The Earth Has a Future

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ABSTRACT

An alternative to visualizing geologic time by looking into the past is to look into the future. Even geologically short future time scales completely outstrip our ability to forecast changes in human society, whereas most geologic changes in the same time will be modest. Many events that are infrequent on a human time scale, such as earthquakes and volcanic eruptions, become commonplace on longer time scales, and events that have not occurred in recorded history, such as major ice ages, large meteor impacts, giant pyroclastic eruptions, or collapses of Hawaiian shield volcanoes, become almost inevitable in a million years.

Keywords: geologic time, process rates, geomorphology, tectonics, environmental geology.

INTRODUCTION

The Earth Has a History is a video produced by The Geological Society of America (Palmer, 1991) to acquaint nongeologists with the concepts of geologic or "deep" time. A less conventional way to visualize geologic time is to peer into the future. Even short geologic time scales outrun our ability to project human history, whereas many geologic processes will have barely begun to produce visible changes. Events that are rare or unknown in recorded history become almost inevitable, even frequent, in the near geologic future. This paper will explore the likely future of Earth on geologically short time scales ranging from 1000 yr to 1 m.y. The intent of this paper is to illustrate geologic time by peering into the future, not to make rigorous predictions or speculate about human history. My emphasis will be on changes in selected systems that are statistically or cyclically predictable, and there will be no attempt to speculate about unknown or unpredictable processes like changes in plate motion, nor any attempt to cover all possible changes. At each time scale I will examine selected geomorphic processes, seismicity, volcanism, plate tectonics, astronomical changes, and human effects. Most processes or events are discussed only at the time scales most appropriate to their rates or frequencies. For brevity and clarity, once sources have been cited for one time scale, they will not be cited for similar extrapolations at longer scales. Given the range of processes considered, an exhaustive bibliography is impractical, and only representative references are cited.

A futurist approach can serve to correct some common misconceptions. One common, frequently unconscious misconception is that history is linear, progressing toward an inevitable end point. We can fail to realize that geologic features are a snapshot of processes that were highly dynamic and changeable. Our inability to see ourselves as part of a continuum of processes that will continue into the future is also directly linked to our shortsightedness in managing our environment. Another misconception is that all geologic changes are slow and imperceptible, whereas many observable changes take place even on the scale of a human lifetime, and even more significant changes have occurred during the span of recorded history.

There are practical applications for long-term geological prediction. Most geohazard projections need to forecast only a few decades or centuries into the future, but geological storage of high-level nuclear waste requires estimates of geological stability on scales ranging up to a million years (Sun, 2001).

A million years is relatively short in geologic terms. For example, even the fastest plates, moving on the order of 15 cm/yr, will have moved only 150 km in a million years, enough to have very significant local geological effects but scarcely enough to be casually noticeable on a globe. It is unlikely that erosion will have greatly lowered any of Earth's major mountain ranges in that time. Given the relatively short spans covered, we can reasonably extrapolate many geologic process rates. On the other hand, the uncertainty of measurement, the range of rates observed for processes, the inherent variability of rates even within a single system, and the likely influence of unpredictable perturbations give us no justification for attempting more than one significant digit of precision, and in many cases no more than an order of magnitude.

In most cases it does not make statistical sense to attach error bars or confidence intervals to these estimates. For example, Graymer et al. (2002) estimated 175 ± 10 km of offset along the East Bay (Hayward-Calaveras) fault systems, but that error estimate is based on possible alignment errors in the rock units being correlated, not on statistical analysis. The age of the rock unit is given as 11–13 Ma with no error estimate. Combining the two pieces of data, we can estimate an average slip rate of 13–17 mm/yr, but the authors note that both overall rates of movement and slip along individual faults are highly variable in time, with long periods of quiescence alternating with periods of rapid slip. Clearly, only a qualitative description of rates is justified for this fault system, and the same is true of virtually all the other processes described in this paper.

The Human Factor

Human impacts already equal or surpass many natural processes. For example, human earth-moving processes exceed natural erosion in the volume of material moved (Hooke, 2000; Wilkinson, 2005). Some authors argue that humans are now creating a mass extinction to rival anything in the geologic record (Leakey and Lewin, 1996), and we are using many resources faster than they are created geologically. Global heat flow, ~4.4×10^{13} W or 1.4×10^{21} J/yr (Pollack et al., 1993), is only about a factor of 3.5 greater than human energy use (~4×10^{20} J/yr; U.S. Department of Energy, 2004). Attempting to forecast human activities on scales up to a million years is the height of speculation, but some discussion of the range of possible impacts is in order. We can consider three broad scenarios for future human environmental impact.

Low impact. Human impact is below present levels. Humans may reform their most destructive practices and remain within the limits of environmental sustainability. Less appealing scenarios are that humans may become extinct,

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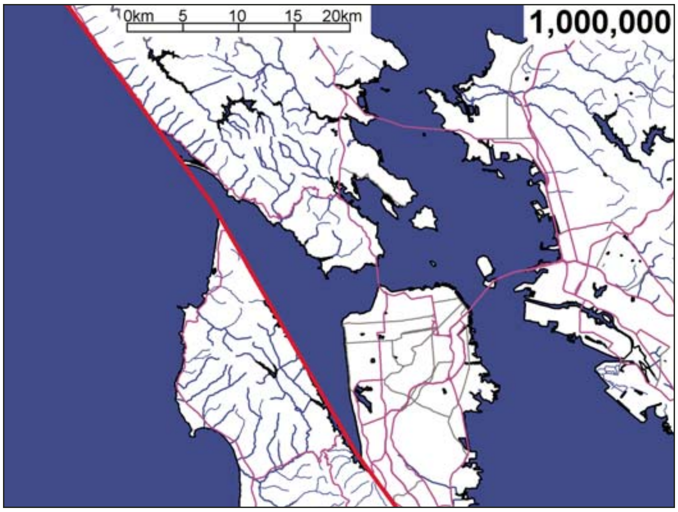
or technological civilization may collapse through war or natural disaster (such as a large meteor impact). The longest time scales considered here might allow several cycles of collapse and recovery. Human activities might also be spatially and temporally variable enough for affected areas to recover naturally. Even within recorded history, major settlements have been so thoroughly forgotten, overgrown, and buried that only detailed excavation has brought them to light. At the other technological extreme, technology might become so advanced that humans will no longer need to modify the natural environment extensively. For example, we might derive our energy and mineral resources from space rather than from Earth's surface.

***Medium impact*.** Human impact continues at a pace comparable to or somewhat greater than present. Perhaps science and technology will reach a plateau at a level not far beyond the present, or occasional reversals might cause technology to collapse or stagnate long enough for natural processes to keep pace with human activity on millennium and longer time scales.

***High impact*.** In this scenario, the hardest to predict, human activity and technological capability continue to grow toward some unforeseeable level. Low and medium impact can be predicted by estimating future natural geological changes with some component of present human effects superimposed, but it is impossible to predict what forms extremely advanced technology might assume, or what motivations and values humans with those powers might have. A million years might be time for the human species itself to evolve significantly. Highly advanced humans might have no need to disturb the natural environment, or they may modify it beyond recognition.

