ES473 / 573 Environmental Geology - Take Home Assignment

Read the Berger 2006 paper entitled "Abrupt geological changes: Causes, effects, and public issues"

Answer the following review questions:

(1) What are the types of geological changes that have significantly impacted human civilizations in the past? What time frame is associated with typical "abrupt geological events".
(2) Discuss the concepts of geological events in the context of spatial and temporal scales. What types of scales are most disruptive to human ecosystems?
(3) What is the difference between an "endogenic" vs. "exogenic" process driver? What are the ultimate driving mechanisms for the range of catastrophic geologic events discussed in the paper?
(4) What are examples of human-induced vs. non-induced geological changes? Give examples of how humans effect geological processes and vice-versa.
(5) Explain how environmental geologists can aid in understanding the Earth record of abrupt geological events, and their effects on human civilizations.

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Abrupt geological changes: Causes, effects, and public issues

Antony R. Berger

10 Trout River Rd., Woody Point, NL, Canada, A0K 1P0

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Abstract

This discussion paper deals with some of the broader questions and issues surrounding rapid geological change and how it affects people, settlements and societies. Examples include both catastrophic (e.g. volcanic eruptions, landslides, tsunami) and non-catastrophic changes (e.g. dune formation and movement, frozen ground activity, and lake level fluctuations). As shown by several examples from arid and semi-arid regions, lives have been altered by rapid changes in landscapes, but separating human causes that may be manageable from non-human drivers that may not is commonly difficult. The question is raised as to whether society should be moving to stop or avoid rapid natural geological change, or learning to adapt to new circumstances.

1. The key questions

The Earth is clearly moving into a period of accelerated environmental change, through climate warming and a wide range of human-induced stresses (see Steffen et al., 2004; MEA, 2005 for thorough summaries). One of the aims of the Dark Nature project and its partner IGCP 490 is to determine what lessons can be learned from the past so as to strengthen the resilience of contemporary societies. What kinds of changes involving landforms, rocks, soil and water are possible, what broad impacts do these have on societies and settlements, and how do they influence the way people think about the natural (non-human) world? How were early settlements and societies benefited or harmed by rapid environmental changes? Diamond (2005) discusses many cases where societal "collapse" was driven by human stresses on land and food resources. There are also many examples where environmental change of non-human origin (e.g. drought and volcanic eruptions) affected landscapes in ways that challenged local peoples and led to major societal upheavals. How do people react to rapid change in their natural environment? One current reaction is to try to stop it, for governments seem to prefer above all stable economies with "externalities," such as the environment, which they think can be readily ignored. Other approaches are mitigation to ease the effects of environmental change, adaptation to new circumstances, and migration to new places.

2. A matter of scale

The spatial scale of abrupt, geologically induced change can vary from the continental and regional to local, individual landscapes. When dealing with change, the time frame of most importance to contemporary society is that of a normal human lifetime or less—decades, years, seasons, days, and even less in the case of earthquakes. The impacts on people and ecosystems may be immediate, as when a volcano erupts or a slope fails, or they take much longer to affect social and political structures (e.g. Driessen and Macdonald, 2000). Abrupt changes may be especially harmful to long-lived and relatively immobile societies and to modern built environments such as cities. Moreover, the same change can have different effects on different peoples in the same region. When Viking settlements failed in Greenland during the Little Ice Age cooling, Inuit peoples nearby appear to have survived as usual (Diamond, 2005).

3. What kinds of geological changes?

There are many kinds of geological changes that can take place in less than 100 years and that are significant for people—and ecosystems—such as variations in the pH of groundwater and the position of the shoreline. A convenient summary of abiotic terrestrial changes is given in

E-mail address: bergerar@telus.net.

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the IUGS geoindicator schema (for arid and semi-arid terrains see Table 1). This identifies 27 parameters in an annotated checklist format (Berger and Iams, 1996; Berger, 2002), which was developed originally as a tool to aid in environmental reporting and ecosystem monitoring. Some geoindicators are simple and easy to measure (shoreline position, lake levels), whereas others are complex and aggregated (volcanic unrest, frozen ground activity, soil quality). They can be useful for describing both catastrophic changes (landslides) and those that are slower and more pervasive (soil and sediment erosion). Geoindicators have been used by national park managers in the USA and Canada to help identify geological processes that affect park visitors and ecosystems (Higgins and Wood, 2001; Welch, 2003). Other applications include state-of-the-environment reporting, assessing the environmental effects of mining, and dealing with rapid karstification (see papers in Berger and Satkunas, 2002).

