UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Performance assessments for radioactive waste repositories: the rate of movement of faults

by

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Open-File Report 82-972

1982

Abstract

Performance assessments of mined repositories for radioactive waste require estimates of the likelihood of fault movements and earthquakes that may affect the repository and its surrounding ground water flow system. Some previous assessments have attempted to estimate the rate of formation of new faults; some have relied heavily on historic seismicity or the time of latest movement on faults. More appropriate emphasis is on the identification of faults that have been active or may have been active under the present teconic regime in a broad region and on estimates of the long-term rate of movement of such faults. Faults that have moved under the current stress field, even at low rates, are likely to move again during the time the wastes will remain toxic. A continuum exists for the present rate of movement of faults which ranges from 10 mm per year for obviously active faults along the western margin of the North American plate to as low as 10^{-4} mm per year for recently documented faults in the Atlantic Coast province. On the basis of regional consistency in movement rates and constraints imposed by geomorphology, I derive upper bounds for the rates of occurrence of fault offsets for various crustal stress provinces in the conterminous United States.

These upper bounds are not meant to substitute for detailed studies of specific faults and seismicity at specific sites. They can help to reduce the considerable uncertainty that attaches to all estimates of future tectonic activity. The principal uncertainty in their estimation is the manner in which total slip across faults is distributed among discrete events especially in regions in which the rate of movement is very low.

I. Introduction

The preferred method of isolating high-level radioactive waste from the biosphere in the United States and several other countries is by burial in mined, near-surface cavities at depths ranging from 200 to 1000 m. The Department of Energy (DOE) intends to site and construct such repositories so that, under expected conditions, there will be no adverse releases of radionuclides. DOE also intends to site and construct the repository so that a series of barriers to radionuclide migration will prevent adverse releases even in the event of most unexpected conditions (DOE, 1980). Draft regulations of the Nuclear Regulatory Commission (NRC, 1981) require such a multiple barrier approach to isolation and also require an evaluation of the projected performance of a proposed geologic repository considering both credible natural processes and perturbations caused by emplacement of the radioactive waste.

Among natural perturbations, tectonic phenomena are among those most likely to occur in and around a repository sometime during the period when the radionuclides remain toxic[1]. Tectonics may involve seismic shaking,

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[1] This period is as much as 10 million years for some nuclides although the toxicity of a repository will decrease markedly over the first 50,000 years of its history (Cohen, 1982).

fault offset, or epeirogenic movement. The effects of distant earthquakes on an underground repository will be small and controllable (Pratt and others, 1978; 1979; Dowding and Rosen, 1978). The effects of epeirogenic movements on an appropriately selected site will be minimal (Mara, 1980). The potential effects of faulting and nearby earthquakes are less well understood (Pratt and others, 1979); therefore, faults and nearby earthquakes must be analyzed in detail in considerations of specific repository sites.

Analysis of the post-closure performance of an underground radioactive waste repository differs from traditional risk analysis of operating facilities such as reactors in two important ways. First, the time over which the analysis applies is much greater and predictions of many geologic events and processes over time periods longer than a few thousand years are highly uncertain (Bredehoeft and others, 1978). Second, unlike operating facilities, a decommissioned waste repository is not a system for which the concept of "failure" is appropriate (Burkholder, 1980). Some degradation of the isolation system is certain to occur; but conversely, some degree of effectiveness will always remain except in extreme situations. A fault or nearby earthquake at a waste repository site cannot be treated as a "failure" as it need not necessarily result in degradation of the isolation system. In some ground-water regimes, such movement may have no effect whatever on the existing ground-water flow system (Davis, 1980; Winograd, 1981).

Because both the probabilities and consequences of faults and nearby earthquakes are highly uncertain, the DOE is evaluating post-closure performance of a repository by considering probabilities of perturbing events and their consequences that vary over wide limits, and then calculating from these values a series of outcomes for the repository performance (Burkholder, 1980). The extent to which these potential outcomes may be deemed acceptable will be determined through a licensing action by the NRC. The DOE's program for the Assessment of Effectiveness of Geologic Isolation Systems (AEGIS) is an example of a computerized simulation of repository behavior; AEGIS attempts to take into account all reasonable sequences and combinations of events and processes that may affect the isolation system (Zellmer, 1980). The simulation requires estimates of the rates of fault movement at and around a repository. Such estimates could be in the form of probability density curves as well as point values (Zellmer, 1980).

As the DOE program to site mined repositories progresses, greater emphasis will be placed on estimating the rates of movement on specific faults at specific sites. Such determinations will require detailed and intensive investigations of known and suspected faults and of historical seismicity. Even with such investigations, however, there generally will be considerable uncertainty in determining such rates of movement and the purpose of this paper is to suggest reasonable upper bounds for them. Such bounds can also be useful in the continuing comparative generic studies of various waste isolation systems in different media such as those of Burkholder (unpub. data, 1981)[1].

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[1]Burkholder, H.C., Engineered components for high-level radioactive waste isolation systems--Are they technically justified? ONWI-286, Office of Nuclear Waste Isolation, Battelle Memorial Institute (Draft Report).

The methods used to estimate the rate of fault offset and nearby earthquakes in connection with repository sites should be based on current understanding of neotectonics and intraplate processes. Such understanding has increased considerably in recent years as intensive studies have been made of some regions in connection with tectonic and seismic risk to engineered structures. Some previous performance assessments for radioactive waste repositories have been based on assumptions which now appear questionable in the light of current understanding. This paper will point out some of the difficulties encountered in previous approaches to this problem and suggest some alternative approaches.