Any attempt to predict technology far in advance is bound to be almost pure speculation, so this paper will focus mostly on low and medium impact scenarios. The emphasis of this paper, after all, is to visualize geologic time by projecting what geologic processes are likely to do at their average rates, not an attempt to predict future human history. Even where humans are significantly modifying natural geological processes (for example, preventing the diversion of the Mississippi River), it is questionable whether those changes will last for geologically significant times. For example, even if New Orleans still exists in 1000 yr, will there still be an economic need to maintain the present course of the Mississippi? Also, even if humans still have a reason to control the course of the Mississippi 1000 yr hence, the likelihood of a flood capable of overwhelming any control measures is quite high over such a long span (as was shown by Hurricane Katrina, which struck as this paper was being revised). Humans may not be able to prevent the diversion of the Mississippi on a long time scale even if they want to.



Animation 1. Motion of the San Andreas Fault near San Francisco for the next million years, shown on progressively longer time scales and larger areal scales. The inclusion of cultural features is solely to illustrate the scale and rate of fault motion, and does not imply any predictions of future seismic hazard. Seismic risk is large throughout the entire figure area. Few if any of the cultural features shown are likely to be extant in their present form even 1000 yr from now, let alone longer time scales. A slip of 2.5 cm/yr on the San Andreas proper is assumed, based on the overall rate of ~4 cm/yr of total Pacific–North American plate motion found by Argus and Gordon (2001), and the roughly 1.5 cm/yr long-term average of slip for other Bay Area faults estimated by Graymer et al. (2002). If you are viewing the PDF, or if you are reading this offline, please visit www.gsajournals.org or http://dx.doi.org/10.1130/GES00012.S1 to view the animation.

IMPACT OF FUTURE CHANGES

One Thousand Years

Tectonic and Volcanic Processes

Paleoseismic studies have shown an average recurrence interval of 150–200 yr for **M** = 8 earthquakes on the most active segments of the San Andreas Fault (Grant and Lettis, 2002). We can therefore expect about five to seven such events in the next thousand years, with total fault motion (at an average 2.5 cm/yr) of ~25 m (Animation 1; Table 1).

TABLE 1. RECURRENCE INTERVALS FOR MAJOR FAULT RUPTURES ON THE SAN ANDREAS FAULT SYSTEM

Locality	Recurrence interval (yr)	Source
Cajon Pass	150–200	Weldon and Sieh, 1985
Wrightwood (San Gabriel Mtns.)	44	Jacoby et al., 1988
Northern California	221 ± 40	Niemi and Hall, 1992
Wrightwood (San Gabriel Mtns.)	45–130 (average 100)	Fumal et al., 1993
Carrizo Plain	73–116	Grant and Sieh, 1994
Santa Cruz Mountains	>340	Schwartz et al., 1998

Note: Actual intervals range from 44 to >300 yr, but the average of 150 yr used in this paper is justified by these data. If anything, a shorter recurrence interval is indicated.

Odds are strong that there will be at least one repeat of the 1811–1812 New Madrid events (Tuttle et al., 2002) and several major earthquakes along the Cascadia margin (Witter et al., 2003). Globally, we can expect 50 or so **M** = 9 earthquakes in that time, based on the list by Abe (1995).

The Holocene volcanic record of Simkin and Siebert (1994) lists ~80 eruptions of Vesuvius in the past 2000 yr, suggesting that we can expect ~40 in the next thousand years, and very likely an eruption in the Campi Flegrei volcanic field west of Naples as well (Table 2). Fuji is likely to erupt ~5–10 times, and there will probably be a dozen or so eruptions in the Cascade chain as well. On the basis of Holocene frequency, there could well be a couple of new cinder cone eruptions in western North America in the next thousand years, and perhaps an eruption in the Chaine des Puys or Eifel volcanic fields of Europe.

Hawaii will have moved ~90 m northwest (Clague and Dalrymple, 1987; Gordon, 1995). If it continues to erupt at its recent historic rate, we could expect ~200 eruptions of Mauna Loa in the next 1000 yr (Lockwood et al., 1987; Lockwood and Lipman, 1987). Spread over the ~5000 km^2 of Mauna Loa's subaerial extent, 1000 yr of activity at present rates would build the volcano ~5 m higher. We could expect somewhat more increase in the elevation of Kilauea. Given its known recent history (Holcomb, 1987), there could be one or more cycles of caldera filling and collapse on Kilauea in 1000 yr. A few Tambora-class eruptions with global climatic effects (Rampino et al., 1988) are likely in 1000 yr.

Even a casual visit to Yellowstone National Park shows it to be a dynamic place with constantly changing hydrothermal activity. Geysers are delicately poised systems that can cease activity though self-sealing, excessive conduit opening, or diversion of water through fractures (White, 1967; Marler and White, 1975). Given the dramatic changes that happen in geysers even on human time scales, there is a very good chance that the Old Faithful Geyser will no longer exist in 1000 yr.

TABLE 2. VOLCANISM OF SELECTED VOLCANOES AND REGIONS (FROM SIMKIN AND SIEBERT, 1994)

Volcano	Country	Events last 1000 yr	Events last 10,000 yr
Rainier	USA	7	18
St. Helens	USA	14	33
All Cascades	USA	50	150
All Western Interior	USA	2	9
All	Canada	4	>10
Popocatepetl	Mexico	>19	No pre–1 ka data
Vesuvius	Italy	83	98
Campi Flegrei	Italy	1(2?)	6
Chaine des Puys	France	1?	15
Eifel	Germany	0	1
Ararat	Turkey	No data	No pre–1 ka data
Demavend	Iran	No data	No pre–1 ka data
El'brus	Georgia	1?	No data
All	Syria	2	4
All	Arabia	1(5?)	9
Kilimanjaro	Tanzania	No data	No pre–1 ka data
Fuji	Japan	6	17
All	Manchuria	3	No pre–1 ka data
All	Tibet	2	No pre–1 ka data
All	Australia	0	3

Note: The table emphasizes well-known volcanoes and areas not normally considered volcanic. The figures for the last 1000 yr often overstate the level of activity, since the catalog lists many small or closely spaced events that are actually parts of a single eruptive episode. The record for 10,000 yr (which includes figures for the last 1000 yr) is certainly incomplete, because historical records are incomplete, and not all early events have been identified from physical evidence such as flows or tephra, or dated. Some clearly volcanic mountains, such as Ararat, Demavend, and Kilimanjaro, have no eruptive record for the last 10,000 yr.