4. Causes of abrupt change

Many rapid changes are related to climate, including droughts, dust storms, weather extremes, glacier retreat, and fluctuating lake levels. Weart (2003) and Alley et al. (2003) have reviewed the evidence of abrupt climate changes of the past and their impacts on ecological and economic systems. Though we may not know exactly what pushed the annual average temperatures preserved by proxy in the ancient ice of Greenland and Antarctica as much as 7 °C over a decade or so, there are a range of possible causes from solar radiation forcing to albedo feedback and ocean circulation patterns. Recent work on Caribbean shelf sediments indicates that the demise of the Mayan civilization in the lowlands of the Yucatan Peninsula of Mexico occurred at the time of a 100-year drought punctuated by shorter but multi-year droughts at approximately 810, 860, and 910 AD. Rapid population

Table 1
Potential causes of geoindicator change in arid and semi-arid terrains

Geoindicator	Exogenetic drivers	Endogentic drivers	Self-organization	Human drivers (direct/indirect)
Arid and semi-arid zones				
Desert surface crusts and fissures	Y	N	N	Y (D)
Dune formation and reactivation	Y	N	Y	Y (I)
Dust storm magnitude, duration and frequency	Y	N	N	Y (I)
Wind erosion	Y	N	N	Y (D)
Marine and coastal zones				
Coral chemistry and growth patterns	Y	N	N	Y (I)
Relative sea level	Y	Y	N	N
Shoreline position	Y	Y	Y	Y (I)
Lakes				
Lake levels and salinity	Y	Y	N	Y (I)
Surface and ground-water				
Groundwater quality	Y	?	N	Y (D)
Groundwater chemistry in the unsaturated zone	Y	Y	N	Y (D)
Groundwater level	Y	Y	N	Y (D)
Surface water quality	Y	N	N	Y (D)
Rivers and streams				
Stream channel morphology	Y	N	Y	Y (D)
Streamflow	Y	N	Y	Y (D)
Stream sediment storage and load	Y	N	Y	Y (D)
Natural hazards				
Seismicity	N	Y	?	Y (D)
Landslides and avalanches	Y	Y	?	Y (D)
Volcanic unrest	N	Y	Y	N
Soils				
Soil and sediment erosion	Y	N	N	Y (D)
Soil quality	Y	N	?	Y (D)

Note: This table is an attempt to shows the cause of geoindicator change within a 100 year time-frame.
Exogenetic drivers are primarily climatic/meteorological (rainfall, wind, temperature, etc.): weather extremes are most important.
Endogenetic drivers result from processes and energy originating beneath the Earth's surface (heat flow, neo-tectonics, gravitational instability, etc.).
Self-organizing parameters are those that develop a high degree of structure and organization without external inputs, such as from climate or from internal Earth energy.
As to *human actions*, most of the indirect influences are via human-induced climate changes.

expansion during the climatically favourable period from about 550–750 AD left the Mayans operating at the limits of the environmental carrying capacity. As a result, Mayan society was highly vulnerable to subsequent repeated droughts, which led to its collapse (Gill, 2000; Haug et al., 2003).

Rapid environmental changes on a variety of spatial scales can also be generated by non-climatic events (see Table 1). The violent eruption of Santorini sometime between 1628 and 1520BC appears to have caused a series of economic and societal disturbances in the Minoan society of Crete, leading to its collapse around 1450BC (Driessen and Macdonald 2000) though there are still doubts about the exact timing. The eruption of Vesuvius that led to the destruction of Pompeii is a well-known example, as are the many great earthquakes that caused widespread damage and death (Lisbon, San Francisco, Kobe, Bam). The Storegga submarine slump off the Norwegian continental shelf 7300 years ago led to a catastrophic tsunami with run-ups of at least 20 m on land in the NE Atlantic (Bondevik et al., 2003), and of course there is the great Indian ocean tsunami of 26 December 2004. Some such geological changes can drive or influence climate locally and even globally, as when volcanic emissions from the 1991 eruption of Pinatubo in the Philippines altered for a brief period global atmospheric circulation patterns and induced a temporary cooling (Pinsker, 2002).