II. Previous approaches

The literature on performance assessments for high-level radioactive waste repositories has grown rapidly in recent years, and an exhaustive review of each study does not appear profitable. Most of the assessments known to me are listed in Table I together with the essentials of the approaches and major assumptions with regard to tectonics. The following paragraphs will discuss these approaches and assumptions in a general way prior to discussion of suggested alternatives. All of the probabilities for faulting derived in the references in Table I are low numbers and may well be close to the real values for these processes. Some assumptions tend to overestimate and some to underestimate the derived numbers. The purpose here is to examine the assumptions critically in the light of recent developments in tectonics.

A. Determination of rate of formation of new faults

Many approaches to risk assessments for radioactive waste repositories have attempted to determine analytically the rate at which faults have formed within a region (e.g., Claiborne and Gera, 1974; EPA, 1980). This is an extremely difficult problem inasmuch as the time of inception of most faults cannot be determined. The available evidence strongly indicates that most fault movements in the shallow crust follow pre-existing zones of faulting or other zones of weakness particularly in the relatively stable eastern two-thirds of the conterminous United States (Sykes, 1978; Zoback and Zoback, 1981). The geologic record is replete with examples in which fault movement has occurred recurrently on pre-existing faults under a variety of stress regimes (Wentworth and Mergner-Keefer, 1981; Zoback and Thompson, 1978). Even the opening and closing of ocean basins appears to result from movement along pre-existing zones of weakness (Ratcliffe, 1971; Rankin, 1975).

New faults possibly will form in response to changes in the pattern of tectonic stress; such changes appear to occur very slowly, however. Zoback and Zoback (1980) note a change of approximately 45° in the direction of least principal stress for the Basin and Range Province within the last 30 million years. In the more stable Atlantic Coast region, the pattern of tectonic deformation, appears to have been essentially the same over the last 63 million years or more (Zoback and Zoback, 1981). For a specific waste repository site, the problems of locating all faults and of estimating the rate of offset on existing faults appear to be much more crucial to evaluating future performance than estimating the rate of formation of new faults.

B. Reliance on historical seismicity

The seismicity in relatively stable, intraplate regions is not well-determined, partly because the recurrence intervals of major earthquakes are much longer than the period of either instrumental or historical seismic records. An estimate of "secular seismicity" (Allen and others, 1965) covering time periods of 10^3 to 10^7 years is needed; the historic record cannot provide this. Even in a moderately active area such as the Basin and Range where earthquake activity is well correlated with fault offset, the locus of fault movement has shifted repeatedly on the relatively short time scale of 10,000 years (Allen, 1975; Smith, 1978). Many faults in the Basin and Range that displace Quaternary deposits are not seismically active today (Slemmons, 1967).

The situation in the more stable eastern parts of the United States is even more uncertain. Until recently very little work had been done on the relation between seismicity and geologic structure. Not only is the period between major earthquakes in the east long, but the cumulative Cenozoic offset on faults thought to be the locus of historic activity is very small (100 m or less). The possibility is thus raised that other presently aseismic faults showing small Cenozoic offset may be the site of future large earthquakes (Zoback and Zoback, 1981; Wentworth and Mergner-Keefer, 1981). Performance assessments which derive a faulting rate solely from historical seismicity, for example Logan and Berbano (1977), are thus incomplete.

C. Determination of time of latest movement

Some estimates of the rates of fault offset have relied on the time of latest movement as an indication of the current rate (EPA, 1980); but this approach involves many uncertainties. In the Basin and Range Province, the time of latest movement of faults in an area of 15,000 km^2 in northern Nevada ranges from 25 to more than 500,000 years, but the pattern of activity over time, if indeed there is one, is not clear (Wallace, 1977). In the Sonorran section of the Basin and Range, the time of latest movement of most faults appears to be greater than 10^6 years (Howard and others, 1978). The reason for this lack of recent activity and the likelihood of renewed activity in the next 10^6 years are unanswered questions at present.

In many of the less tectonically active parts of the country, not even the time of latest movement on faults is well constrained because of an absence of stratigraphic markers for key intervals. For a fault cutting Paleozoic rocks and overlain by undisturbed Holocene colluvium, the time of latest movement could range from 10^8 to 10^4 years. Undisturbed Quaternary deposits, where present, may constrain the time of latest movement to as much as 10^6 years; but extensive Quaternary deposits are lacking over much of the mid-continent. Only the latest Quaternary is present in many places (Colman and Pierce, 1979).

D. Use of in situ stress orientation and rock strength

The orientation of a fault with respect to the present in situ stress field is a factor to be considered in estimating its future likelihood of movement. The in situ stress field within the stable part of the North American plate varies in a complex way but very widely spaced data suggest broad provinces in which the stress tensor is relatively consistent (Zoback and Zoback, 1980). Measurements of in situ stress at specific waste repository sites should be required to determine if the local stress tensor conforms to the regional orientation. Changes in the stress field have obviously occurred over geologic time, but as noted, these must be very slow.

Cranwell and Donath (1980) suggest that the strength of rocks along a fault zone be compared with the existing stress field to determine in a direct way what the likelihood of future faulting may be. This innovative approach should be attempted; problems may arise in determining a realistic value for the strength of a large body of probably anisotropic rock that would be involved in the fault.

