6 Surviving natural disasters

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Introduction

Natural disasters pose a rather different threat to that of disease. Volcanoes, tsunamis, hurricanes, floods and earthquakes are rare events, but when they hit they have the potential to obliterate communities in seconds. In this chapter I will focus on the threat posed by earthquakes and will discuss in particular the dreadful vulnerability of megacities in the developing world.

Surviving earthquakes: vulnerability in the modern world

It has already been a bad century for earthquakes, with well over a third of a million people killed in just four catastrophes: at Bhuj in India (2001; 20 000 dead), Bam in Iran (2003; 40 000 dead), Bandah Acheh in Indonesia (2004; over 200 000 dead) and Muzaffrabad in Pakistan (2005; 80 000 dead). As a seismologist, I am frequently asked whether disastrous earthquakes are more common now than they were in the past. It is an easy question to answer. Over the last thousand years, I know of 110 earthquakes that each killed more than 10 000 people (Figure 6.1). Yet 34 of them happened in the last century. In other words, a disaster of that magnitude happened, on average, about every 11 years from 1000 to 1900, about every 3 years for the next century, and now virtually every year.

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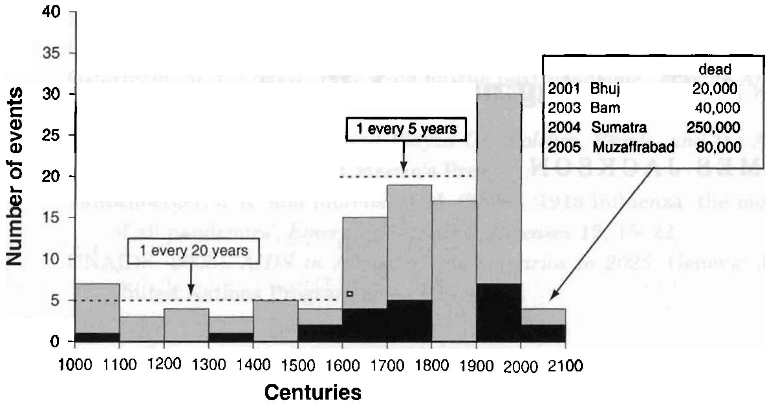

FIGURE 6.1 Histogram of the number of earthquakes killing more than 10 000 (gray) or 50 000 (black) people per century over the last 1000 years. There are 113 earthquakes in this figure, with 34 of them occurring in the last 100 years alone. Until about 1600 they averaged about one every 20 years, increasing to nearly one every 5 years between 1600 and 1900. This century we have had nearly one every year.

The answer to the question is obviously 'yes', and in fact the dramatic increase in such disastrous earthquakes has been since about 1600, but the emphasis is on *disastrous* – the effect is not caused by any change in the natural behaviour of our planet, as the earthquakes themselves are no more or less frequent now than they ever were, but is related to the way we now live, to our historical response to the natural environment, and to the rapidly increasing global population. A closer look at these recent disasters reveals the situation in which we now live. We will start with an apparently innocuous example.

A bull's-eye hit in the desert

In February 1994 the small desert village of Sefidabeh in south-east Iran was destroyed by an earthquake of moderate size (magnitude 6.1). Most of the 300 or so buildings in Sefidabeh collapsed, having been built of adobe, or sun-dried mud-brick, the traditional indigenous building material for desert villages, from which both walls and heavy roof domes are constructed. Adobe is a notoriously dangerous material in earthquakes, and the fact that only six people died in this case is attributed to the lucky chance of a small warning foreshock 24 hours beforehand, and to the local time of the mainshock (11.30 am), so that many people were outdoors anyway. But there is more to this story.

Sefidabeh is a desperately remote and inhospitable location, sandwiched between the two deserts of the Dasht-e-Margo (*lit.* 'desert of death') in Afghanistan and the Dasht-e-Lut (*lit.* 'barren desert') of south-east Iran; one of the very few stops on a long, lonely trans-desert trade route between north-east Iran and the Indian Ocean. It is the only habitation of any size for nearly 100 km in any direction, and yet the earthquake apparently targeted it precisely. Was this a case of extreme bad luck, or is there more to it?

Earthquakes happen when faults move. Faults are giant, planar knife-cuts through rock, in the case of Sefidabeh extending 20 km along the surface and 10 km deep into the Earth. The two sides are held together by friction, but occasionally jerk past each other in earthquakes, shaking and vibrating as they do so. The vibrations travel round the Earth as sound waves and are recorded, as seismograms, by permanent worldwide networks of sensitive instruments.

