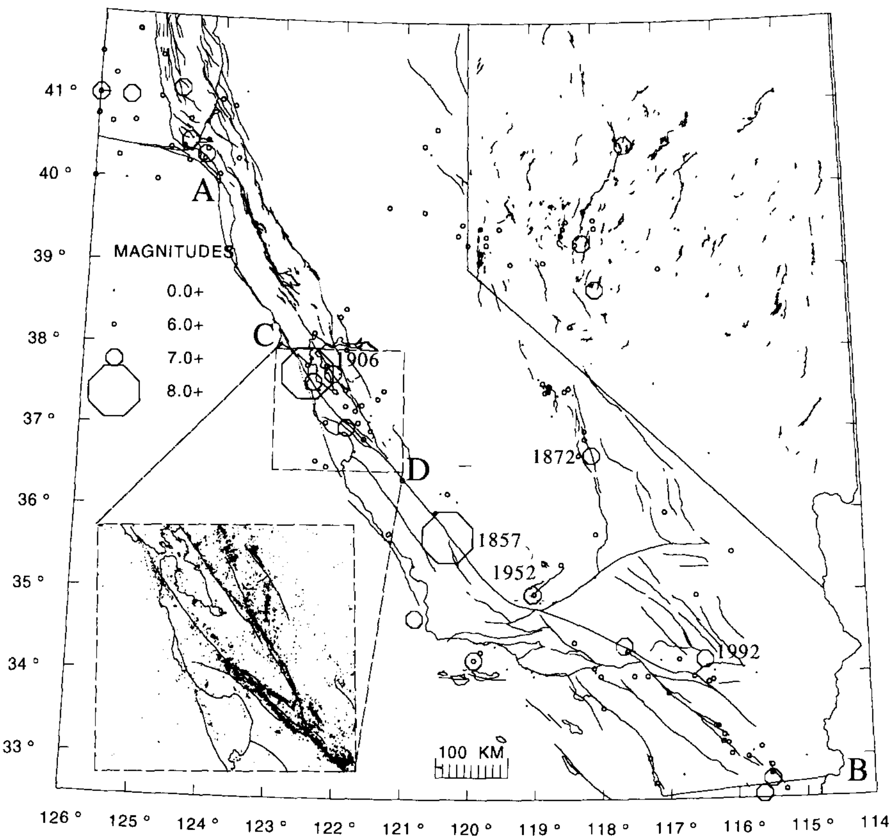

Fig. 1. The seismicity of Nevada and California since 1850 [33]. A–B shows the length of the plate boundary used to calculate slip rates. Symbol size represents the source dimension of a circular rupture for the Ellsworth moment magnitude with a 100 bar stress drop. Symbol location indicates earthquake epicenter. The inset shows seismicity for the San Francisco Bay Area since 1969. C–D shows the length of boundary used to calculate slip rates for this subregion. Symbol size in the inset is constant to preserve fault detail.

lel faults in California. In eastern California and Nevada a smaller number of earthquakes have occurred along a zone trending from the Mojave Desert northwards into Nevada, and within the Basin and Range province a few events have also been recorded.

Because the period for which seismic information is available is small in relation to the recurrence interval of many faults, the deformation pattern is not defined in the Basin and Range by historical and instrumental seismicity. However, geologic data suggest that narrow zones of deformation have persisted through the Quaternary [31,32]. In earlier periods deformation occurred elsewhere but apparently also in a localized fashion [34]. Thus, while the locus of the Basin and Range extension has changed with time, there is evidence to suggest that deformation has been restricted to persistent faults or zones of faults.

The catalog of earthquakes in California is probably complete above $M7$ since 1836 and $M6.5$ since 1850, and $M6.0$ since 1880 [35]. Using the moment magnitudes from Ellsworth [33] and excluding events related to the Gorda plate the $M > 5.5$ events in California and Nevada since 1850 give a total scalar moment of 2.1×10^{21} N m for the Western United States. The length of the boundary (A–B in Fig. 1) is 1160 km. Assuming that all of the moment release results from plate motion, and that the average seismogenic zone depth is 15 km, the scalar moment results in a displacement of 4.0 m or an average slip rate of 28 mm/yr. The largest contributions come from five events: Southern California (1857, 5.0×10^{20} N m), Owens Valley (1872, 2.5×10^{20} N m), San Francisco (1906, 3.5×10^{20} N m), Kern County (1952, 1.3×10^{20} N m) and Landers (1992, 1.3×10^{20} N m).