E. Evaluation of likelihood of undetected faults

Performance assessments should consider also the possibility of existing but undetected faults being present at or in the vicinity of a repository site. Site characterization will attempt to identify all faults that may undergo significant movement in and around a repository, but the need to limit the number of drill holes at a site means there will always be some residual uncertainty as to whether all such faults have been located. Geometric, probabilistic approaches to this problem, such as that of Cranwell and Donath (1980) assume a regional density of faults and calculate the probability that one or more will intersect a given area. This approach is valid as long as the faults in a region much larger than the size of a repository (10 km^2) are uniformly distributed. Remote imagery, aerial photographs, potential field measurements, and microseismicity must all be examined to see if evidence exists that the putative faults might be concentrated in some preferred zone or direction.

III. Recurrence rates for movement on faults

Predictive uncertainties in estimating the future rate of movement on faults stem from inadequacies in the geologic record and from the fact that future rates may be different from past rates (Bredehoeft and others, 1978). The approach advocated here is to consider the neotectonic history of broad regions whithin the conterminous United States, and to estimate the past rate of recurrence of fault movements within these regions. From these regional long-term data, conservative upper bounds for future rates of fault offset may be proposed. These fault movement rates are thus presented within regional stress provinces which appear relatively homogeneous in terms of active stresses and strain rates.

For some faults, the stratigraphic record has preserved evidence of major discrete offsets in the past. Most of these are along the western margin of the continent; many are listed in Wallace (1981). The offsets that can be documented are usually those associated with major earthquakes (magnitude 7 or higher). From the point of view of performance assessments for radioactive waste repositories, we are also interested in the history and a future rate of recurrence of smaller offsets down to a few centimeters associated with smaller shocks.

The secular rate of slip across a fault - but not a record of discrete offsets - may be decipherable from progressive offset of a series of well-defined stratigraphic horizons. Thirteen faults in a variety of tectonic settings for which such a slip rate has been reasonably well determined are listed in Figure 1. Faults with the highest slip rates occur at the western margin of the continent at the North American plate boundary; all faults in the eastern two thirds of the country for which the rate of slip can be determined have very low rates (less than 10^{-3} mm/yr). In the region between the Pacific Coast and the eastern front of the Rocky Mountains, fault slip rates vary widely although all rates greater than 10^{-1} mm/yr are confined to the general region of the western plate margin. Figure 1 indicates that a continuum in the secular rate of slip of faults exists and that a potential for renewed movement is present even on faults with a low rate. No criteria now exist to determine when a fault showing evidence of brittle deformation in the past is truly "dead." The Poorman Gulch and Mother Lode faults of the Sierra Nevada foothills (fig. 1) are good examples of faults on which the long term rate of slip is low but which are capable of continued movement to the present as shown by scattered seismicity and the 1975 magnitude 5.7 Oroville earthquake which resulted in a displacement of 17 cm (Clark and others, 1976).

The slip rates of figure 1 can be translated into recurrence intervals for earthquakes and fault offsets by a variety of theoretical (Anderson, 1979) and empirical (Slemmons, 1977) approaches. Figure 2, modified from Slemmons (1977), shows one relationship between slip rates, recurrence rates, and earthquake magnitudes which is instructive for the purpose of performance asessments for radioactive waste repositories. Use of Figure 2 is relatively straightforward for the western one-third of the country where, except on some parts of the San Andreas system, fault offset appears to occur mainly as sudden movement accompanied by earthquakes rather than as slow tectonic creep. The relationship between fault offset and earthquakes in the east is much less clear (Hamilton, 1981) and will be discussed further below. On the basis of these generalizations and reservations, however, reasonable upper bounds for the probabilities of fault offset can be proposed for some parts of the conterminous United States.

IV. Western United States

A. General

Numerous studies of fault offset and seismicity have been made in the relatively active western one-third of the United States. Site specific studies in the west stand the greatest chance of providing direct data on the rate of recurrence of fault offsets and earthquakes. Wallace (1981) has reviewed the data on both rate of recurence and slip rate for the region extending from California, across the Great Basin to the Colorado Plateau. The rate of occurrence of large earthquakes ranges from approximately 100 years along the San Andreas system in California to more than 100,000 years in parts of the Great Basin. Where slip rates can be measured on faults, they translate into recurrence rates consistent with these numbers.

B. Basin and Range

The Yucca fault at the Nevada Test Site and the Bernalillo County Dump fault near Albuquerque (fig. 1) are two faults within the Basin and Range Province (fig. 3) for which long-term movement rates have been determined. In the absence of specific data to the contrary, performance assessments for radioactive waste repositories in the Basin and Range Province can make use of the recurrence rates derived from figure 2 for that province. Such rates agree with those suggested by Wallace (1981) for much of the Great Basin. Within a large part of eastern Nevada and within the Sonorran section of the Basin and Range province in Arizona, faults on which major offsets have occurred within the past 1 million years appear to be missing (Wallace, 1981; Howard and others, 1978). Until the nature of this tectonically quiet zone is better understood, recurrence rates in these regions should be assumed to be the same as in the rest of the Basin and Range Province unless site-specific data clearly indicate that rates over geologic time have been lower.

C. Columbia Plateau

The Columbia Plateau (fig. 3) has had a history of north-south compression leading to folding and faulting since the outpouring of the Columbia River basalts 14 million years ago. The history of fault displacement is not well known and there does not appear to be a large number of faults. Coombs (1979) stated that most of the deformation occurred between 8 and 4 million years ago. Some Quaternary movement has been noted, however (Howard and others, 1978).