TABLE 3. TYPICAL DENUDATION RATES FROM RECENT STUDIES

Locality	Rate (m/m.y.)	Reference
Northern U.S. Piedmont: residual uplands	0.2	Stanford et al., 2002
Mammoth Cave area, Kentucky	2–7	Granger et al., 2001
Western U.S.	2–19	Small et al., 1997
Northern U.S. Piedmont overall	10	Stanford et al., 2002
Southern Appalachians	27 ± 4	Matmon et al., 2003
Sierra Nevada	9–68, average 39	Riebe et al., 2001
France-Germany	20–100	Schaller et al., 2001
Idaho	20–150; average 60	Kirchner et al., 2001
Himalaya	2100–2900	Galy and France, 2001

TABLE 4. TYPICAL VALLEY INCISION RATES FROM RECENT STUDIES

Locality	Rate m/m.y.	Reference
Mammoth Cave area, Kentucky	30	Granger et al., 2001
Southern Sierra Nevada (Quaternary)	30	Stock et al., 2004
Clearwater River, Washington: mouth	100	Tomkin et al., 2003
San Juan River, Utah	110 ± 14	Wolkowinsky and Granger, 2004
Southern Sierra Nevada (late Pliocene)	200	Stock et al., 2004
Northern U.S. Piedmont: glacially rerouted streams	600	Stanford et al., 2002
Clearwater River, Washington: headwater	900	Tomkin et al., 2003
Nepal, High Himalaya	4000–8000	Lavé and Avouac, 2001
Nepal, Sub-Himalaya	10,000–15,000	Lavé and Avouac, 2001

Geomorphic Processes

Studies of erosion, crustal uplift, and exhumation typically find denudation rates of a few meters per million years in areas of low relief, and tens of meters in areas of moderate relief (Table 3). Valley incision rates can be an order of magnitude greater, commonly limited by the rate of uplift (Table 4). Mountains could not exist unless uplift exceeds erosion, and uplift rates of kilometers per million years in active orogens are not uncommon (Table 5). In 1000 yr, we might expect typical mountainous areas to experience a few centimeters of mass wasting, a few tens of centimeters of valley incision, and possibly meters of uplift in the most active orogens. In some areas, the change might result in visible changes, but in many mountain belts, uplift and erosion may approach a steady state (Bernet et al., 2001) so that little change might be evident to a casual observer.

The Mississippi River is already overdue for a change in course (Table 6), and in fact we now allow it to do so in a controlled manner by diverting floodwaters down the Atchafalaya spillway (Hebert, 1967; Martinez, 1986). In a thousand years the Mississippi will almost certainly have changed course one way or another. In fact, given the postglacial delta growth of the Mississippi (Tornqvist et al., 1996; Roberts and Coleman, 1996; Coleman et al., 1998), it is likely that the Mississippi will have outgrown the Atchafalaya delta and will be poised for yet another diversion. Although the relative importance of natural and human-induced coastal subsidence in Louisiana

TABLE 5. TYPICAL UPLIFT AND EXHUMATION RATES FROM RECENT STUDIES

Locality	Rate (m/m.y.)	Reference
Santa Cruz Mtns., California	130–350	Valensise and Ward, 2001
Central Andes	200–300	Gregory-Wodzicki, 2000
British Columbia (exhumation)	220–370	Farley et al., 2001
Corinth Basin, Greece	300	Collier et al., 1992
Alps (exhumation)	400–700	Bernet et al., 2001
Colombian Andes	600–1000	Gregory-Wodzicki, 2000
Northwest Tibetan Plateau (basin fill rate)	1000	Zheng et al., 2000
Southern Italy	1000 ± 100	Westaway, 1993
Rhine and Rhone Valleys	1400–1600	Schlunegger and Hinderer, 2001
San Bernardino Mtns., California	≥1500	Spotila et al., 1998
Taiwan	5000–7000	Chen and Liu, 2000
Nanga Parbat, Pakistan	7000	Butler et al., 1989
Tibet	7800 ± 7600	Xu et al., 2000
Southern Tibet	16,200 ± 7900	Xu et al., 2000
Alps (peak orogenic exhumation)	16,000–34,000	Rubatto and Hermann, 2001

Note: Uplift and exhumation are not necessarily the same, because exhumation can be offset by erosion. Nevertheless, exhumation sets an upper limit on uplift and may approximate uplift in areas where it greatly exceeds erosion.

TABLE 6. MISSISSIPPI RIVER DELTAS

Delta	Age C-14 years	Duration (yr)
Maringouin/Sale-Cypremont	7500–5000	2500
Teche	5500–3800	1700
St. Bernard	3600–2000	1600
La Fourche	2500–800	1700
Plaquemines	1300–600	700
Balize	1000–0	>1000
Atchafalaya	~100	Incipient

Note: Data from Coleman et al. (1998), Frazier (1967), Roberts and Coleman (1996), Roberts (1997), Stanley et al. (1996), and Tornqvist et al. (1996). Note that ages overlap. The total of at least seven deltas in 7500 yr implies an average interval of <1000 yr between changes in course, but the actual life span of an outlet is longer because the river will empty through two outlets for a time.

is hotly debated (Morton et al., 2002; LaCoast, 2005) it seems obvious that aggradation of new floodplains and construction of new deltas will result in sediment starvation and coastal subsidence in former delta areas.

Animation 2 shows the possible future evolution of the Mississippi delta in schematic form. The map for the present shows known Holocene delta fronts (from Frazier, 1967) as colored arcs. Based on past periodicity of ice advances, Animation 2 assumes that ice advance and sea level lowering will begin 20–30 k.y. in the future, reach maximum ~+80 k.y., and return to interglacial conditions by +100 k.y. Maximum sea level lowering is assumed to be 100 m. The periodicity of delta relocation is taken as 1000 yr until sea level drops substantially; then it is assumed that delta growth will slow as the bottom slope steepens and sediment is more easily transported across the shelf edge. As sea level rises, most old deltas are submerged, eroded, or buried. The +100 k.y. map assumes some net growth of the coastal plain.

The present Niagara River outlet became ice-free at ~12,000 yr ago. Philbrick (1974) noted that recession of Niagara Falls has historically varied between 0.6 m/yr when the falls had a horseshoe shape, and 1.2 m/yr when the lip of the falls was irregular and notched. The recession of 11 km in 12 k.y. yields a long-term average of ~0.9 m/yr. If Niagara Falls continues to retreat at that rate, Niagara Falls will have retreated ~900 m in 1000 yr, almost to the end of Goat Island. When the Canadian Falls clears Goat Island, the American Falls will cease to exist, and there will only be a single falls (Animations 3 and 4). As the falls continues to retreat southward around Grand Island, the height of the falls will decrease, and the rate of retreat will decrease. Thereafter the river will cut a gorge upstream from the falls in the soft Salina Group rocks until resistant rocks are again encountered at Buffalo, where a second "Final Falls" begins to develop. The combination of falls retreat and upper gorge incision makes it impossible to predict the distant future with great precision; Philbrick estimated 30–50 k.y. for the retreat to the Final Falls.

Astronomical Processes

There is a significant chance of a meteor impact, with a rating of 8 or above on the Torino scale (Binzel, 1999; Beatty, 1999; Table 7), causing significant damage or casualties and excavating a crater 100 m or more in diameter.

Many astronomical changes are more rapid than geologic changes. In 1000 yr, Earth's celestial pole will have precessed ~14°. The best north pole star will still be Polaris, but at 6° from the pole, a poor one. The north celestial pole will be ~8° from Gamma Cephei, which will take over as the northern pole star a couple of centuries later. The south celestial pole will still be unmarked by any conspicuous star (as for most of the precessional cycle). Earth's axis tilt is now decreasing at 47.5 arc s per century (Rubincam et al., 1998), and in 1000 yr it will have decreased by ~8 min of arc. The tropics will have moved toward the equator by 14.7 km, and the Arctic and Antarctic Circles toward the poles by an equal amount.