5. Human and non-human drivers of change

Most state-of-the-environment reviews concentrate on human pressures (inputs, impacts, drivers) on natural systems (e.g. Bright et al., 2003; EEA, 2003). For those responsible for environmental management and decision-making, it seems important, as far as possible, to distinguish human-induced change, which may be manageable, from natural changes, which may not. However, in many cases this distinction is a difficult task. For example, rapid changes are common in many alluvial river systems, as people who live near them know full well. The shape, dimensions and locations of stream channels and the capacity of rivers to store and discharge sediments can be altered as a result of dams and reservoirs, irrigation systems, and river diversions. Similar changes can also result from variations in rainfall and flash floods, failure of watershed slopes, or changes in glacial sources. Rivers can undergo sudden and irreversible changes in flow paths and river-bed patterns related to the internal dynamics of fluvial flow and the ability to self-organize. The latter refers to the regular behaviour and stable structures that can emerge rapidly as natural systems organize themselves without external forcing (Smolin, 1997; Peat, 2002), as in shoreline position and patterned ground (see Table 1).

Earthquakes are natural phenomena, but they can also be induced by surface loading of water in reservoirs, or where waste fluids are pumped into the sub-surface. Soils can be degraded by farm tillage, road operations, salinization due to groundwater extraction, and by acidification from fertilizers and acid rain. Their physical and chemical properties can also be affected by rainfall, drought, windstorms, and wildfires. Indeed, volcanism, glacier fluctuations and changes in sea level may be the only rapid geological processes that cannot be induced directly by human activities (Table 1).

Trying to stop natural processes in some circumstances may be both futile and harmful to ecosystem well-being—as in the former public campaign in North America to eradicate the forest fires now known to be essential to natural forest renewal. Policies and declarations that aim to change human behaviour may also be misguided when they assume that nature left alone is inherently stable, in equilibrium and beneficial to life. The emergence of "disturbance ecology" has done much to dispel former assumptions of stasis, climax succession, and simple deterministic models (Abel and Stepp, 2003). As the 2001 Amsterdam Declaration on Global Change put it, the Earth "behaves as a single, self-regulating system comprised of physical, chemical, biological and human components. Earth System dynamics are characterized by critical thresholds and abrupt changes. Global change cannot be understood in terms of a simple cause-effect paradigm" (Steffen et al., 2002, 2004). Many local changes cannot be readily related to simple and identifiable causes. The difficulty in separating human-induced from natural environmental change is a real challenge to the management of landscapes and urban areas, because ignoring natural forces in policy and practice would seem to guarantee failure.

6. Assessing environmental change—a critique

An example of the difficulties involved is provided by the pressure-state-response (PSR) framework now in common use in one form or another for environmental assessment and reporting activities (Moldan et al., 1997; Environment Canada, 2003). In this approach, environmental change is driven by pressures (stresses or drivers) which result from human actions and lead to new environmental conditions (state). Governments then respond with new or improved policies to deal with the changes. There are two difficulties here (Berger and Hodge, 1997). The first problem stems from the fact that the condition of the environment at any time reflects not only human influences, but also the natural processes that can be viewed as running in the background. Industrial, urban, and agricultural activities certainly have direct impacts on the environment, and these influences generally become more marked as populations increase and economic growth proceeds. However, away from obvious sources of disturbance (e.g. towns and cities, waste disposal sites, mines, farms, forest harvest areas), it may be very difficult, as shown above, to separate the effects of human actions from those due to natural processes. Moreover, in remote and unpopulated areas there may be indirect, far-travelled human influences, such as the long-range aerial transport of acid and toxic contaminants now affecting many people in the Arctic (Einarsson et al., 2004).

