$$\mathfrak{R} = \frac{E(hk)^4}{12(1 - \nu^2)\rho g h}$$

gives the rigidity of the ice, $\mathfrak{R}$. Values for the elastic modulus of ice, E, and Poisson's ratio, ν, are 9.2×10^9 Pa and 0.365, respectively [M. Ewing, A. P. Crary, A. M. Thorne, Jr., *Physics (N.Y.)* **5**, 165 (1934)]. For ice 1 m thick, $\mathfrak{R} \approx (hk)^4 \times 10^5$, so rigidity of the ice is negligible at wavelengths of several hundred meters ($hk < 10^{-2}$). Differential pressure is then negligible compared to hydrostatic pressure from surface displacement.

19. The expression (*21*) $\omega^2/gk = (\delta\rho/\rho)(1 - e^{-2kd})/2$ gives the dispersion of waves at frequency ω and wave number k propagating on a sharp pycnocline at depth d with a density contrast $\delta\rho$.
20. One must use coordinates fixed to isopycnal surfaces in the integration of u_z [R. Pinkel, J. A. Smith, J. T. Sherman, S. A. Anderson, *J. Phys. Oceanogr.* **21**, 527 (1991)]. The ADCP, with a vertical binning of 4 m, allowed us to approximate the coordinates by using the value of u_z at the current value of depth in the running integral.
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24. For flexural waves in a thin plate ($hk \ll 1$), surface tilt is given by the expression [(*26*), p. 277] $\mathbf{d}_h = -(h/2)\boldsymbol{\tau}$, where $\mathbf{d}_h$ is horizontal displacement at the surface.
25. Strains from nondeviatoric compression dominated strainmeter records at internal wave frequencies and had amplitudes of many times 10^{-7}. They arose from ice deformation driven over large spatial scales and usually obscured the local signal from internal waves. Only two of the nine strainmeter axes revealed the energetic internal wave packet. The measurements showed that the packet locally forced bending instead of nondeviatoric compression, contrary to earlier speculation [T. O. Manley *et al.*, *Eos* **63**, 627 (1982)].
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27. Our coordinate convention defines a right-handed system with the x-axis positive northward, the y-axis positive westward, and the z-axis positive upward. We define tilt as the positive gradient of vertical displacement and strain as positive for extension.
28. The phase shift relates horizontal velocity to tilt at the same location. Horizontal velocity was actually measured 337 m south of the tiltmeter. Using the wave speed and propagation direction, we shifted the time coordinate of horizontal velocity to represent velocity at the tiltmeter.

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Sudden Extinction of the Dinosaurs: Latest Cretaceous, Upper Great Plains, U.S.A.

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Results of a three-year field study of family-level patterns of ecological diversity of dinosaurs in the Hell Creek Formation of Montana and North Dakota show no evidence (probability $P < 0.05$) of a gradual decline of dinosaurs at the end of the Cretaceous. Stratigraphic reliability was maintained through a tripartite division of the Hell Creek, and preservational biases were corrected for by comparison of results only from similar facies as well as through the use of large-scale, statistically rigorous survey and collection procedures. The findings are in agreement with an abrupt extinction event such as one caused by an asteroid impact.

THE CAUSE OF EXTINCTION OF DINOSAUR faunas at the end of the Mesozoic era remains controversial. Two principal endmember hypotheses have been developed. One is that dinosaur populations dwindled gradually at the end of the Cretaceous, probably as a result of climatic changes (*1–3*). The other is that an asteroid impact produced sudden environmental changes that caused an abrupt extinction (*4, 5*). Resolution of the mechanism responsible for the extinction requires knowledge of changes in dinosaur populations immediately before and at the end of the Cretaceous. Earlier field studies, however, were not designed to examine patterns of dinosaur diversity during this interval in a statistically meaningful fashion (*6*). We therefore undertook a 3-year study in which dinosaur fossils were sampled through the Hell Creek Formation, a unit that represents the last 2 to 3 million years of the Cretaceous Period (7) in the upper Great Plains of the United States (Fig. 1). Patterns of family-level dinosaur ecological diversity are used to assess the general robustness of dinosaur populations.