Careful observation will show that some stars have moved noticeably to the unaided eye. Based on HIPPARCOS data (European Space Agency, 1997), the four fastest moving first magnitude stars are Alpha Centauri (3.7 s/yr), Arcturus (2.28 s/yr), Sirius (1.34 s/yr), and Procyon (1.26 s/yr). In 1000 yr, Alpha Centauri will have moved 1.03°, Arcturus 0.63°, Sirius 0.37°, and Procyon 0.35°, all easily discernible to the unaided eye. There should be at least one and possibly more brilliant supernovae in our region of the Milky Way (Bergh and Tammann, 1991).

The Solar System takes ~220 m.y. to orbit the center of the galaxy (Freedman and Kaufmann, 2002, p. 574). At a radius of 26,000 light-years from the center, the Solar System travels a circuit of ~160,000 light-years or roughly one light year in 1350 yr. With respect to nearby stars, the Sun is moving at ~19 km/s in the direction of the constellation Hercules (Fehrenbach et al., 2001). Because we are moving nearly away from Orion, and its stars are bright but fairly distant from Earth, Orion will probably be one of the most enduringly recognizable constellations.

Human Processes

Even a mere 1000 yr in the future challenges our ability to visualize human society; after all, even the television series *Star Trek* was set only a few centuries in the future. But even assuming one or more global nuclear wars, many present-day human settlements should still be extant, and very likely some cultural institutions and political entities. Numerous existing structures from the Pyramids to Mount Rushmore should still be preserved. Steel, the mainstay of our most massive constructions, is prone to corrosion at rates of centimeters per 1000 yr even under favorable conditions (Shackelford et al., 1994, p. 689–690), and anyone familiar with automobiles or old plumbing knows that rates can be orders of magnitude faster under hostile conditions. It is not the overall corrosion of steel that limits the lifetime of steel structures but the failure of some critical structural element. Large steel-frame structures, such as the Eiffel Tower, Golden Gate Bridge, or Empire State Building, could be expected to survive 1000 yr only with careful maintenance. Corrosion of steel, expansion owing to oxidation and hydration, and the resulting fracturing of concrete are likely to limit the lifetime of reinforced masonry as well. In most of the engineering literature reviewed, longevity refers to decades or a few centuries rather than millennia. Because iron and steel corrode quickly in seawater, the revered wrecks of the *Titanic* and the *Arizona* should have mostly crumbled away in 1000 yr (Ballard and Archbold, 1987, p. 209–210).

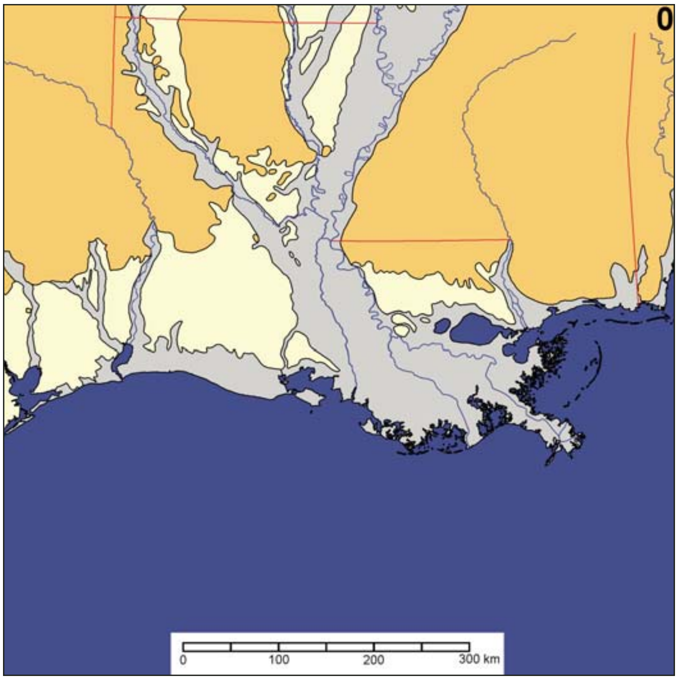
The present anthropogenic increase in atmospheric carbon dioxide should be waning in 1000 yr from exhaustion of fossil fuel resources, the switch to alternative sources of energy, or from technological collapse as a result of climate change and resource depletion. However, it is impossible to predict how long changes from human climate modification will persist or what they will be. Petroleum should be long past its peak, if not close to exhaustion, but coal and natural gas will probably still be fairly abundant (Ahlbrandt, 2002a, 2002b; Deming, 2001; Edwards, 1997).

Ten Thousand Years

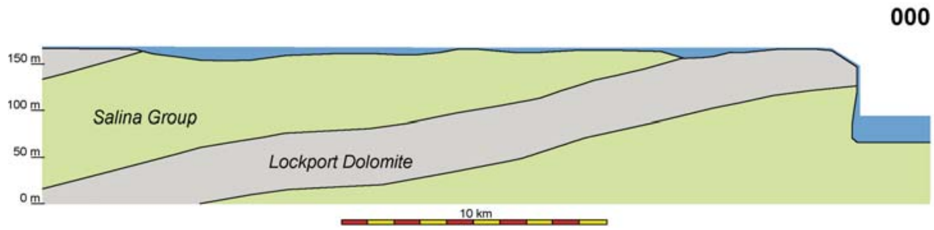
Tectonic and Volcanic Processes

The San Andreas Fault will slip ~250 m and have had 50–70 **M** = 8 earthquakes. Hawaii will have moved ~900 m northwest, probably not enough to result in a major shift of volcanic activity. If we assume that Kilauea erupts at a higher rate than Mauna Loa, we might expect Kilauea to have built itself on the order of 100 m higher in 10 k.y.

Loihi, the next seamount southeast of Kilauea, is presently active. We naturally wonder when Hawaii's newest beachfront real estate will appear. Loihi has a present volume of 660 km^3, is about a kilometer below sea level, and stands an average of two kilometers above its base (Malahoff, 1987). If it erupts at the same rate as Mauna Loa, in 10 k.y. it will have added 250 km^3 to its volume. If it maintains constant slope geometry, its height will have increased on the order of 200 m, leaving it still >700 m below sea level.