The second challenge to the PSR approach comes from the realization that the change in environmental state from any imposed stress may from another perspective be a stress on a different part of the ecosystem. Establishing cause and effect may be next to impossible in such multi-component systems. A volcanic eruption can perturb local and regional ecosystems, through impacts on regional weather patterns and air quality, local slope stability, fluvial systems, soil quality, glaciers, and hillslope erosion. Likewise, lacustrine ecosystems are affected by changes in lake levels which can be intimately connected with climate change, fluctuations in groundwater levels and quality, frozen ground activity, wind erosion, or dust storms. Rising or falling relative sea levels influence shoreline position and coastal and estuarine environments, and can affect local streamflow and groundwater quality, or cause surface uplift or subsidence.

7. Changing landscapes of western Canada

The Palliser Triangle of south-western Alberta and southern Saskatchewan preserves in its geological archive an extensive record of marked environmental change (Lemmen et al., 1998; Lemmen and Vance, 1999). Climatic variations of the past 10,000 years have been reconstructed by tree-ring studies and research on lake sediments, especially where varves are preserved. An early Holocene (10,000–7000 yBP) humid climate, characterized by high lake levels and freshwater conditions, was succeeded by mid-Holocene (7000–5000 yBP) aridity, with low lake levels prevailing, some lakes drying completely. Summer temperatures were then about 2 °C warmer than at present. After about 5000 yBP, rising groundwater led to regional filling of lake basins, and conditions were significantly more humid than the first half of the Holocene. However, climatic variability was pronounced, with long droughts (Medieval Warm Period—AD 900–1200) under much the same climatic conditions as at present. The instrumental record indicates a warming of nearly 1 °C from 1895 to 1991, and there is evidence of a drying trend since 1948.

Throughout the Holocene, rivers exhibited the most complex response to climate change, with trunk streams and tributaries commonly out of phase. The chronological pattern of landslides matches that of fluvial activity, with most slope failure occurring along major river valleys. Landslides can be triggered by extreme precipitation, or by stream incision and later channel migration. Sand dunes and sheets are highly sensitive to climate. Severe drought in late 1700s, which was preceded by 100 years or more of below average precipitation, caused widespread sand-dune activity over the north central portion of the Palliser Triangle (the Great Sand Hills of Saskatchewan, see Wolfe et al., 2001). Synchronous dune activity began in early 1800s, with the formation or reactivation and migration of parabolic dunes. Dunes remained active for about 80 years, and were then stabilized.

The Holocene record provides a long-term context for the many human-induced changes of the past two centuries. These include the modification of most of the grass cover by grazing cattle, its replacement by cereal crops, and the suppression of natural fire, most of which took place since the start of European settlement a little over 100 years ago. Soil erosion, which appears to have been insignificant prior to breaking of the grassland by European settlers, is now the most regionally important surface process in terms of sediment redistribution and the associated economic costs. Nevertheless, it is clear that human actions here must be seen against a moving background of natural change.

8. Migrating rivers of Northern India

An example of the powerful influence of river avulsion and channel switching on settlements and societies comes from northern India. Changes in river courses, driven by climate, neotectonic movements, or simply the dynamics of sedimentary systems, had profound effects on settlements and societies which depend on rivers for food and water supply.

The "lost" River Sarasvati is described in many places in the Rigveda, one of the world's oldest texts and the foundation of Indian culture. According to Radhakrishna and Merh (1999), it once flowed from the Himalayas to the shores of the Arabian Sea (see also Valdiya, 2002). On its flood plain around 8000 years ago, agriculture began and the earliest Vedic civilization flourished. Around 3000 BC, the upper reaches (known as the Yamuna River) were "pirated" by the Ganges, and another important tributary (the Sutlej) later became diverted to join the Indus River, leaving the Sarasvati to dwindle into an ephemeral stream and finally become lost in the sands of the Thar desert of NW Rajasthan (Goudie, 2002). Along the valley of the Indus arose the great civilization of the Indus Valley Tradition from 3300–1790 BC (Rao, 1991; Radhakrishna and Merh, 1999; Belcher and Belcher, 2000). Many of their cities had well-developed hydraulic systems of water and sewage and were clearly dependent on nearby rivers. At Mohenjodaro are the remains of public baths, granaries, city drains and sewers and almost every house had water piped in from nearby reservoirs or streams. The Indus Valley Tradition is believed to have declined in part because of a change in climate and as a result of neotectonic movements that changed the course of rivers away from the towns and cities (Belcher and Belcher, 2000).