Several considerations hinder analysis of the extinction in the Hell Creek. The Hell Creek has complex, laterally discontinuous facies that make biostratigraphic distributions difficult to determine. Fossils are found in interfingering channel and floodplain deposits that reflect the repeated erosion of floodplains by ancient meandering streams. Superimposed soils were formed during potentially long intervals of nondeposition. Correlation of beds across tens of meters is often impossible because of such complexity (*8, 9*). For example, a stream meandering over a floodplain can erode a broad channel that is later filled by much younger deposits. As a result, sediments at approximately the same topographic level can be of quite different ages because of channel erosion and infilling by younger sediments. Moreover, equivalent thicknesses of floodplain and channel sediments cannot easily be compared, because the former took orders of magnitude more time to be deposited than the latter (*7–10*).

Detailed correlations are tenuous beyond a limited area, even though broad areas must be searched to find significant numbers of fossils. To overcome the problems of the lateral nonpersistence of strata and differing sedimentation rates, we divided the Hell Creek Formation into three approximately equal, successive intervals, against which dinosaur ecological diversity could be measured. The top of the upper stratigraphic interval was the boundary clay (commonly associated with coal) containing the iridium anomaly (*11*). No dinosaur bones were found above this layer, and the closest dinosaur specimen was found 60 cm below it. The lower stratigraphic boundary was established at the lithostratigraphic contact between the terrestrial Hell Creek and underlying, marginal-marine Fox Hills Sandstone, which contains no dinosaurs. Because the upper boundary is approximately isochronous and the Hell Creek Formation is 70 to 90 m thick in all of the study areas, it is reasonable to infer that crude correlations can be made between equivalent, measured

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thirds in geographically distinct areas. The thirds are not precisely contemporaneous; however, multiple exposures of all facies are contained within each interval, and sequential time is represented by the three successive Hell Creek subdivisions.

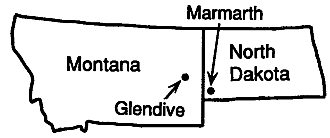

Fig. 1. Index map of study areas. Region south of Marmarth, North Dakota, surveyed during 1987 field season; region east of Glendive, Montana, surveyed during 1988 and 1990 field seasons. Locality data on file in the Department of Geology, Milwaukee Public Museum.

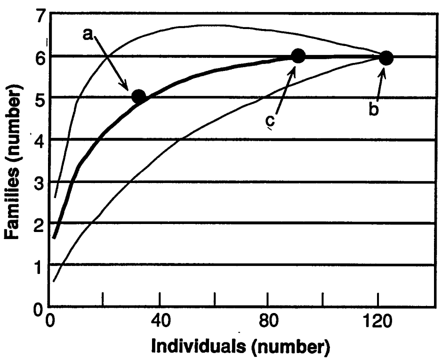

Fig. 2. Rarefaction curve (heavy line) for all families identified in both facies A and B from the middle third of the formation from Montana and North Dakota (a, lower interval; b, middle interval; and c, upper interval). The 95% confidence interval is enclosed by thin lines. The positions of the lower third and upper third lie within the confidence interval.

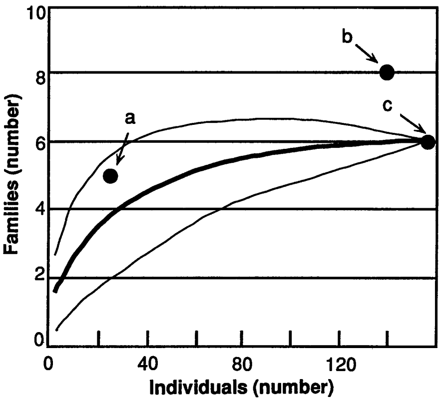

Fig. 3. Rarefaction curve (heavy line) for all families identified in facies C from the upper third of the formation from Montana and North Dakota (notation as in Fig. 2). The 95% confidence interval is enclosed by thin lines. The position of the middle third lies above the confidence interval of the rarefaction curve for the upper third, but that of the lower third lies within the confidence interval.

Preservation of fossils in Hell Creek sedimentary rocks is strongly controlled by the depositional processes that produced the different facies. For example, dinosaur bones found in a stream channel deposit constitute a death assemblage likely derived from many different upstream habitats. Floodplain sediments, by contrast, commonly preserve the remains of individuals that died in the immediate vicinity. For this reason, patterns of diversity are reliable only if identical facies are compared through time (*9*).