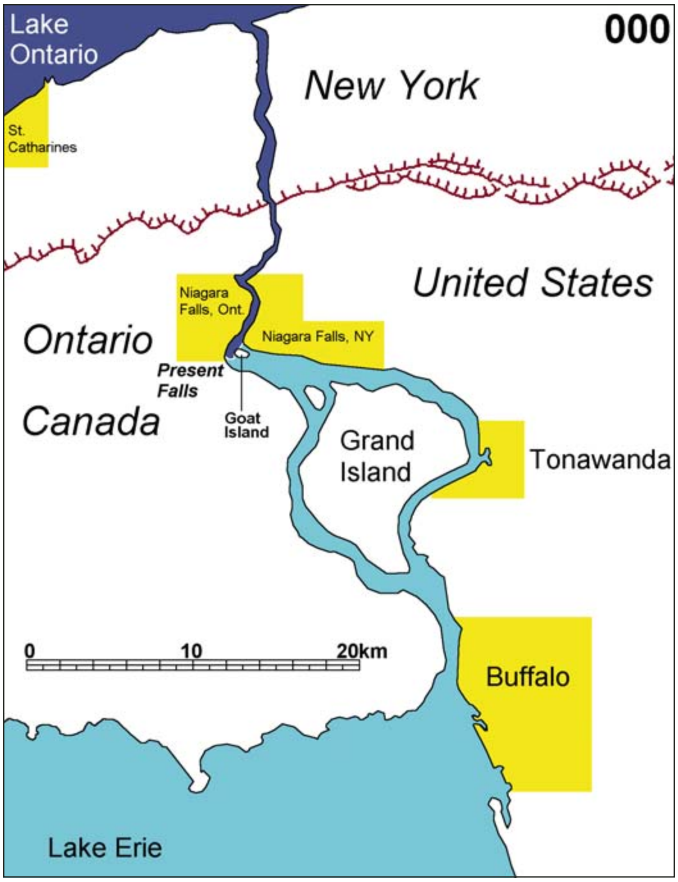


Animation 2. Hypothetical evolution of the Mississippi River delta through the next glacial maximum. Apart from the plausible guess that the next cycles of delta growth will be in the coastal bight west of the present delta, locations of deltas and channels are purely speculative for the purpose of showing the complexity of future geology and the relationship between eustasy and delta formation. Pliocene and older deposits are shown in peach, Pleistocene deposits in cream, and Holocene deposits in light gray. Recent deltas at each 10 ka interval are shown brightly colored, and older delta complexes are in subdued tones. If you are viewing the PDF, or if you are reading this offline, please visit www.gsajournals.org or http://dx.doi.org/10.1130/GES00012.S2 to view the animation.



Animation 3. Cross-section along the international boundary showing the retreat of Niagara Falls to 30 k.y. in the future, based on the interpretation of Philbrick (1974). A retreat rate of 900 m/yr is assumed until the retreat of the present falls stops (14 k.y. from now in the figure). Resistant dolostone is in gray; non-resistant, mostly shaly rocks are in green. Water is in blue. The undercutting beneath the falls is exaggerated for effect. If you are viewing the PDF, or if you are reading this offline, please visit www.gsajournals.org or http://dx.doi.org/10.1130/GES00012.S3 to view the animation.

In 10 k.y. we can expect several hundred eruptions of Vesuvius, probably enough to fill the Monte Somma caldera completely. There will probably be a hundred or so eruptions of Fuji and in the Cascade chain as well, and a number of eruptions elsewhere in the western United States. Based on Holocene eruption history, it is highly likely that new eruptive centers will have appeared in many major volcanic chains, but also in places not normally considered volcanic. Areas with Holocene volcanism, but with little or no historic activity, include Australia, Syria and Arabia, Turkey and Iran, and Manchuria.



Animation 4. Map showing the retreat of Niagara Falls from its inception 12 k.y. ago to 30 k.y. in the future. Upper Niagara and Lake Erie flow is in light blue, the gorge below the retreating Lockport Formation falls is dark blue, the future Salina Gorge is purple, and abandoned channels are in gray. The red hachured line represents the Niagara escarpment. If you are viewing the PDF, or if you are reading this offline, please visit www.gsajournals.org or http://dx.doi.org/10.1130/GES00012.S4 to view the animation.

TABLE 7. TORINO SCALE, SHOWING EXPECTED IMPACT DAMAGE

0	No hazard	No risk of impact; object will vaporize on entry into atmosphere, or object will land without causing significant damage.
1	Normal	Object will pass by earth, but likelihood of impact is extremely low.
2	Merit attention	Close pass predicted, but likelihood of impact low.
3		At least 1% chance of impact capable of causing local destruction.
4		At least 1% chance of impact capable of causing regional destruction.
5	Threatening	Possibility of impact capable of causing regional destruction; government contingency planning warranted if within 10 yr.
6		Possibility of impact capable of causing global catastrophe; government contingency planning warranted if within 30 yr.
7		Possibility of impact capable of causing global catastrophe; international contingency planning warranted if within 100 yr.
8	Certain collision	Collision certain, capable of causing localized destruction on land or possible tsunami if near shore. Recurrence interval 50–1000 yr.
9		Collision certain, capable of causing regional devastation on land or a major tsunami in the ocean. Recurrence interval 10,000–100,000 yr.
10		Collision certain, capable of causing global climatic catastrophe. Recurrence interval >100,000 yr.

Postglacial isostatic rebound of Hudson Bay and the Baltic is still in progress. Eronen et al. (2001) determined an average uplift rate of ~10 m/k.y. for the Baltic over the past 7000 yr, exponentially declining to ~5 m/k.y. in the past 2000 yr. Ekman and Makinen (1996) estimated that future residual uplift in the Baltic would amount to ~90 m, and Andrews (1968) estimated 100 m for Hudson Bay. Since both seas are shallow, these figures suggest that in 10 k.y. they will have greatly shrunk. Both bodies have maximum depths well >100 m, so neither will entirely disappear.

Geomorphic Processes

Pleistocene glacial advances have typically occurred at intervals of ~100 k.y. (Berger, 1988; Neeman et al., 1988; Imbrie et al., 1993; Zahn, 2002), punctuated by interglacials. Since the last glacial maximum occurred at ~18 ka, in 10 k.y. we may be nearing the end of the present interglacial.

Niagara Falls will have retreated ~9 km upstream. About 6000 yr from now it will reach the northwest tip of Grand Island and will briefly form a triple falls. By 10 k.y. from now the falls will have retreated several kilometers upstream along either side of Grand Island. There will be two falls, one American and one Canadian, but they will be too far apart to see from any one vantage point.

Ten thousand years is enough time for significant soil formation (Catt et al., 2000; Edwards and Zierholz, 2000) and for a small opening in carbonate rocks to enlarge into a passage large enough for humans to enter (Mylroie and Mylroie, 2004). Given its Holocene history, in 10 k.y. the Mississippi delta will probably have changed location 10–20 times.

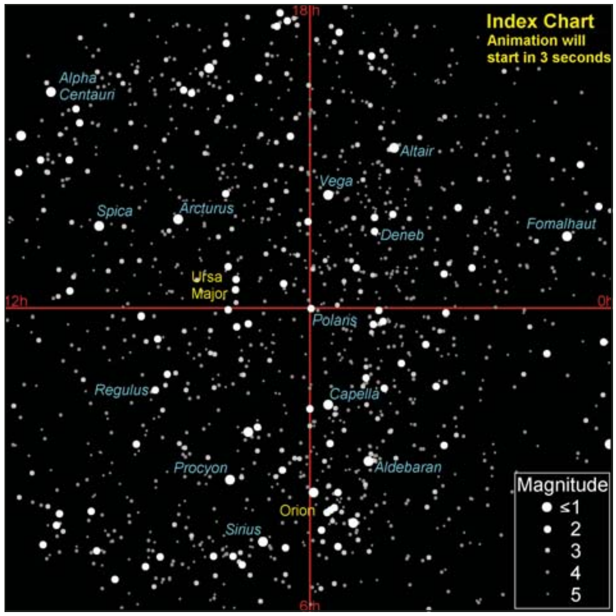
Astronomical Processes

Several impacts of 8 or above on the Torino scale are likely, with a good chance of at least one meteor crater–level impact excavating a crater a kilometer or so in diameter. There is a significant possibility of a level 9 event, capable of causing regional destruction on a scale of hundreds of kilometers through blast, ejecta, and tsunami.