The assumption that all of the scalar moment represents relative plate motion is equivalent to assuming that, in a coordinate system for which two of the axes are parallel and perpendicular to the plate motion, the summed moment tensor is dominated by horizontal shear. Since most of the above events are strike-slip along planes orientated parallel to the plate motion, the error involved is small. Four of the five largest events (1857, 1872, 1906 and 1992, which comprise 59% of the total moment release) certainly represent relative plate motion. Only Kern County, which represents about 6% of the total moment release, had a significant component unrelated to horizontal motion close to the relative plate motion. Thus a slip rate of 28 mm/yr is unlikely to be substantially overestimated (< 15%). Another source of overestimate could be that the 142 yr period includes two $M8$ 1/4 events (1857 and 1906) with recurrence intervals of about 300 yr [36]. Allowing for this would reduce the moment by a further 15%. However, as we suggest later for the San Francisco Bay area, evidence exists to suggest that during time periods when big events ($M8$) do not occur, $M7$ events may be more frequent. Consequently, reducing the average moment release rate may be inappropriate.

A more significant factor influencing the calculation of the slip rate is the assumed seismogenic thickness. Nowhere in the region, however, are maximum earthquake depths greater than 20 km or less than 10 km over any significant area. A seismogenic thickness of 8.7 km, which would cause the seismic moment rate to agree with the plate rate of 48 mm/yr [30], is less than any reasonable average value [37]. If 15 km is an appropriate seismogenic thickness and the 142 yr interval is sufficient to obtain a representative estimate of the deformation rate, 42% of the deformation occurs as creep.

3. Deformation of the San Francisco Bay

The low rates of motion or the lack of detailed seismic or geodetic data prevent a more refined study of deformation processes in the Basin and Range or much of California. However, for the San Francisco Bay area (inset in Fig. 1) more is known. The relative plate motion is 39 mm/yr along N30°W [30], the geodetic rate over more than 20 years is 34 mm/yr along N33°W [38], and the combined rates of motion on all of the major faults determined by geologic methods is 40–44 mm/yr parallel to the plate motion [39]. It is important to note that these rates are all in substantial agreement.

The catalog of earthquakes in the San Francisco Bay area is better known than that of the entire state. It is complete above $M7$ since 1836 and $M6$ since 1850 [35]. Most seismic events can be related to particular faults either by instrumental locations or through historical accounts of damage. A dense seismic network has operated since 1969, producing reliable hypocentral locations of $M > 1.2$ earthquakes. The comparison of geodetic, geologic and plate reconstruction slip rates with the slip rates estimated from the seismic moment release allows us to consider in detail the way in which seismic and aseismic deformation is distributed in this region.

Summing the seismic moment for all events except for 1906 gives 1.3×10^{20} N m. The largest contributions come from four events: Hayward (1836, 1.3×10^{19} N m), San Francisco Peninsula (1838, 3.2×10^{19} N m), Hayward (1868, 3.2×10^{19} N m) and Loma Prieta (1989, 3.2×10^{19} N m). The deepest small events in the region occur at 18 km, but excluding a few places a more typical estimate of the seismogenic depth is 15 km. For the 220 km boundary, C–D (Fig. 1) gives a slip