A modern example of rapidly changing river courses is provided by the Kosi River of north central India, which also originates in the Himalayas (Gole and Chitale, 1966). Frequent floods result in nearly annual changes of course (Fig. 1). Between 1736 and 1964, it moved over 110 km

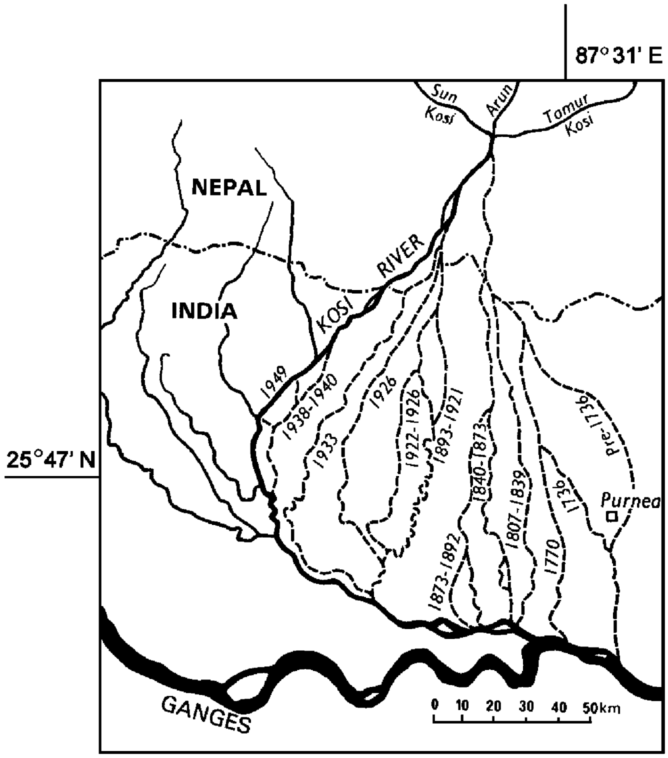

Fig. 1. Lateral migration across its wide alluvial fan of the Kosi River of Northern India (after Holmes, 1978).

westward. Once the river reaches the gently dipping alluvial plains, the sediment load carried from the steep watershed is too large to be carried, and is then deposited rapidly. Levees are easily eroded by new floods, avulsion occurs, and the river changes course frequently. Those living close to the Kosi were always in danger from sudden floods and sediment loads that converted fertile fields into sandy flats. Traces of former courses can be seen on the huge alluvial fan of the Kosi system, where the river has deposited its load as it migrates from side to side. Between 1933 and 1936, the rate of migration of channel was about 6.5 km/year. As Geddes (1982, p. 163) describes it, "The shifts of the Kosi damaged or destroyed homesteads, crops fields and trees in differing ways down the Cone. First came the sweeping water of great floods from the hills carrying floating trees like battering rams and spilling and heaping sands where the current was checked by a village site or by west-east embankments or road or rail to heights of 3 m. Thereafter the rise of the subsoil water tables drowned the roots of the trees, the moisture percolating through the sandy soil as far as 8–10 km from its course."

9. Desertification

The original definition made popular by Aubreville (1949) was that this is a "human-induced process of degradation of land into desert-like regions." The 1992 Rio Conference on Environment and Development recognized the role of climate in causing deserts, and the UN Convention to Combat Desertification (1996) defined desertification as "land degradation in arid, semi-arid and dry sub-humid areas resulting from climatic variations and human activities". Others have proposed various refinements, with one group continuing to point to human causes, a second arguing for climatic variations, and a third group acknowledging that both human and non-human processes are at work, including social, economic and political drivers (cf. Smith and Koala, 1999; Reynolds and Stafford Smith, 2002).