In 10 k.y., Earth's axis tilt will be about at its minimum value of 22.6° and will start to increase again. Earth will have precessed ~40% of the way through its cycle. The best north pole star will be Delta Cygni, ~4° from the pole. The south celestial pole will be only 10° from Canopus, passing within 5° 1000 yr later. The Southern Cross will be visible over much of North America, but Orion will be low in the summer sky at mid-northern latitudes. The average proper motion of all stars in the

HIPPARCOS catalog brighter than magnitude 3 is 0.22 s of arc per year, or ~0.6° in 10 k.y. (Animations 5 and 6). Some distant star patterns like Orion should be recognizable, but many constellations will have changed noticeably. Alpha Centauri will have moved fully 10°, Arcturus 6°, and Sirius and Procyon ~3.5°. There will likely have been 20 or so brilliant supernovae in our region of the galaxy. The solar system will have moved ~7.5 light-years around the galaxy.

Note the general divergence of stars away from the top center of Animation 5 and convergence toward the bottom center, reflecting the motion of the solar system. An average of the apparent motion vectors of bright stars in the HIPPARCOS catalog actually agrees quite well with published values of the sun's apex, or direction of travel. Most constellations lose their identity in a few tens of thousands of years, but because of the distance of its stars, Orion will remain recognizable for several hundred thousand years. This diagram is only approximate, because measurement errors and interstellar and galactic gravitational attractions will affect the long-term motions of the stars. Also, many faint stars for which there are insufficient data to make predictions will probably become visible. No attempt has been made to portray new star formation or supernovae.

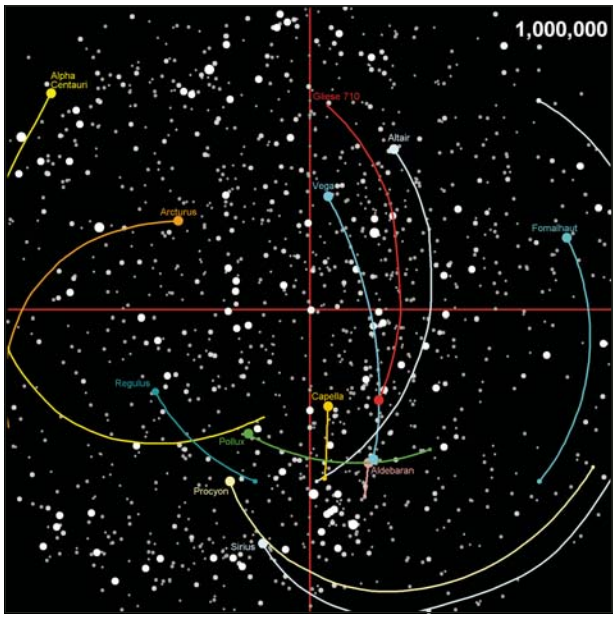


Animation 5. Appearance of the northern skies over the next million years. Star positions are shown at intervals of 10 ka until 100 k.y. in the future, and 50 ka after that. Present-day right ascensions are shown for reference, and precession is ignored. Positions were calculated using the methods of Nash (2002), based on HIPPARCOS proper motion data (European Space Agency, 1997) and radial velocity data of the Centre de Données astronomiques de Strasbourg (2005). If you are viewing the PDF, or if you are reading this offline, please visit www.gsajournals.org or http://dx.doi.org/10.1130/GES00012.S5 to view the animation.

Human Processes

No present-day human settlement is 10 k.y. old, although a few approach that age (Neev and Emery, 1995). Ten thousand years is beyond our cultural horizon. Many large present-day structures like large highway cuts and major monuments should still be preserved. Most existing reservoirs will have been filled in, or their dams will have failed by overtopping or internal failure. Only the most fastidiously preserved present-day steel structures will have survived. With its hollow construction, we can safely assume that the Statue of Liberty, shown half buried on the seashore at the climax of the original *Planet of the Apes* (Schaffner, 1968), would not survive any lengthy period of natural battering.

In <2000 yr, Latin evolved into French, Italian, Spanish, Portuguese, and Romanian. In 6,000–8,000 yr, Proto-Indo-European radiated into languages as diverse as English, Latin, and Russian (Ruhlen, 1994). In 10 k.y., even allowing for the stabilizing effects of information storage and mass communication, it is entirely possible that no single word in any present language will have survived in recognizable form. It is conceivable, but by no means certain, that some present-day political entities and cities may still exist in 10 k.y.



Animation 6. Motions of nearby first-magnitude stars over the next million years at the same intervals as Animation 1. The present constellations are shown for reference. About 50–60 k.y. from now, Arcturus and Spica will form a bright double star. Most stars again diverge from the top of the figure toward the bottom. Also shown is the track of Gliese 710, which remains below naked-eye visibility for the next 900 m.y., then brightens quickly to first magnitude. At its closest, it will move across the sky at ~15 s of arc per year. If you are viewing the PDF, or if you are reading this offline, please visit www.gsajournals.org or http://dx.doi.org/10.1130/GES00012.S6 to view the animation.

One Hundred Thousand Years

Tectonic and Volcanic Processes

At present slip rates, there will have been 2.5 km slip on the San Andreas Fault and ~700 **M** = 8 earthquakes. That amount of slip will be enough to bring the coastal hills west of the fault nearly to the Golden Gate but not enough to close it. If Earth is in another ice age with sea level 100 m lower at the time, San Francisco Bay will be dry, and the Golden Gate will again be reduced to a river valley.

Hawaii will have moved ~9 km northwest. That may be enough of a shift to channel more magma to Kilauea and Loihi at the expense of Mauna Loa. Kilauea will have erupted a few thousand cubic kilometers of lava, enough to raise its summit perhaps a kilometer. If Loihi erupts at comparable rates, it will probably be well above sea level. Mauna Loa may still continue to build upward, but the fact that both Mauna Loa and Mauna Kea are almost identical in elevation, and that somewhat older Haleakala on Maui is lower, suggests that ~4 km above sea level is the limit for Hawaiian shield growth. The duration of conduit connections, hydrodynamics of magma migration, subsidence resulting from isostasy and draining of magma chambers, and collapse all probably act jointly to limit shield growth.

Geomorphic Processes

At 1 cm/yr uplift, typical of many tectonically active regions (Rubatto and Hermann, 2001), there will be a kilometer of uplift in 100 k.y. If erosion proceeds at rates comparable to uplift, the overall effect would be to expose deeper rocks without otherwise greatly changing the landscape. However, in areas where one process is dominant, we could expect to see significant uplift or lowering of the landscape. In flat landscapes, 100 k.y. is more than enough time even for laterite soils to form (Gunnell, 2003).

In 100 k.y., given the periodicity of recent ice advances, it is quite possible that Earth will have experienced its next glaciation.

Niagara Falls will require only 30–40 k.y. to reach Lake Erie, but as it retreats south, its cap rock thickens and the exposed depth of soft underlying rock thins. Eventually the cap rock will be overlain by an increasing thickness of softer rocks. The present falls will stabilize at ~15 m high while the river cuts a gorge upstream in the softer rocks. Eventually the knickpoint will retreat to Lake Erie, where it will encounter another series of resistant layers and form a second falls. Lake Erie will probably drain rapidly (though probably not catastrophically), and drainage of the other lakes will accelerate. However, because all the other Great Lakes have bottoms far below sea level, they will not drain, though they may undergo some lowering of water level. By 100 k.y. in the future, however, they may be under ice again.