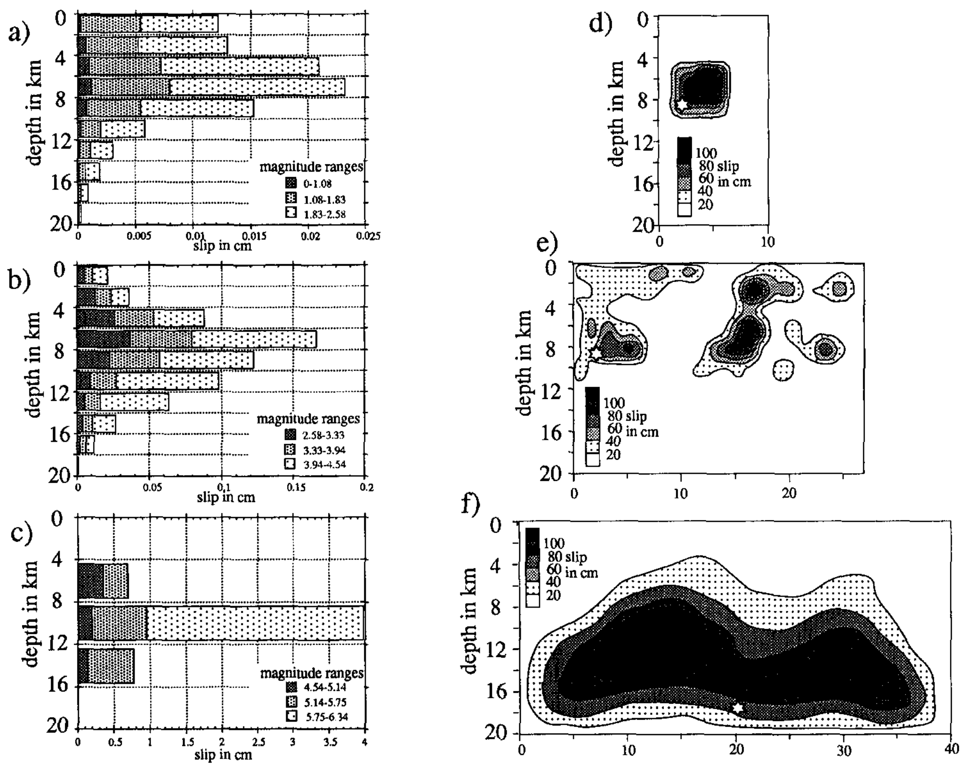

Fig. 2. The distribution of seismic slip as a function of depth for the San Francisco Bay area following the methods of Bakun et al. [56] and King et al. [54]. The events, located by the northern California seismic network of the USGS, have an RMS of ≤ 0.3 s, and horizontal and vertical standard errors of ≤ 2.5 and 5.0 km respectively. In (a), (b) and (c) seismic moment for all events in the magnitude ranges indicated has been summed and then expressed as equivalent slip along the boundary C–D in Fig. 1. Stars indicate hypocenter location. The ranges of magnitude are the same as employed by Bakun et al. [56] and give factor of eight moment ranges. Depth windows of 2 km are used for magnitudes 0–4.54. Because slip is not localized within such narrow depth ranges for larger events 4 km windows are used for events with magnitudes of 4.54–6.34. Shallow slip is overestimated because of location errors for shallow events. This effect can be seen in (a). Individual event slip distributions for the Coyote Lake event [58] are shown in (d), for Morgan Hill [59] in (e) and for Loma Prieta [45] in (f). Where several authors report slip distributions for the same event all report a slip concentration at some depth. The localization is better constrained than the depth of the maximum, but appears to be similar to the depth at which slip is at a maximum for smaller events.

contribution of 1.3 m. Except for the 1989 Loma Prieta earthquake, all of the $M > 6.8$ events in the San Francisco Bay area since 1836 are thought to have had strike-slip mechanisms with fault planes close to N30°W [36]. Thus, we again assume that all of the moment represents relative plate displacement and anticipate a small overestimate. Not all of the rupture zone of the 1906 event falls in the region we study (Fig. 1); only slip that occurred within the region based on reported surface rupture [40] and geodetic data [40] is considered. Adding the appropriate slip from 1906 results in 3.6 m of seismic slip over 157 yr, giving a slip rate of 23 mm/yr, which is approximately 58% of the rate determined from plate motion, geodesy or geology.

Almost two thirds of the moment in this estimate comes from the 1906 event with an estimated recurrence time of 201–281 yr [36], which is longer than our sample time. Thus, the moment release observed over the last 157 yr may be an overestimate of typical seismic slip. On the other hand, during other time intervals, smaller events may occur on parts of the fault ruptured in 1906, as suggested by the WGCEP [36], such that the average moment release remains the same. We therefore do not adjust the values to account for such effects and conclude that about 42% of the deformation may occur as creep. In the San Francisco Bay area we can consider evidence for where the creep occurs.