A fault in the Kittitas Valley at the west edge of the plateau has moved at a rate of 1.4×10^{-2} mm/yr for the last 3.5 million years (Waitt, 1979). At Manastash Ridge, also on the western margin, the largest fault on the plateau has moved at a rate of 3×10^{-2} mm/yr (Coombs, 1979). The present rate of slip on these faults may be much lower than these rates which could, however, serve as upper bounds for performance assessments.

D. Colorado Plateau Interior

This small, relatively stable province, is surrounded on all sides by more active regions. The Basin and Range - Rio Grande Rift Province of extensional tectonics appears to be encroaching on the Plateau margins on three sides at a rate of a few centimeters per year (Thompson and Zoback, 1979). The province as shown on figure 3 is not coincident with the Colorado Plateau physiographic province. For many properties, such as crustal thickness and heat flow, the province is intermediate in character between the mid-continent and the Basin and Range-Rio Grande Rift province (Thompson and Zoback, 1979). The record of faulting is complicated by Quaternary faults related to salt flowage and slumping due to dissolution near the surface (Howard and others, 1978). Relatively high relief and rates of downcutting make it difficult to put upper bounds on the rate of fault movement from geomorphic considerations. Thick evaporites in the Paradox

Basin portion of the province, which is the site of investigations for locating high level radioactive waste repositories, may attenuate fault movements and seismic energy generated within the basement. Rates of differential vertical movement must be lower than in the Basin and Range Province and may be close to those in the Central Interior described below.

V. Eastern United States

A. General

Over the large region of the eastern United States there are relatively few faults on which Quaternary movement can be demonstrated and for which an estimate of the secular slip rate can be made (fig. 1). This observation, coupled with the much lower number of earthquakes in the east compared to the west, suggests that the rate of fault offset and the rate of recurrence of earthquakes are much lower than in the west; but it is difficult to evaluate how much lower. Because attenuation of earthquake energy in the east is much lower than in the west (Hamilton, 1981) and because small rupture zones may generate significant shocks, all potentially active rupture zones near a repository must be considered in the performance assessment of radioactive waste repositories in the east. However, distant earthquakes are not thought to cause significant consequences. One approach to estimating the rate of fault offset and earthquakes in the east would be to simply use the values for the Basin and Range Province from figure 2 as a firm upper bound or "worst case." I believe, however, that recent neotectonic studies in the east together with some reasonable inferences can establish defensible rates that are lower.

B. Atlantic Coast and Central Interior

Faults in the east showing progressive offset of a series of Cenozoic horizons have been documented in the Atlantic Coast Province and in the upper Mississippi embayment of the Central Interior (fig. 3). Northeast-trending reverse faults have moved sporadically from the Cretaceous to at least upper Tertiary time along the Piedmont and Coastal Plain of the Atlantic Coast. Post-Pliocene movement has been reported for several of these fault zones. The magnitude of the offsets is small; on the best studied examples, total offset over the past 100 million years ranges from 30 to 100 m (Prowell, 1981). The offsets are best documented along the Fall Line where crystalline rocks have been faulted against the Coastal Plain sequence and the latter is relatively thin (Wentworth and Mergner-Keefer, 1981). The poor exposure and subtle stratigraphic differences in the Coastal Plain section require careful, slow and deliberate field work to find and map these offsets. They are, however, some of the best documented examples of very low rates of movement. One of the more poorly defined faults is the Cooke fault (fig. 1) which has been suggested as a possible source for the 1886 Charleston, S.C., earthquake (Behrendt and others, 1981).

Poor to well-defined seismicity in the Atlantic Coast Province also suggests movement on northeast-trending faults; and several focal mechanism solutions indicate northwest-southeast compression with at least one steep, northeast-dipping focal plane (Wentworth and Mergner-Keefer, 1981). The best documented case of seismicity defining a fault zone is in northern New Jersey in the vicinity of the Ramapo fault zone. The focal mechanisms of numerous small earthquakes indicate oblique reverse dip slip along a 100-km long system that strikes northeastward and dips 60° to the southeast (Aggarwal and Sykes, 1978). Earlier Triassic movement on parts of this system had a dip-slip sense of movement connected with continental rifting. No geomorphic evidence indicating recent faulting is available along this system and the sedimentary record is not adequate to document post-Jurassic movement (Aggarwal and Sykes, 1978). The combined data on long-term fault offsets and the focal mechanisms of earthquakes of low-magnitude along the Atlantic Coast define a province in which the maximum compressive stress is horizontal oriented northwest-southeast. The long-term average rate of movement on faults that have moved since the Cretaceous is something less than 100m in 100 million years and averages 0.3 m/10^6 yr over the past 50 million years (3 x 10^{-4} mm/y) (Wentworth and Mergner-Keefer, 1981).

Recent reflection seismic investigations in the northern Mississippi embayment indicate that Cenozoic offset has occurred on a series of northeast-trending strike-slip faults and on northwest-trending reverse faults within a reactivated northeast-trending graben (Zoback, 1979; Zoback and others, 1980). The total amount of Cenozoic offset inferred from these studies is relatively small. Vertical movements are best documented on the Reelfoot fault and show a slip rate very close to those for the reverse faults of the Atlantic Coast Province (fig. 1). The northern Mississippi embayment has been the site of intensive historic seismicity, and there is an indication from trenching studies that major earthquakes have occurred as frequently as every 600 to 700 years (Russ, 1979). This rate of recurrence is hard to reconcile with the small amounts of Cenozoic offset observed.