Our modern technology and understanding of earthquake-related faulting give us a forensic-like ability to work out exactly what happened at Sefidabeh in 1994. Analysis of the earthquake seismograms shows that the fault which moved was inclined at about 45° to the horizontal, and its movement pushed one side towards, and on top of, another. More detailed information comes from analysis of space-based radar measurements, which determine precisely the changes to Earth's surface that result from the fault motion, and allow us to fix exactly the location of the fault (a few kilometres south of Sefidabeh), its length (approximately 12 km), how deep it goes (approximately 10 km) and how much it moved (approximately 2 metres). In particular, the radar analysis shows that the top of the fault was about 4 km below the ground surface; in other words, that the slip on the fault was entirely confined below ground and did not reach the surface at all.

Instead of a fault rupture or scarp at the surface, what formed was a fold. As a useful analogy, imagine sliding the top half of a telephone directory over the bottom half towards the binding: the slip surface would be the fault but, because of the binding, a fold develops at the end of the fault. A fault of this type, in which slip fails to reach the surface, is called a 'blind' fault, and is shown in Figure 6.2a. Slip in a single earthquake is only a metre or two, but repeated earthquakes over hundreds of thousands of years cause the fold to grow into a ridge. The ridge adjacent to Sefidabeh is about 100 metres high and a dominant feature of the landscape. Furthermore, the landscape itself preserves clear evidence that the ridge is young in origin and had been growing as a result of previous earthquakes (see Figure 6.2b). Sefidabeh is built on an old 'alluvial fan', formed where an ephemeral river that used to flow through the ridge discharged its water, and with it sediment known as 'alluvium', onto the desert plain. But as repeated earthquakes caused the ridge to grow, not just in height but also by increasing its length towards the north-west, the river had to incise a gorge through it, eventually becoming blocked, and forming a lake. Finally the river abandoned this course altogether, and now flows round the north-western tip of the ridge instead. The old lake beds remain, now dry and elevated 70 metres above the desert plain. From the age of the sediments within them we can date the switch in the river course to about 100 000 years ago.

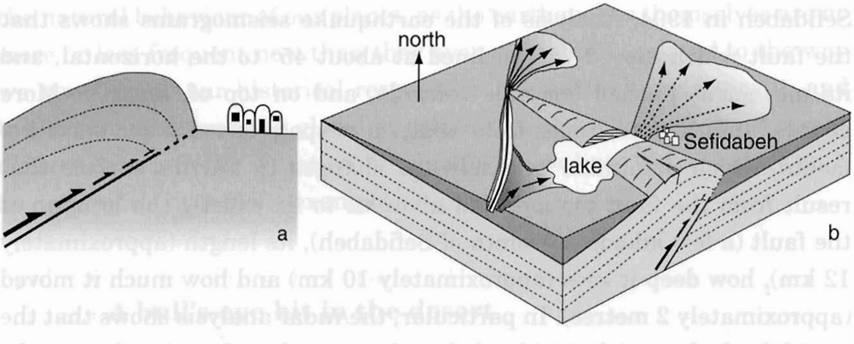

FIGURE 6.2 (a) Schematic cross-section of a 'blind' fault, adjacent to a village (not to scale). Slip on the fault (arrows) dies out towards the surface, which deforms by creating a fold. (b) Simplified cartoon of a blind fault and its fold at Sefidabeh in eastern Iran. The fold is about 10 km long. As the fold grew in repeated earthquakes, a river that used to flow across it first incised to make a gorge, then flooded to make a lake, and was finally abandoned when the river course switched to flow round the north-west end of the fold.

Thus, well before the earthquake, all the signals were there in the landscape that Sefidabeh was in a vulnerable location – if people had only seen them and known how to read them (they hadn't: Sefidabeh was too remote for anyone to have noticed). 'Blind' faults of this type are very common in Iran, as the whole country is being squashed in a north–south direction between the converging Arabian and Eurasian plates at about 25 mm per year. But our ability to recognise the folds created at the surface by blind faults like the one at Sefidabeh dates only from 1980, when one moved in the El Asnam earthquake in Algeria. Earlier devastating Iranian earthquakes of modern times that occurred on similar blind faults include those at Ferdows in 1968 (magnitude 6.3, approximately 1000 killed) and Tabas in 1978 (magnitude 7.3, approximately 20 000 killed). In neither of these cases were the causative faults recognised at the time, though, in retrospect, they are clear in the landscape. The city of Bam, destroyed in 2003 (magnitude 6.8, approximately 40 000 killed) was also located on a blind fault of this type, which was recognised beforehand, though the faulting in that earthquake was more complicated. In each of these cases, at Sefidabeh, Ferdows, Tabas and Bam, the earthquakes involved blind faults that we now know about in detail. But they share another characteristic too; each place was the only substantial habitation for tens of kilometres in any direction, and yet the earthquakes apparently targeted them precisely. We have not yet explained why the earthquakes apparently scored bull's-eye hits in each case.

Faults and water

The answer is water. Sefidabeh means 'white water', and the village obtains its water from the white lake beds in the uplifted ridge, which leak in a series of springs at its base. The fault is responsible for the subsurface aquifer of the lake beds, and ensures their continual uplift and elevation above the plain, causing the formation of springs. Sefidabeh is the only place where it is possible to live and attempt a meagre agricultural existence in this extremely inhospitable desert environment, as it is the only place with water. It is the fault that provides the water, but the fault may kill you when it moves.