Fig. 2 shows the distribution of seismic slip in the San Francisco Bay region since 1969 as a function of depth for all events $< M2.58$ (Fig. 2a), for events between $M2.58$ and 4.54 (Fig. 2b) and for events between $M4.54$ and 6.34 (Fig. 2c). The depth distribution of slip for the smallest events (Fig. 2a and b) peaks near 7 km, the middle of the seismogenic depth range. Fewer events occur in the $M4.54$ and 6.34 range (Fig. 2c), making the plot less reliable. Nonetheless, the distribution of slip is similar to that for the smaller events. If the different faults in the region are examined separately similar distributions are found, although where the seismogenic range is less (e.g., 10 km for the central Calaveras fault), the peak is commensurately shallower (about 5 km). If we assume that all of the slip is seismic at the depth where the slip distribution peaks in Fig. 2 and the deficit at greater or lesser depths is a result of creep, the proportion of creep varies between 30 and 50%.

The slip for the larger events since 1969 (Loma Prieta, Morgan Hill and Coyote Lake) are shown in Fig. 2d, e and f respectively. These are not reliable in detail [42–45], but slip certainly concentrates over narrow depth ranges. Thus, Fig. 2 indicates that for larger events as well as for small ones, seismic slip is not distributed uniformly with depth, and substantial creep in the upper and lower parts of the seismogenic zone must be widespread.

While the proportion of fault creep to seismic slip appears similar in the figures we show, variation is apparent between different parts of the fault system. For example, the 1906 event produced substantial surface rupture [40], suggesting that slip was more uniform across the entire seismogenic depth range. Savage and Lisowski [46] show that creep on the Hayward fault extends from the surface to a depth of 5 km, while the entire seismogenic zone of the 'creeping section' of the San Andreas fault between latitudes 35.5° and 37.0° (Fig. 1) moves almost entirely by creep [47].

4. Discussion

Over the period of time for which we have reliable information about the seismicity in California and Nevada, the rate of moment release accounts for about 60% of the relative plate motion if we assume the seismogenic zone extends from the surface to a depth of 15 km. Thus, apparently, about 40% of the deformation occurs as creep. The proportion of slip released seismically for the San Francisco Bay area is similar but more details of the processes can be resolved. For many faults the effective seismogenic depth inferred from small earthquakes overestimates the depth range for which seismogenic fault slip occurs. Near the surface and at depth some deformation must occur by creep. Fig. 2 provides a clue to where this is occurring. Seismic slip peaks at mid-depths in the seismogenic zone, thus deformation must be localized on the faults at these depths. Above and below these depths deformation may be less localized, but it cannot occur far from the fault. Along some faults like the 'creeping section' of the San Andreas, creep can be shown by instrumental measurements to be localized on surface faults (Fig. 3a). Along other faults, like the Calaveras, the surface deformation may be more diffuse and spread over several kilometers [48], as shown in Fig. 3b.

With time such deformation must accumulate to produce drag folding. Although such folding is not easily recognized where strata are predominantly horizontal [49], it may also produce rotations of small blocks adjacent to the fault, resulting in rotation of measured palaeomagnetic directions. In dip-slip environments the same processes have been shown to produce surface folds [50–52] with widths related to the depth at which seismic slip localization occurs. If such a process is widespread, it has implications for models proposed to explain paleomagnetic observations [53]. They suggest that surface blocks displace and rotate passively in response to uniform motion in the lower crust and mantle (Fig. 3c). We suggest that the reverse occurs, with superficial 'ductile' processes (Fig. 3b) diffusing block motion at depth.