Zhang et al. (2000) and Liu (2000) found corrosion rates of a meter or more per 1000 yr in karst regions of China. In 100 k.y. these areas would undergo 100 m or more of corrosion. There might still be karst in those regions, but probably none of the present-day landforms of China's famous karst areas such as Guilin will still exist. Some caves have been shown to have ages well >100 ka (Mylroie and Mylroie, 2004), so some present cave systems may still exist, though solution and deposition rates in karst systems are so rapid that probably no present features will be recognizable.

Astronomical Processes

There will probably be tens of impacts rating 8 or above on the Torino scale, probably several rating 9, and there is a significant likelihood of a level 10 event with global effects.

In 100 k.y., Earth will have completed three precessional cycles and be more than three-fourths of the way through a fourth. On average, moderately bright present-day stars would move ~6° in 100 k.y., enough to scramble most constellations beyond recognition, and many would move far more. However, a simple extrapolation of the stellar motions in the HIPPARCOS catalog (Nash, 2002) shows no bright stars moving far enough to assume the role of a new pole star.

Several hundred bright supernovae visible from Earth will have occurred. Some new stars will have formed in nearby star-forming regions like the Orion Nebula (Tielens, 1988; Welch, 1988). Orion may still be recognizable (but smaller) if it will not have been too badly changed by supernovae or new star formation. We will have traveled ~75 light-years in our circuit of the galaxy.

Human Processes

We have no continuous cultural tradition long-lasting enough to enable even a rough guess about human society in 100 k.y. One hundred thousand years is a significant fraction of the time since anatomically modern humans first appeared (Smith and Spencer, 1984). It is also enough time that, even if civilization collapses and humans regress to Paleolithic technology, they could literally "reinvent the wheel" and return to our present level. We might anticipate that recovery to high levels of technology would be harder each time because of the depletion of natural resources by each previous cycle, but metals might actually be easier to extract from old anthropogenic deposits than from ores, and the mere knowledge of previous high civilizations might prove a stimulus. Recovering societies would find fossil fuels much scarcer on a time scale of 100 k.y., but they might then be spared the need to wean themselves from nonrenewable energy sources.

One Million Years

Tectonic and Volcanic Processes

In a million years, the San Andreas Fault will have slipped 25 km and had ~7,000 **M** = 8 earthquakes. The Golden Gate will be blocked by the hills of present San Mateo County, though erosion will probably maintain a valley northward along the fault trace as slip occurs.

Hawaii will have moved 90 km northwest. Kilauea and Loihi by this time will have been building as long as present-day Mauna Loa and would probably be about the same size. Loihi will be the main vent, and new vents to the southeast may have formed. Mauna Loa and Mauna Kea will be as old as present-day Maui and will likely be similarly dissected. Almost 70 large landslides have been recognized along the 2,200 km of the Hawaiian island chain (Moore et al., 1994; Moore and Chadwick, 1995; Smith et al., 1999; McMurtry et al., 2004). Coupled with the average rate of plate motion over the Hawaiian hotspot, we can estimate an average recurrence time of ~350,000 yr for large landslides, or about three in the next million years.

Several of the present-day Cascade volcanoes will have become extinct, and others will have collapsed owing to caldera collapse or mega-landslides (Crandell et al., 1984). Very likely the same can be said of a number of other well-known present-day volcanoes. New eruptive centers will probably have formed and grown to heights comparable to the largest present-day Cascade peaks. Given the Quaternary record of Long Valley, Yellowstone, and Toba, among others, it is virtually certain that there will be several eruptions involving the collapse of magma chambers in the next million years (Rampino et al., 1988).

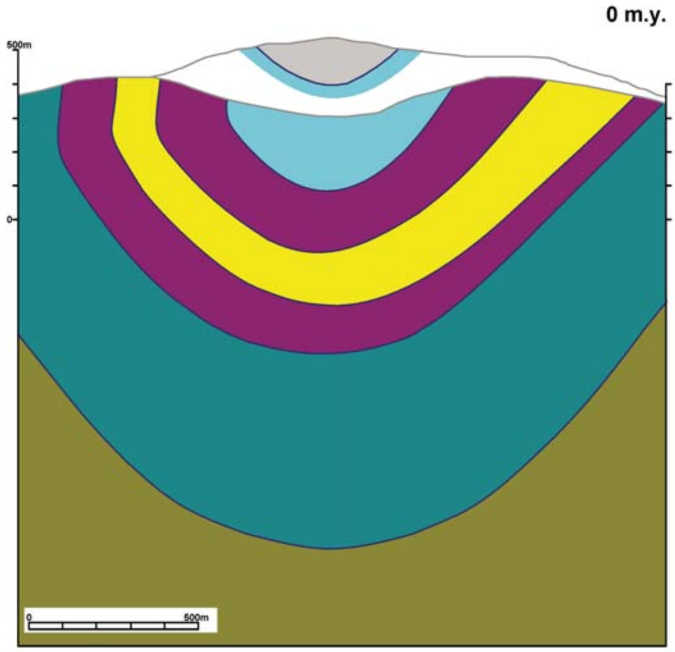
Geomorphic Processes

At a centimeter per year, the most active orogens could see 10 km of uplift, and the accompanying erosion will be enough to remove all presently exposed rocks. Many present river valleys will still exist, but many others probably will have been diverted by giant landslides, glaciation, or crustal movement. We do not know enough about the long-term balance between uplift and erosion to predict the futures of specific areas. Some present minor ranges may grow to great heights; others might be significantly lowered by erosion. In areas of steep relief but little uplift like the Appalachians, a million years would mean ~30 m of mass wasting (Matmon et al., 2003).

Animation 7 illustrates the interplay of deformation, uplift, and erosion in the Berkeley Hills, California. The area was chosen because the structure is simple and well established, rock units are precisely dated, deformation was recent and moderately rapid, and the author is familiar with it. In less than 8 m.y., a conformable sequence of Miocene sedimentary and volcanic rocks was folded into a syncline with an overturned western limb. The stratigraphic sequence, from oldest to youngest, begins with the marine Claremont Formation, the Orinda Conglomerate, the Moraga Volcanics with intercalated sedimentary rocks, the Siesta Formation (nonmarine siltstone and clay), and the Bald Peak Basalt. Curtis (1989) reported ages of 9.0–10.2 Ma for the Moraga Formation and 8.37–8.46 Ma for the Bald Peak Basalt. It is assumed that the Siesta Formation was slightly above sea level at deposition, providing a good basis for paleo-elevation estimates.

The periodicity of Pleistocene ice advances suggests that Earth may see 10 or so major glaciations in the next million years. Given the events following the Wisconsinan advance, we can expect each to be followed by catastrophic outburst floods (Bretz, 1928, 1969; Waitt, 1985; Rudoy and Baker, 1993; Rudoy, 1998) and major reorganization of drainage systems (Anderson, 1988; Melhorn and Kempton, 1991; Granger et al., 2001).

A million years is long enough for some natural resources to form. It is much longer than the time scales of soil formation (Edwards and Zierholz, 2000; Gunnell, 2003) or aquifer recharge (Robbins, 1998). Pleistocene petroleum occurrences (Ujiie et al., 2004) and coal formations (Sakorafa and Michailidis, 1997) are known, showing that fossil fuels can form at million-year scales. Activity at present hydrothermal areas is likely to create new metal deposits, while deep erosion in mountain belts will expose others.