In other areas of the Central Interior (fig. 3), Cenozoic deposits, which by their offset could give an indication of the slip rate of faults, are mostly lacking. The mid-Continent has undergone deformation since the Cretaceous, however. Fairbridge (cited in Sykes, 1978) showed a contour map with 1000 m of present relief on the Lower Cretaceous planation surface. Post-Cretaceous deformation of the reconstructed 70 m.y.-old land surface in the eastern mid-Continent has been analyzed in detail by Dutch (1982). He finds from 100 to 200 m of subsidence in some parts of the region, which translates to 10^{-3} mm per year if the rate of subsidence was constant. The rate very probably was not constant and much of the deformation probably occurred as broad epeirogenic warping--not as faulting. Nevertheless, some of this motion may have been concentrated along linear zones such as the Great Lakes Tectonic Zone (Sims and others, 1980; Dutch, 1982). For the purposes of performance assessments for radioactive waste repositories, a conservative approach in the absence of more definitive data would be to assume a secular vertical slip rate for faults in the central interior which is the same as for the Atlantic Coast province, i.e., 3 x 10^{-4} mm/yr.

A consideration of erosion rates provides confirmatory evidence that the secular rate of slip on faults in the eastern United States has been low. The rate of denudation, or lowering of the land surface is proportional to relief (Ahnert, 1970). As fault scarps are formed, the rate of erosion is accelerated. Where there are no obvious scarps the rate of uplift of the land along fault scarps can be no higher than the local rate of erosion. Erosion rates have been determined by a variety of methods for the eastern United States and range from 1.4 x 10^{-3} mm/yr to 8.8 x 10^{-2} mm/yr for a variety of settings and time periods (Hack, 1980; Ahnert, 1970; Doherty and Lyons, 1980; Dutch, 1982). The rates could be higher or lower than these for specific sites; and I cannot emphasize too strongly the need for detailed study of individual faults near a site by all available means including geomorphic analysis. It seems unlikely, however, that there has been widespread occurrence of faults in the eastern United States with secular rates of vertical movement higher than 10^{-2} mm/yr.

Conversion of secular slip rates into recurrence rates for discrete events in the eastern United States is difficult because the amount of offset in the shallow subsurface caused by large earthquakes is apparently quite small. Thus, it is not possible to use figure 2 to predict the rate of recurrence of earthquakes. In the Atlantic Coast Province, offset in the shallow subsurface at depths of concern to radioactive waste repositories on faults that have moved in the Cenozoic ranges from 30 to 100 m over Cenozoic time. This offset could be distributed in time in many different ways, but the recurrence interval for discrete events must be relatively large. For example, Wentworth and Mergner-Keefer (1981) assumed that most or all of the offset can be accounted for by magnitude 7 earthquakes involving a small average displacement of 0.24 m. The late Cenozoic average slip rate of 0.3 m/10^6 years translates roughly to one event per 10^6 years for a single fault or a recurrence rate of 10^6 years. Wentworth and Mergner-Keefer show that the historic seismicity in the province could be accounted for by such a distribution of offsets provided there are on the order of 1000 faults, or source areas, within it. Other assumptions regarding the amount of offset per earthquake and the number of faults could be made. I believe the estimated recurrence rate of 10^6 years for large earthquakes and moderate displacements of about 20 to 30 cm is a conservative upper limit for the Atlantic Coast Province.

Over the rest of the Central Interior, the rate of movement of faults is not well determined, but evidence summarized above suggests that it is no higher than in the Atlantic Coast Province and in many places may be lower (Wesnousky and Scholz, 1980). One possible exception is the northern Mississippi embayment (fig. 3) where a relatively large number of faults may be involved in the historic seismicity although the displacement on any one is apparently small. The northern Mississippi embayment is not under consideration for a radioactive waste site; however, long-term rates of movement in other parts of the Central Interior could be comparable. Seismicity within much of the mid-continent region appears to be concentrated along the flanks of interbasin ridges (York and Oliver, 1976). The long-term rate of movement along such graben as defined by the Rough Creek-Kentucky River fault system or the Wabash fault system or half graben, such as that adjoining the Nemaha Ridge (Sykes, 1978), could well be comparable to the rate of movement on faults within the northern Mississippi embayment even though the level of historic seismicity in these regions is lower.

The state of stress in the Atlantic Coast Province and in the Central Interior involves horizontal compression; and movement on recently active faults has occurred by both reverse and strike-slip motion (Zoback and

Zoback, 1980). Moreover, the magnitude of the stress, as near as can be told from limited data, appears to be relatively uniform; faulting and earthquakes may occur at the loci of weak zones within the crust rather than in areas of stress concentrations (Zoback and Zoback, 1981). The rate of strain under these conditions might be expected to be relatively constant, as indeed it appears to be, also on the basis of limited data.

C. Southern Great Plains and Gulf Coast

Within the southern Great Plains and the Gulf Coast provinces (fig. 3) in the eastern United States, which include potential sites for radioactive waste repositories, the stresses are tensional rather than compressional (Zoback and Zoback, 1980). There is virtually no data in these provinces on the long-term rate of fault movement and they are very quiet seismically. The situation in both provinces is further complicated by the presence of thick salt beds. Dissolution and collapse of salt near the surface can lead to disruption of near-surface beds that may be difficult to distinguish from tectonic deformation. Many faults beneath the evaporite section in the Delaware Basin of eastern New Mexico do not extend upward into the evaporites (Powers and others, 1978). Reactivation of basement faults in this region might therefore have little effect on a waste repository within the salt mass.