An essential component of the study was, therefore, the recognition and interpretation of facies in the Hell Creek. Nine facies were recognized (Table 1); however, fossil collections of statistically significant size were obtained from only three facies: A (thalweg deposits), B (point bar deposits), and C (floodplain deposits). Data from facies A and facies B were also analyzed together, because these two facies are functionally parts of a coherent depositional system (the stream channel). Collections from each of the facies (and the combination A + B) were then compared through time to assess whether dinosaur populations in the ecosystem were remaining stable (see below).

Taphonomic studies have demonstrated that in modern fluvial terrestrial systems the preservation of large bones is favored over small ones (*12*). Regardless of whether this has occurred in the Hell Creek, the degree that preservation may have modified in vivo ecological diversity was probably constant throughout the Hell Creek because fluvial environments and diagenesis were relatively stable through the thickness of the Hell Creek Formation (*13*). Therefore, the dinosaur ecological diversity assessed here, while not precisely that of the late Cretaceous, is a proxy for it and should reflect a pattern of stasis or change similar to that undergone by the actual dinosaur populations.

This study required large numbers of fossils; however, the differing methods and goals of previous collectors made the use of existing museum collections inappropriate. Commonly, dinosaur specimens have been collected because they are either rare or of high quality, hardly criteria for the recognition of patterns of diversity. In this study, large-scale, standardized survey procedures were implemented so that the resulting database would be as precise a reflection of preservational diversity as could be achieved. The goal was to conduct a census of dinosaur remains, not augment collections; most material was observed and recorded but not collected.

To implement comprehensive unbiased survey procedures, we co-opted the long-standing volunteer-based "Dig-a-Dinosaur" program of the Milwaukee Public Museum (*14*). Sixteen to 25 carefully trained and closely supervised volunteers and 10 to 12 staff members were present during each of seven 2-week field sessions during three summers. The primary objective of each volunteer was to search a predetermined area for all bone visible on the surface. The volunteers were arrayed in "search party" fashion across exposures so that all outcrops were surveyed systematically. Associated with the field parties were geologists whose function was to measure stratigraphic sections and identify facies.

After making a discovery in the field, volunteers flagged the fossil site. A judgment was then reached, upon inspection by project personnel, as to whether or not the fossil was in place. If the fossil was out of place (for example, washed down a hillside or resting in a gulley), it was rejected from the database of this study. As many as half of the fossils discovered were rejected for this reason. If the fossil was in place, information about the specimen was recorded on computer-coding sheets. Relevant data recorded included location on a topographic map, identification of skeletal elements and taxon, stratigraphic level, and facies type. Data were entered into a computer at camp (*15*). A total of 15,000 hours of fieldwork was logged.

An important component for the objectivity of this study was that fossil areas surveyed had not been collected recently, because collection would bias the relative proportions of faunal components in the preservational assemblage. On the basis of interviews with private landowners, government officials, and scientists, it was possible to identify and avoid those areas where intensive collecting had occurred. The areas selected had not been heavily collected within the past 10 years; long enough, because of active erosion, to ensure an accurate sampling of the preservational assemblage. The regions were located south of Marmarth, North Dakota (year 1), and south of Glendive, Montana (years 2 and 3; Fig. 1).

For analysis we used the minimum number of individuals, identified at family level (Table 2), that could have been present in a particular locality. Two individuals of a taxon were recorded at a site only if unique, replicate skeletal elements were identified (for example, two left maxillae). Familial identifications were used because family level is the lowest taxonomic rank at which a statistically meaningful database could be generated (*16*).

All of the eight families recorded in this study range into the upper third of the Hell Creek Formation (*6*). Therefore, simple taxonomic diversity at the family level did not change. This study assesses ecological diver-

Table 1. Facies and interpreted fluvial subenvironments used during the course of this study. Descriptions are abbreviated facies, and interpretations are done as in (*8*).

Facies	Description	Interpretation
A	Medium-grained, cross-stratified sandstone	Stream channel thalweg deposit
B	Inclined heterolithic strata in medium- to fine-grained sandstone	Point bar deposit
C	Purple- and green-banded rooted mudstone	Floodplain paleosol
D	Non-coalified organic accumulation	Floodplain peaty accumulation
E	Planar-laminated siltstone and mudstone	Floodplain pond deposit
F	Fine-grained, cross-stratified sandstone interbedded with rooted mudstone	Upper point bar deposit
G	Inclined heterolithic strata in medium-grained, cross-stratified sandstone	Toe-of-point bar deposit
H	Fine-grained, cross-stratified sandstone	Crevasse splay deposit
I	Coal	Peat swamp deposit

Table 2. Families of dinosaurs recognized. Number of genera identified in each family is in parentheses.