Animation 7. Long-term interplay of deformation, uplift, and erosion in a typical area of active uplift: the Berkeley Hills, California. The first frame is an index map to the cross-section area; the second frame shows the cross-section area in detail. A and B are the topographic profiles used in the cross sections. Ca-24 is California Highway 24, and BART is the Bay Area Rapid Transit line. The present-day cross section is that of Rogers and Peck (2000), which is based on subsurface data from the BART tunnel. The remainder of the animation shows schematic evolution of the Siesta Valley Syncline from 8 Ma to the present, looking northwest along the axis. Profile A is in the distance, and B in the foreground, and they are shown on all frames for reference. From oldest to youngest, the Claremont Formation is brown, the Orinda Conglomerate is dark green, the Moraga Volcanics are purple with intercalated sedimentary rocks in yellow, the Siesta Formation (nonmarine siltstone and clay) is light blue, and the Bald Peak Basalt is gray. The initial section was constructed with the top of the nonmarine Siesta Formation slightly above paleo–sea level, and uplift, erosion, and folding were approximately linearly adjusted to achieve the present structure and topographic profiles. Beginning at 3 Ma, the cross section shows the incision of the Siesta Valley separately from the slower erosion of the resistant Bald Peak Basalt. If you are viewing the PDF, or if you are reading this offline, please visit www.gsajournals.org or http://dx.doi.org/10.1130/GES00012.S7 to view the animation.

Astronomical Processes

There will probably be hundreds of meteor impacts rating 8 or above on the Torino scale, tens rating 9 or above, and a high probability of one or more level 10 events with global effects.

Tidal deceleration of the Earth-Moon system, even at this time scale, will be small. The day will be longer by ~20 s, and the moon will have receded by ~38 km (Brosche, 1990; Cheng et al., 1992; Dickey et al., 1994).

In 1 m.y., Earth will have completed nearly 39 precessional cycles. The solar system will have traveled ~750 light-years in its orbit around the galaxy. There will have been thousands of visible supernovae and numerous new stars formed. Many of today's stars will be visible, but no constellations will be recognizable. Some distant stars like Deneb or Rigel will have barely moved, and one relatively nearby star will be nearly in its present position for a remarkable reason: Algol (Beta Persei) passed only 8 light-years from the sun 7 million years ago (García-Sánchez et al., 1999) and is traveling almost directly away from us. Arcturus will have traveled deep into the southern sky, and Alpha Centauri into the northern. Both will have faded beyond easy naked-eye visibility. Polaris is moving almost tangentially to the precessional path of the pole and will continue to be a fairly good pole star every 26 k.y. for about a quarter of a million years. Thereafter it diverges, and by a million years from now it will be 14° from the pole at closest approach. Its radial velocity of ~−17 km/s means it will be ~50 light-years closer in a million years.

The Sun will be undergoing its closest approach to any known star at about this time. Gliese 710, a red dwarf now 63 light-years away in Ophiuchus, will be only about a light-year from the Sun (García-Sánchez et al., 1999). In contrast to today, when no red dwarf star is even visible to the unaided eye, Gliese 210 will rival Antares in color and brightness.

Human Processes

Species commonly have lifetimes of several million years and sometimes far longer (Novacek and Norell, 1982; Smith and Peterson, 2002). Thus, it is likely that *Homo sapiens* will still be *Homo sapiens*. However, if human civilization experiences a protracted collapse into several geographically isolated gene pools, it is possible that geographically isolated segments of the human race may undergo speciation. Even if humanity does not experience any catastrophic changes, we simply have no idea what it would be like to have a million years of recorded history, or how the perspectives of people with such a long history would differ from our own. Even if humans avoid causing a mass extinction, many species will have become naturally extinct and new ones will have evolved.

Looking Back from a Million Years

The average length of a geologic period is >50 m.y., and even the shortest, the Silurian, was 30 m.y. long. Apart from the Pliocene through Holocene, Cenozoic epochs were 10–20 m.y. in length. In a million years, we will not even be remotely close to entering a new epoch, let alone a new period.

Observers a million years hence will be able to look at our era in its geologic context. Will they see another great mass extinction as Leakey and Lewin (1996) warn? It is certainly within our power to create one. If we remain within the limits of environmental sustainability, what will future observers see? They will see the Pleistocene extinction, but contemporary humans had nothing to do with that, even if the early human role is hotly debated (Alroy, 2001; Graham and Mead, 1987; MacPhee and Marx, 1997). They will see the extinction of once common species like the passenger pigeon (Schorger, 1955) and the displacement of forests and wild animal species by crop plants and domestic animals. They will certainly find a global, geologically instantaneous spread of human artifacts, and the conclusion that the spread of humans was responsible for the paleontological changes they see will be inescapable. However, the fossil record is strongly biased in favor of abundant shallow marine and coastal plain organisms with hard parts. The combination of a lack of hard parts, a terrestrial setting, localized occurrence, rapid decay, and intensive recycling of nutrients makes it unlikely that most rain forest organisms (or their extinctions) would ever show up in the fossil record. Species that were probably never common, like the ivory billed woodpecker or Steller's sea cow, would show up sporadically or not at all in the fossil record. Furthermore, many extant species are defined by differences in soft body anatomy or coloration. Even if the now extinct dusky seaside sparrow (Walters, 1992) were to be found as a fossil, would it be recognized as a distinct species? Comparisons between modern extinctions and the fossil record must be made with care; observers a million years from now would see our time as one of sweeping global change but probably not (yet) a major mass extinction.

Cultural, not geologic, factors are likely to dictate what human artifacts endure. If large human structures have a half-life of 1000 yr (far longer than is presently the case), a million years is 1000 half-lives, and the likelihood of a single structure surviving intact by chance is negligible. Cato (2002) speculated on the present human structures that might be extant in a million years. Noting the vulnerability of steel to corrosion, and of dams to overtopping or internal failure, he concluded that the likeliest structures to survive would be solid and would not rely on metal for their structural integrity: open-pit mines, earth-fill flank dams, and large landfills. To these structures we could add a few others: large highway and canal cuts, spoil and slag piles, and perhaps a few large monuments like Mount Rushmore or the Pyramids. The survival of these structures will depend not only on their geologic stability but on future humans not modifying or removing them.

It is ironic that one of the human structures most likely to endure for a million years is also one of the oldest: the Pyramids. However, the Pyramids largely owe their preservation to an arid climate. Much younger monuments in vegetated regions like Central America or southeast Asia suffered much more degradation in shorter times, largely from chemical weathering and tree roots (Marinos and Koukis, 1988). Pyramids are steeper than the angle of repose, and even in arid Egypt they have undergone structural failure (Lehner, 1997). If the climate of Egypt becomes much less arid during the next million years, even the Pyramids might be largely destroyed by solution and mass wasting.

One human structure that is not likely to be preserved in a million years is the nuclear waste repository at Yucca Mountain. Wholly apart from geologic and engineering considerations of longevity, I suspect the actual residence time of the waste will be a few centuries at most. Long before geologic processes affect the integrity of the storage, I consider it all but certain that the waste will be moved to a safer disposal location, treated by some as-yet-uninvented technology to reduce its hazard, or, most likely, reprocessed to extract its remaining nuclear fuel.

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