The climate in most of the southern Great Plains Province is arid and if slip rates along faults were similar to those in the Basin and Range - Rio Grande rift province, where stresses are also tensional, we would expect a similar landscape to develop. The fact that it has not, means that the rate of slip along faults in the southern Great Plains is certainly less than 10^{-2} mm/yr, but a more realistic rate cannot be determined until additional neotectonic studies have been undertaken. Greater crustal thickness and lower heat flow in the southern Great Plains compared to the Rio Grande rift (Thompson and Zoback, 1979) also suggest a tectonically less active province.

Shallow Cenozoic listric faults in the Gulf Coastal Plain are completely unrelated to tectonic forces in the bedrock underlying the thick sedimentary pile and are caused by sediment loading and large-scale down-to-the-coast slumping (Zoback and Zoback, 1980). The axis of most currently active faulting runs near and seaward of the present shoreline (Howard and others, 1978). Those salt domes which are being considered as potential sites for radioactive waste repositories lie well inland from this axis. However, sporadic listric faulting may be occurring on appropriately oriented faults as far inland as these domes. Collins and others (1980) mapped slight Quaternary movement on a portion of the Mount Enterprise-Elkhart fault system along the Trinity River at 31°30' north, 95°55' west. The sense of movement is mainly down to the coast. None of the faults in the vicinity of the salt domes under consideration show geomorphic expression. The level of seismic activity is low, and any movement on such listric faults may be aseismic. Collins and others (1980), however, suggest that a belt of low level seismic activity follows the Mount Enterprise-Elkhart system. The slip rate of faults in the Gulf Coast Province is certainly less than 10^{-2} mm/yr, but as in the southern Great Plains additional neotectonic studies are needed to make a better estimate.

VI. Conclusion

This paper has attempted to derive reasonable upper bounds for the rate of future fault movement within various parts of the conterminous United States for use in performance assessments for radioactive waste repositories. Table 2 summarizes the results for large earthquakes (mag 7) and moderate (cm) to large (m) offsets when the best estimates for maximum slip rates on faults in each region are translated into yearly rates. All of the values in Table 2 are subject to revision with further work. The estimates refer to faults which are either known or assumed to be present at a site or in its vicinity; thus, probabilities derived from these rates are higher than the probabilities given in some earlier studies which assumed a site initially free of faults and calculated the probability that new faults would develop at a site.

The rates estimated in Table 2 suggest that loss of isolation due to fault movement will be unlikely. In the worst case, the Basin and Range province, major offsets of a meter or so would occur at most only once every 12,000 years and probably not at all during the period of short-lived fission product decay (600 years). It is reasonable to require that waste repositories be sited and designed so that barriers to the migration of radionuclides will prevent loss of isolation even in the event of fault offsets at the rates indicated.

Acknowledgments - D.C. Prowell and C.M. Wentworth read an early version of this paper and made many helpful suggestions for its improvement. This work is part of the U.S. Geological Survey program of research in radioactive waste disposal.

Table 1 - Summary of performance assessment procedures for evaluation of mined repositories for high-level radioactive waste.

Study/ Author(s)	A. Determination of rate of formation of new faults	B. Reliance on historical seismicity	C. Reliance on time of latest movement	D. Reliance on rock strength and in situ stress	E. Evaluation of likelihood of undetected faults
Bedded salt, SE New Mexico; Claiborne and Gera (1974)	X	0	0	0	0
Bedded salt, SE New Mexico; Logan and Berbano (1977)	0	X	0	0	X
Pre-Cambrian of Sweden; KBS, Nuclear Fuel Safety Group (1978)	X	0	X	X	0
Los Medanos Region, New Mexico; Bingham and Barr (1979)	X	0	0	0	0
Generic for various media; EPA (1980)	X	0	X	0	0
Northeastern Belgium; D'Allessandro and others (1980)	X	0	0	0	0
Bedded salt, Germany; Bertozzi and others (1977)	X	0	0	0	X
Generic approach; Cranwell and Donath (1980)	X	0	0	X	X

X Included in risk assessment

0 Not included in risk assessment

Table 2 - Suggested upper bounds for long-term slip rates and yearly rate of occurrence for major offsets and large earthquakes on faults in large regions within the United States.

Region	Slip rate (mm/yr)	Yearly rate (events)
Basin and Range - Rio Grande Rift1/	8×10^{-2}	8×10^{-5}
Columbia Plateau1/	2×10^{-2}	3×10^{-5}
Colorado Plateau1/	10^{-2}	1×10^{-5}
Atlantic Coast2/	3×10^{-4}	1×10^{-6}
Central Interior2/	3×10^{-4}	1×10^{-6}
Southern Great Plains	10^{-2}	3/
Gulf Coast	10^{-2}	3/

1/ Based on figures 1 and 2.

2/ Based on comparison with slip rates and projected rates of recurrence for reverse faults in Atlantic Coast Province.

3/ Well-founded bounds for yearly rates not possible.

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Figure Captions

Figure 1 - Long-term rate of slip across faults and fault zones in the conterminous United States. Faults on which strike-slip movement is predominant not included. Rates may have varied over relatively short time spans but long term trends are reasonably well defined. T, primarily thrust motion; N, primarily normal motion. Approximate locations shown on figure 3.