Ceratopsidae (2)
Hadrosauridae (2)
Hypsilophodontidae (1)
Pachycephalosauridae (2)
Tyrannosauridae (3)
Ornithomimidae (1)
Saurornithoididae (1)
Dromaeosauridae (2)

sity (rather than taxonomic diversity) of dinosaurs because ecological diversity measures changing abundances of taxa rather than just presence or absence. The method can reveal stasis or change in the patterns, because the taxonomy of this study is consistent in each of the three units of the Hell Creek and because the taxa used are monophyletic (*17, 18*).

Two commonly used, statistically testable indices of ecological diversity—the Shannon Index (*19*) and rarefaction (*20*)—were applied to the data. Each index measures the proportional abundances of individuals in the taxa (in this case, families) that are being compared. Tests were then performed to determine if the indices differed significantly. A decrease in ecologic diversity would occur, for example, if one or more families declined in relative abundance, even if they did not become extinct (*21*). For each facies A, B, and C, the goal was to test the null hypothesis that ecological diversity was not declining from the lower to the middle to the upper intervals of the Hell Creek Formation (*22*).

The Shannon Index values are presented in Table 3, and the rarefaction data are in Figs. 2 and 3. A one-way analysis of variance with the Waller-Duncan multiple comparisons adjustment was used to compare Shannon Indices for different stratigraphic intervals between Montana and North Dakota. Both the Shannon Index and the rarefaction curves indicate that there was no significant change in ecological diversity among the lower, middle, and upper thirds of the Hell Creek Formation in facies A and B or the combination A + B. This result is true for data from the separate regions in North Dakota and Montana, as well as for the combined regions.

Ecological diversity patterns of dinosaurs from facies C are more complex. When the data from Montana and North Dakota are combined, the Shannon Index from the middle interval (Table 3) is significantly greater than that from the upper interval ($P < 0.001$), and the middle interval falls outside the confidence interval of the rarefaction curve for the upper interval (Fig. 3). When the analysis was carried out for the separate regions, the Shannon Index for the middle interval in Montana was also significantly greater than that from the upper interval ($P < 0.02$). In North Dakota, however, the ecological diversity in the upper and middle intervals cannot be distinguished, although, because of the small sample size of the middle interval, the standard error is large. In North Dakota the lower part of the formation had only two sites, and the sample size is too small for evaluation. In Montana, as well as in the data for the combined regions, the Shannon Index for the lower interval (Table 3) cannot be distinguished from the index for either the middle or upper intervals, but it is closest to the value of the upper interval. No progressive decline in diversity is observed in facies C.

Facies A, B, and A + B have extremely close indices of ecological diversity. Because there is no significant change between the

Table 3. Shannon Indices for facies A, B, A + B, and C. Data are presented for the lower, middle, and upper thirds of the Hell Creek Formation for the two regions studied in North Dakota (ND) and Montana (MT) and for the combined areas (ND + MT). We calculated the Shannon Index ($-H'$) using base 10. SE = standard error; *n* = minimum number of individuals; *P*-values computed from one-way analysis of variance.

Stratigraphic interval	Facies A			Facies B			Facies A + B			Facies C		
	ND	MT	ND + MT	ND	MT	ND + MT	ND	MT	ND + MT	ND	MT	ND + MT
						Upper						
n	19	42	61	25	4	29	44	46	90	108	49	157
Shannon ($-H'$)	1.028	1.075	1.115	1.015	0.693	1.020	1.134	1.055	1.107	0.788	0.987	0.884
SE	0.233	0.160	0.135	0.201	0.416	0.188	0.161	0.151	0.111	0.085	0.142	0.075
						Middle						
n	9	67	76	12	35	47	21	102	123	27	103	130
Shannon ($-H'$)	0.637	1.097	1.060	1.44	1.336	1.364	0.996	1.225	1.210	0.920	1.393	1.323
SE	0.266	0.128	0.118	0.309	0.195	0.170	0.218	0.110	0.099	0.185	0.116	0.101
						Lower						
n	1	19	20	8	4	12	9	23	32	2	22	24
Shannon ($-H'$)		1.016	0.984	1.321	0.693	1.237	1.273	1.020	1.145		1.046	1.038
SE		0.231	0.222	0.406	0.416	0.321	0.376	0.211	0.189		0.218	0.208
P	0.98	0.95	0.88	0.41	0.35	0.42	0.79	0.55	0.78	0.50	0.08	0.002

lower, middle, and upper thirds of the formation, we reject the hypothesis that the dinosaurian part of the ecosystem was deteriorating during the latest Cretaceous. These findings are consistent with an abrupt extinction scenario.