Sand dunes and sheets figure largely in the process of desertification. Migrating dunes and sand sheets can bury agricultural fields, forests and settlements (Fig. 2). They can also lead to changes in groundwater level as sand acts as an insulating blanket, reducing evaporation and causing water tables to rise. A review for the UN Convention to Combat Desertification (Yang et al., 2002) gives many such examples from Kazakhstan, Kenya, Nigeria, and China, but little indication of the relative importance of natural processes versus human actions. The challenge again is to be able to distinguish the two and to decide how best to respond to the natural forcings of drought and aridification.

The implications for history and, thus, for our understanding of cultures and traditions, can be significant. Issar and Zohar (2004) discuss the significance in the Negev Desert of the ruins of 6 cities of Nabatean to Byzantine age (300 BC–500 AD). The traditional view was that these cities flourished because of extensive irrigation and water abstraction, and that their downfall was due to invasion of the desert by Arab nomads who did not care about agriculture and did not maintain dams and terraces. However, careful paleoenvironmental research has shown that it was a period of natural climatic change that led to northward migration of the desert over this region, and that many sand dunes were deposited after the end of the Byzantine Empire when the Arabs ruled over the Levant. If

Fig. 2. Desert sands invading the ancient Mauritanian city of Chinguetti. Inset shows detail of abandoned homes on the edge of the settlement.

this view is correct, it throws a quite different light on the way the history of the Arab peoples is understood.

Far beyond the deserts, there are climatic, environmental and health problems caused by dust wind-blown for great distances from drylands. One estimate is that as much as 2 billion metric tonnes (MT) of dust are transported in the atmosphere each year, including 15 MT from Africa to the Amazon basin (Griffin et al., 2002), with a single storm moving up to and beyond 200 MT. Dust can carry toxic chemicals (entrained from sewage and waste dumps), micro-organisms (bacteria, fungi, viruses), and soil pollutants (herbicides, pesticides). Dust storms originating in China have been tracked from west to east in the USA. Bacteria and fungi transported with dust clouds from the Sahara have been cited as a probable cause of coral reef die-off in the Caribbean and for a 17-fold increase in asthma incidence in Barbados (Griffin et al., 2002). Dust is also a major health problem in the desert margins of central and eastern Asia (Derbyshire, 2003), where it has been exacerbated by deforestation and grazing in source areas. Although the evidence is not yet clear, a likely source of pneumoconiosis (non-industrial silicosis from the breathing in of silica-rich particles) is the Pleistocene loess deposits of northern China. Here, then, is a far-travelled natural hazard related to rapid change.

10. Commentary

In the cases quoted above, major and often abrupt natural changes had profound effects on people, settlements and ecosystems. The historical record contains many other examples where societies and settlements were harmed or failed in the face of abrupt environmental change (Issar and Zohar, 2004; Diamond, 2005). Nevertheless, there have been many recent expressions, especially in Europe and North America, of the belief that nature is inherently benevolent, with the only "downside" coming from human activities (Berger, 1998), though public attitudes may be changing after the Indian Ocean tsunami of 26 December 2004. In any case, if we are indeed moving into a period of rapid climatic and environmental change, there may be lessons for the near future from the record of past changes and their impacts on people. In addition to those given above, other potentially useful case studies might include

- the ways in which successive early Chinese dynasties coped with the dynamic Yellow River system (Zheng et al., 1998),
- the collapse of the Moche society, in what is now Peru, when their intricate system of canal irrigation was disrupted by neotectonic movements (Moseley, 1999),
- the response of the Anasazi people of the US Southwest to drought and local desertification (Gumerman, 1988),
- the control of human development by changes in glaciation and precipitation in the Tien Shan region of eastern Siberia (Aubekerov et al., 2003),
- the reaction of early peoples in the Arctic to post-glacial landscape change (McGhee, 1996),
- the way Bangladeshis living on islands and sand bars in the Ganges, Meghna, and Brahmaputra rivers respond to frequent flooding, erosion and deposition (Sarker et al., 2003), and
- the reaction of people living along the shores of the Caspian and Aral seas to frequent changes in shoreline position (Goudie, 2002; Nihoul et al., 2004).

Earth scientists have an important role to play here by de-coding the past and establishing the record of environmental change throughout human history. Recognizing more clearly the role of non-human inputs to abrupt environmental change could make a difference in the way people think about the world around them and the kinds of policies that might be adopted in the search for some kind of sustainability.

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