1. Cucamonga fault, Transverse Ranges, Calif. (D. Morton and others, unpub. data, 1981)
2. Wasatch Front (Kaysville), Utah (Swann and others, 1979)
3. Owen's Valley, Calif. (Anderson, 1979)
4. Wasatch Front (Utah Valley), Utah (Scott, 1981)
5. Santa Monica fault, Transverse Ranges, Calif. (Ande son, 1979)
6. Yucca Fault, Nevada Test Site (Carr, 1974; Campbell, 1980)
7. Bernalillo County Dump fault, New Mexico (Machette, 1978)
8. Poorman Gulch fault, Sierra Foothills, Calif. (Wentworth and Mergner-Keefer, 1981)
9. Mother Lode fault, Sierra Foothills, Calif. (Bartow, 1980)
10. Cooke fault, South Carolina (Behrendt and others, 1981). Dashed extension based on hypothesis that Cooke fault is source of 1886 Charleston earthquake.
11. Reelfoot fault, Missouri-Tennessee (Wentworth and Mergner-Keefer, 1981)
12. Stafford fault, Virginia (Mixon and Newell, 1978)
13. Belair fault, Georgia (Prowell, 1981)

Figure 2 - Relation between slip rate across a major fault or fault zone, rate of earthquake occurrence, and earthquake magnitude based on one set of assumptions about the distribution of fault offsets in time. Approximate fields for faults in some seismotectonic provinces also shown. Modified from Slemmons (1977).

Figure 3 - Map of conterminous United States showing provinces referred to in text outlined by heavy solid lines within which crustal stresses and the rate of strain appear to be broadly consistent. Numbers indicate approximate locations of faults listed in figure 1. Modified from Zoback and Zoback (1980).

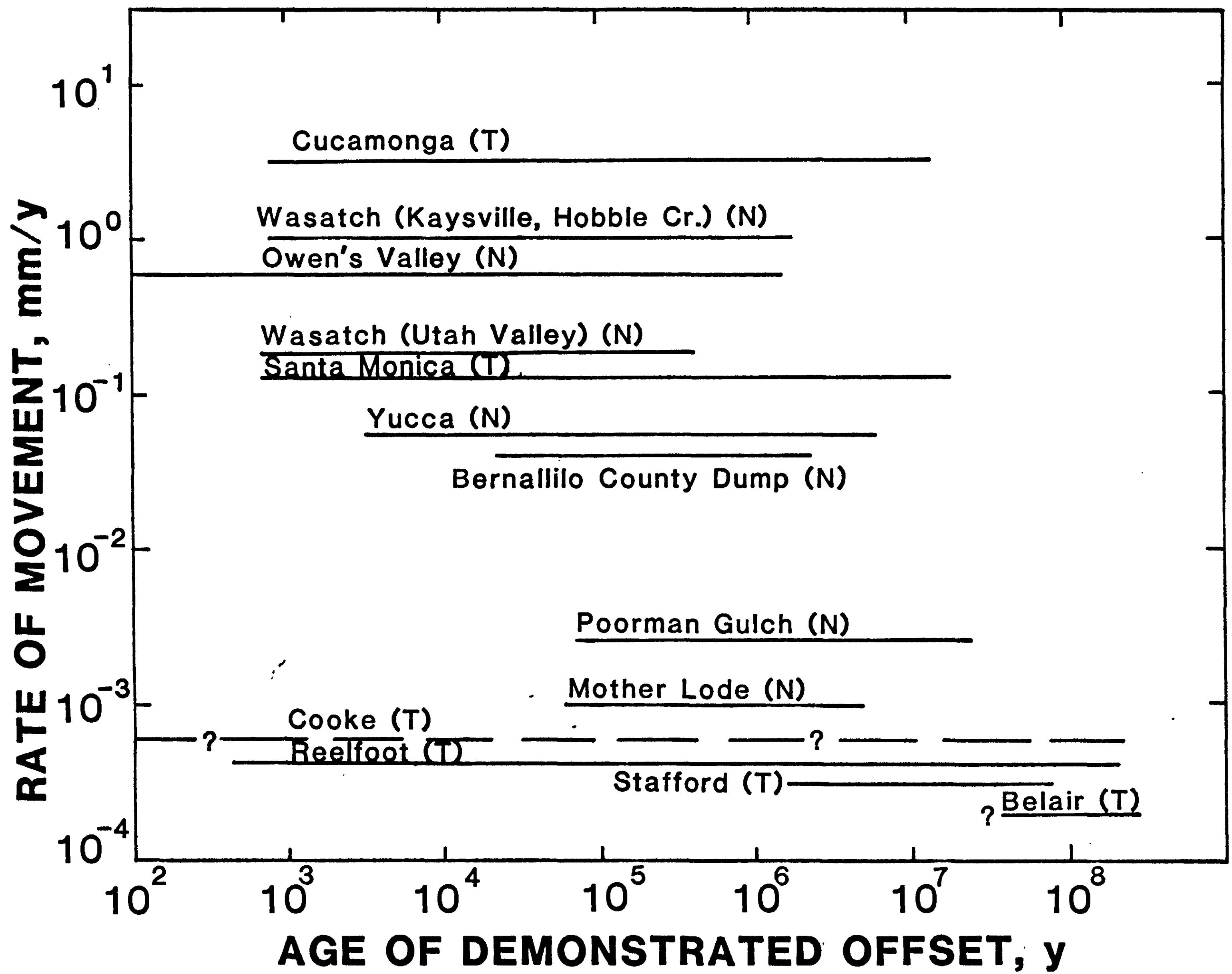
RATE OF MOVEMENT, mm/y
AGE OF DEMONSTRATED OFFSET, y
Cucamonga (T)
Wasatch (Kaysville, Hobble Cr.) (N)
Owen's Valley (N)
Wasatch (Utah Valley) (N)
Santa Monica (T)
Yucca (N)
Bernallilo County Dump (N)
Poorman Gulch (N)
Mother Lode (N)
Cooke (T)
Reelfoot (T)
Stafford (T)
Belair (T)
?
?
?
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
10^4
10^5
10^6
10^7
10^8