Data from facies C are equivocal but seem to indicate increased diversity of the middle interval relative to the lower and upper. This pattern may be an artifact of preservation and sampling in facies C. Fossils found in ancient stream channels (facies A, B, and A + B) were derived from diverse environments upstream. On the other hand, fossils from the floodplain (facies C) more likely represent only the local or proximal community. In most communities, animals are not equally distributed across landscapes, and samples of local populations within a community can vary greatly (*23*). The diversity pattern found in the floodplain sediments may reflect the effects of local populations that differ slightly in composition. A much larger floodplain sample would be needed to resolve this issue. Regardless, the pattern of relatively increasing and then decreasing ecological diversity from bottom to top of the formation does not fit predictions of a gradual dinosaur extinction.

The results indicate that there is no statistically meaningful drop in the ecological diversity of dinosaurs through the Hell Creek Formation. These findings are consistent with other recent research on Cretaceous-Tertiary boundary events (*24*). Although Hell Creek dinosaurs have long been invoked as documenting a gradual extinction [that is, (*1–3*)], our data from the Hell Creek are compatible with abrupt extinction scenarios.

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16. Use of fossils identified at the generic level would actually bias the database. Among the ceratopsians, for example, the genera *Triceratops* and *Torosaurus* are difficult to distinguish. Many postcranial elements of *Torosaurus* have never been found and are hence unknown, and many cranial elements of the two genera are similar. As a result, when one of these skeletal elements is found, it cannot be assigned to either genus. To confidently assign these problematic elements to the Ceratopsidae, however, is relatively easy. Analysis at the generic level could be misleading, because so many ceratopsian fossils would be excluded that the importance of ceratopsians, the most abundant group and the dominant large herbivore in the communities, would be greatly underestimated.
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21. Assigning individuals to families rather than to genera could mask a gradual extinction event if the relative decline of one genus in a family were exactly made up for by a corresponding increase in abundance of another genus in the same family. This scenario is unlikely, however, because our data reveal no obvious replacement of one genus by another in any family [within the limits of our ability to identify at the generic level; see (*16*)].
22. The analysis used in our study can detect a gradual reduction in dinosaurian ecological diversity through the upper third of the formation as well as a gradual reduction in dinosaurian ecological diversity throughout the entire formation. Because the localities used in our study are not concentrated in any part of the upper interval, if ecological diversity of dinosaurs declined gradually through only the upper third of the formation (say, from an average level at the beginning of the interval to near extinction at the end of the interval), this pattern would be detected as a low average value for the entire upper interval when compared with the lower and middle intervals. Gradual decline could go undetected if it occurred in only the uppermost part of the upper interval, but such a decline (over ±250,000 years) is incompatible with gradualistic theories.
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Structural Control of Flank Volcanism in Continental Rifts

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Many volcanoes emerge from the flank (footwall) of normal faults in continental rift zones. Because such locations are commonly topographically high and exhibit minor compressional structures, the association is enigmatic. A simple flexing plate model shows that deformation of a flexurally supported upper crust during normal faulting generates a dilational strain field in the footwall at the base of the crust. This strain field allows cracking and tapping of preexisting melt.

A COMMON OBSERVATION IN REGIONS of continental extension is the occurrence of flank volcanism, in which volcanism and associated shallow level intrusions are found in the footwalls of normal faults. The association is temporal as well as spatial. Volcanism is generally active as long as the fault is active, and, as fault activity migrates, so too does volcanism. These observations suggest that there is a coupling between processes of brittle deformation in the upper crust and those involving magma injection in the lower crust.

We explain this association with the use of a numerical model (*1*) in which the upper crust is modeled as an elastic beam with a reduced effective elastic thickness, and the lower crust behaves as a fluid. Deformation is driven entirely by gravity and includes the modifying effects of erosion and sedimentation.