The data we present show that deformation is localized for strike-slip processes in the Western United States. If we accept that the seismogenic crust alone is very weak, localization processes must occur in the lower crust and upper mantle. On the basis of geodetic data it is argued [54] that this must occur in California. Evidence for deformation localization for dip-slip environments in the Western United States exists but is not conclusive. Some active fault zones have certainly remained unchanged for periods of perhaps a million years and faults within these zones have developed offsets of the order of the thickness of the brittle crust [55]. Long before such large dip-slip offsets develop, buoyancy forces should shift deformation elsewhere. If this does occur, how can such features develop? Two mechanisms can be proposed: Localization by strain weakening in the lower crust and upper mantle [24,27] certainly occurs in California [54], and the same processes will resist a tendency for deformation to change location in dip-slip regions. This may be assisted by the erosion and deposition of sediment which can annul the buoyancy forces which would otherwise prevent further motion [55].

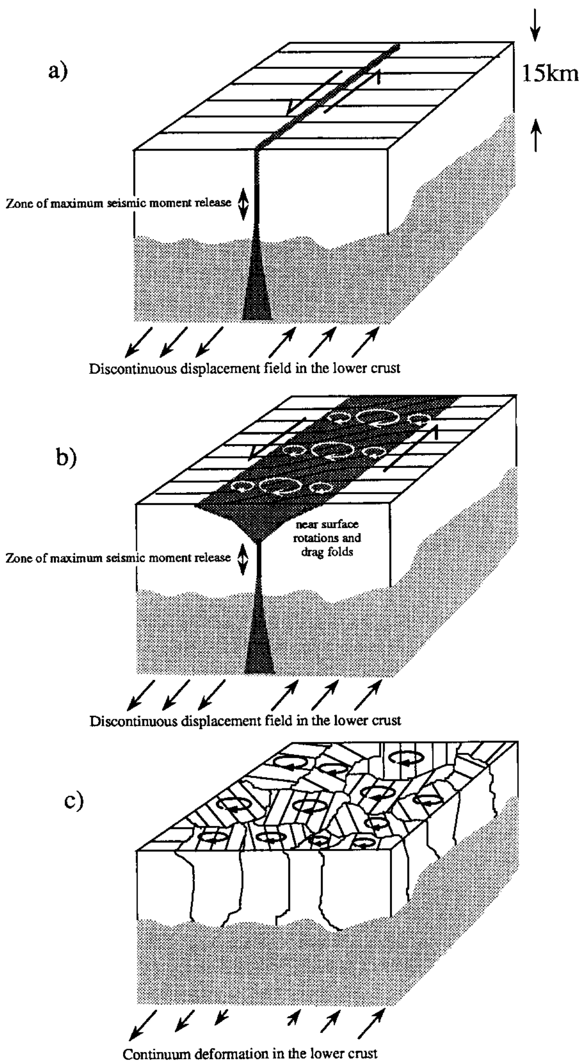

Fig. 3. (a) Distribution of deformation as a function of depth for block deformation. (b) The effect of surface drag folding can be to cause near-surface deformation to be spread over a zone near to faults even though deformation is localized at depth. (c) The model proposed by McKenzie and Jackson [1] to explain paleomagnetic observations. The major faults play a minor role. In each case the unshaded part represents the seismogenic crust with a nominal thickness of 15 km.

5. Conclusions

Seismic moment release in the Western United States since 1850 results in a rate parallel to the relative Pacific–North American plate motion that is approximately 60% of the rates estimated from plate motion studies. These moment calculations assume that seismic moment can be reliably estimated from historical magnitudes, the time period of the catalog of earthquakes is representative, most of the moment release is parallel to the plate motion, and that the thickness of the seismogenic region is 15 km. Despite the uncertainty in these assumptions we conclude that substantial creep must occur either localized on faults or as distributed deformation.

When a similar analysis is undertaken for the San Francisco Bay region, we find the same ratio of seismic to aseismic slip over the seismogenic depth range. In this region it can be demonstrated that distributed deformation does not play a significant role; all creep is closely associated with faults. Geodetic and geologic results also require such localization.

If other regions behave in the same way, a deficit in seismic moment release cannot be used as evidence for broadly distributed deformation. Near-surface creep, as well as creep at depth, appears to be important and can produce local rotations. If this phenomenum is widespread, such rotations may not necessarily provide evidence for continuum deformation deeper in the lithosphere.
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