Fig. 1

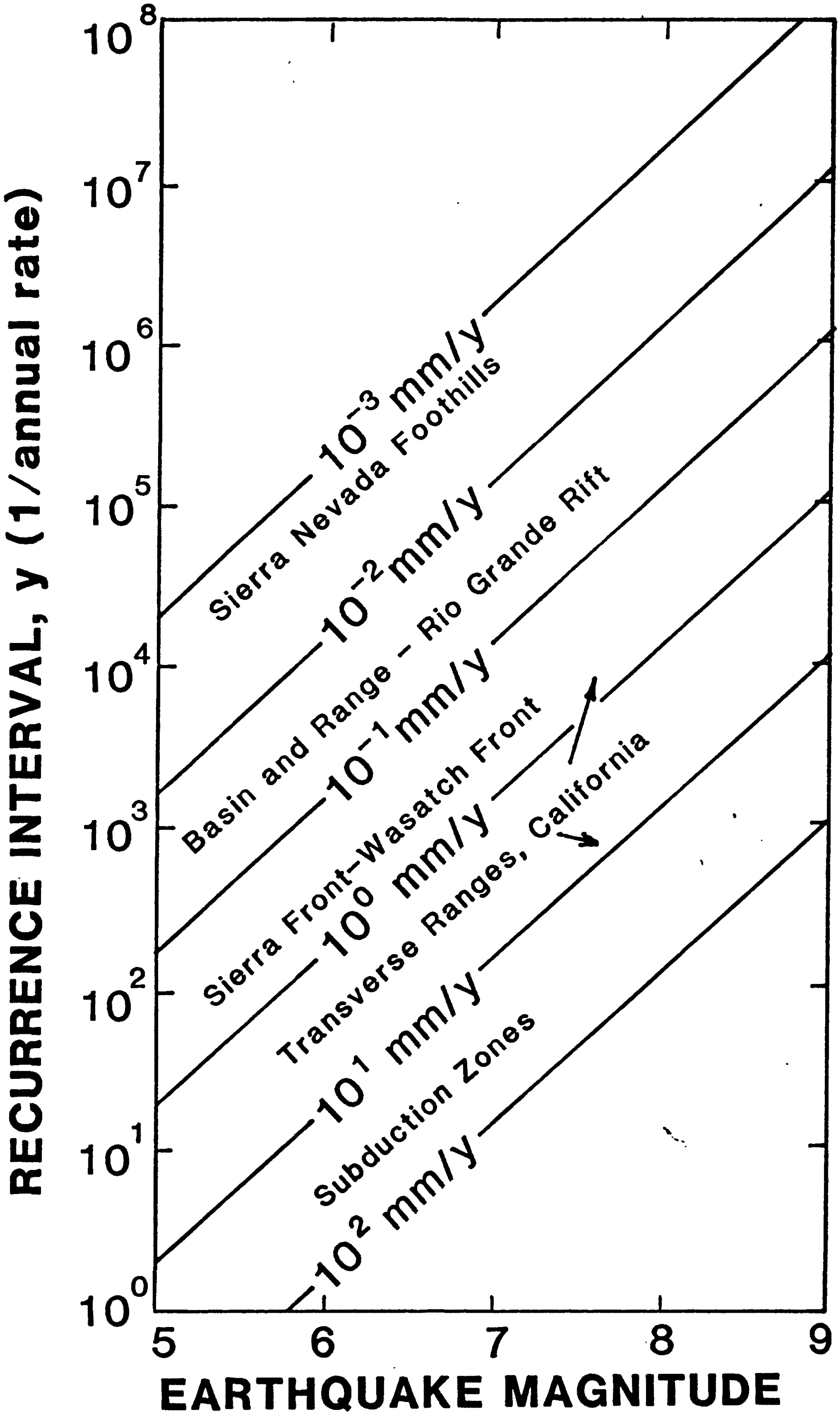
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
RECURRENCE INTERVAL, y (1/annual rate)
5
6
7
8
9
EARTHQUAKE MAGNITUDE
10^-3 mm/y
Sierra Nevada Foothills
10^-2 mm/y
Basin and Range - Rio Grande Rift
10^-1 mm/y
Sierra Front-Wasatch Front
10^0 mm/y
Transverse Ranges, California
10^1 mm/y
Subduction Zones
10^2 mm/y

Fig. 2


COLUMBIA
PLATEAU
BASIN
AND
RANGE
COLORADO
PLATEAU
COLORADO
SOUTHERN
GREAT PLAINS
CENTRAL
INTERIOR
NORTHERN
MISSISSIPPI
EMBAYMENT
GULF
COAST
ATLANTIC
COAST
1
2
3
4
5
6
7
8
9
10
11
12
13