The temporal and spatial association between normal faulting and volcanism is most evident in regions where crustal extension is active and in its early stages. For example, in the Taupo rift of North Island, New Zealand, two volcanoes, Mount Tarawera and Mount Edgecumbe, are on the footwall side of the major Edgecumbe-Onepu fault and outside the zone of active rifting (Fig. 1A). The fault last moved in the 1987 Edgecumbe magnitude $M_s \approx 6.3$ earthquake, and it offsets basement by ~1 km (*2*). In the 1987 fault scarp, Holocene soils are interlayered with volcanic ash derived from Mount Tarawera. Moreover, the Taupo eruptive event of ~A.D. 150, considered to be the largest volcanic eruption of the last 7000 years (*3*), appears to have occurred immediately to the southeast (in the footwall) of the main rift-bounding faults.

In the Rungwe volcanic field (Fig. 1B), part of the western arm of the East African rift system (*4*), the oldest source of volcanism associated with the rifting is late Miocene [~7 million years old (Ma)] and is sited on the flank of the rift-bounding Livingstone faults (*4*). Active rifting has migrated toward the axial zone, where a series of Pliocene and Quaternary volcanoes sit in the footwall of the active Mbaka fault system, the most prominent fault system in the axial zone. Extensive volcanism also occurred on the flanks of the Gregory rift [for example, the Kapiti volcanic rocks along the tilted Aberdare Range and basalts along the Nguruman escarpment (*5*)]. Farther north, in the Ethiopian rift, the Gorfu, Entotto, and Gara Mariam centers are further examples of flank volcanism (*6*). In general, volcanic activity throughout the eastern rift follows that of faulting (*5, 6*).

Another example comes from the active Long Valley magmatic complex (Fig. 1C). Present seismic activity under Mammoth Mountain (Figs. 1C and 2D) is confined to a well-defined dike-like shape below about 6 km; above this level, events spread laterally (*7*). Seismic swarms are typical in this region and are generally attributed to the development of a dike (*8*). Mammoth Mountain lies in the footwall of the active Sierra Nevada range-bounding normal fault (*9*), although this relation is partly obscured by the 700,000-year-old caldera rim.

In 1980, a series of moderate earthquakes occurred in the footwall of the active Hilton Creek fault (Figs. 1C and 3) that were characterized by significant non–double-couple focal mechanisms (*10*). Julian (*11*) suggested that these earthquakes were associated with active magmatic intrusion. During the early part of 1990, the resurgent dome within the caldera was extending at a rate five times that of normal (*12*), presumably from the motion and intrusion of magmatic material at depth. Both the resurgent dome and the initial vent for the Plinian deposit of the 700,000-year-old Bishop tuff are in the footwall of the Hilton Creek fault (*13*) (Fig. 1C). We suggest that the volcanic processes and associated seismicity within the Long Valley caldera complex are connected to the evolution of the main Sierra Nevada (Hilton Creek) range-front fault system.

There are many other examples from virtually every rift system in the world. These systems include the Latir volcanic field and the Spanish Peaks complex, which represent the early stage of extension in the Rio Grande rift, United States (*14*); early volcanism along the flanks of the Baikal rift, Soviet Union (*15*); early volcanism along the eastern margin of the Red Sea (*16*); basaltic magmatism along the eastern edge of the Basin and Range province, particularly the St. George field in southwest Utah, which lies in the footwall of the active Hurricane normal fault (*17*); middle Miocene and Pliocene volcanism in the Death Valley region, California (*1, 18*); Mount Etna, Sicily, which has an unusual location on the nonvolcanic side of an island arc (*19*) that may be explained by its position in the footwall of the active Messina normal fault; the Quaternary volcanic Chaine des Puys, which is related to Quaternary normal faulting near Clermont Ferrand that has reactivated structures associated with the Oligocene Limagne graben (*20*); and the large volcanic complexes of Mount Kilimanjaro, Mount Kenya, and Mount Elgon along the Gregory rift, East Africa (*5*).

The approach to modeling these structures follows from that used by King and Ellis (*1*). In the model the x_1 axis is vertical and positive downwards, and the x_3 axis is horizontal. Two horizontal gravitating interfaces are defined. One represents the earth's surface, and the second represents the base of the brittle layer. At $x_3 = -60$ km, the horizontal displacement along a vertical

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