This situation is common in Iran. The country is mountainous except for flat regions in the interior, which are barren salt flats. The mountains provide the water, so habitations are common at the foot of range fronts, many of which exist because they are elevated by movement on faults, just like the ridge at Sefidabeh. For centuries, the indigenous people have exploited this situation. Some horticulture is possible on the toes of alluvial fans coming off the ranges, on the finer-grained material away from the coarse debris adjacent to the steep slopes; but only if water is available. The water table is usually elevated at the range front, sometimes exaggeratedly so if there is an active fault, because repeated grinding of rocks on the fault creates a very fine, impermeable clay (called 'fault gouge') that can act as an underground dam to the water table, elevating it still further. Tunnels are dug, by hand, back to the range through the semi-consolidated fan material, to tap the elevated water table at the range front. In Iran, these tunnels are called *qanats*, and are one of the glories of the ancient Persian civilisation. They can be several tens of kilometres long, up to 100 metres deep at the range front, and are marked at the surface by lines of circular craters, where vertical shafts are sunk down to the tunnels to provide access, ventilation and removal of excavated material during construction. Many have been in continuous use for centuries, and the oldest are thought to have been dug more than 2000 years ago. More details of qanat history and construction are given by in a book by Anthony Smith and in an article by Hans Wulff.

Qanats provide fresh, continuous supplies of water, with little evaporitic loss, to thousands of villages in the deserts of Iran and other countries in the Middle East and central Asia. They are engineering wonders, and the very lifelines by which existence is possible for many. For example, the oasis city of Bam, destroyed in 2003, uses water from qanats that tap the nearby aquifer above a blind fault to feed the date-growing region of Baravat, one of the most famous date-producing regions in the Middle East (Figure 6.3). It is this fault-controlled water supply that determines where Bam–Baravat is located, and why it was destroyed. Elsewhere in the desert, qanats bring water to fantasy pleasure-gardens, with cascading pools of water surrounded by trees and pavilions, such as at the central Iranian town of Mahan (Figure 6.4a) and the oasis of Tabas (destroyed in the 1978 earthquake).

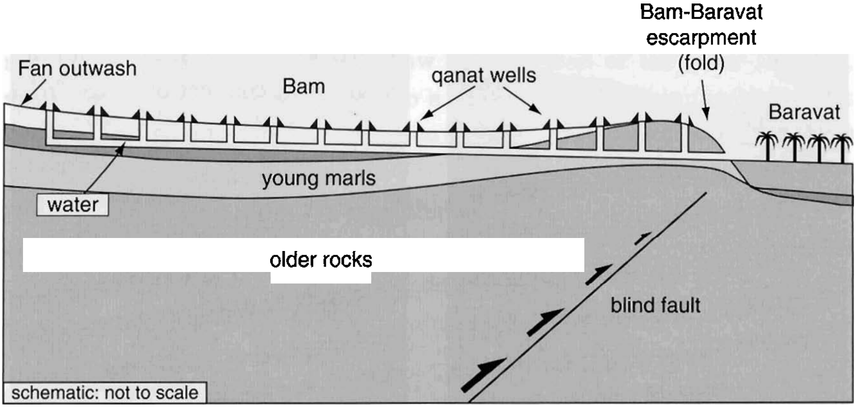

FIGURE 6.3 Schematic section of the irrigation tunnel ('qanat') systems feeding the date growing region of Baravat adjacent to Bam. The blind fault has created a fold which ponds the sub-surface water flow through the young outwash from the adjacent mountains, as the underlying lake beds (marls) are relatively impermeable.

Living in the desert

For centuries, Iranian civilisation and desert existence has lived with, and exploited, the link between mountains, faulting and water supply. This relationship can be illustrated by three short examples.

The beautiful desert oasis of Tabas, properly known as Tabas-e-Golshan (*lit.* 'Tabas the flower garden'), visited by Marco Polo in the thirteenth century, was destroyed in 1978 by movement on a series of blind faults, whose folds are clearly visible in the landscape. The water supply for Tabas comes from the adjacent range front by qanats which penetrate the nearby fold. The fold is also cut by the ephemeral Sardar river, which has incised a deep gorge through the rising ridge, in the same way as the stream at Sefidabeh, before its gorge was finally abandoned (Figure 6.2b). But unlike at Sefidabeh, the Sardar river at Tabas still maintains a gorge through the rising fold, though it only occasionally contains water. In the past, this river caused problems of its own, when flash summer thunderstorms in the mountains produced great volumes of water that were trapped within the Sardar gorge and then discharged when the river emerged through the fold, to flood Tabas. The local response, attributed to Shah Abbas (seventeenth century), was to build a dam or water-gate where

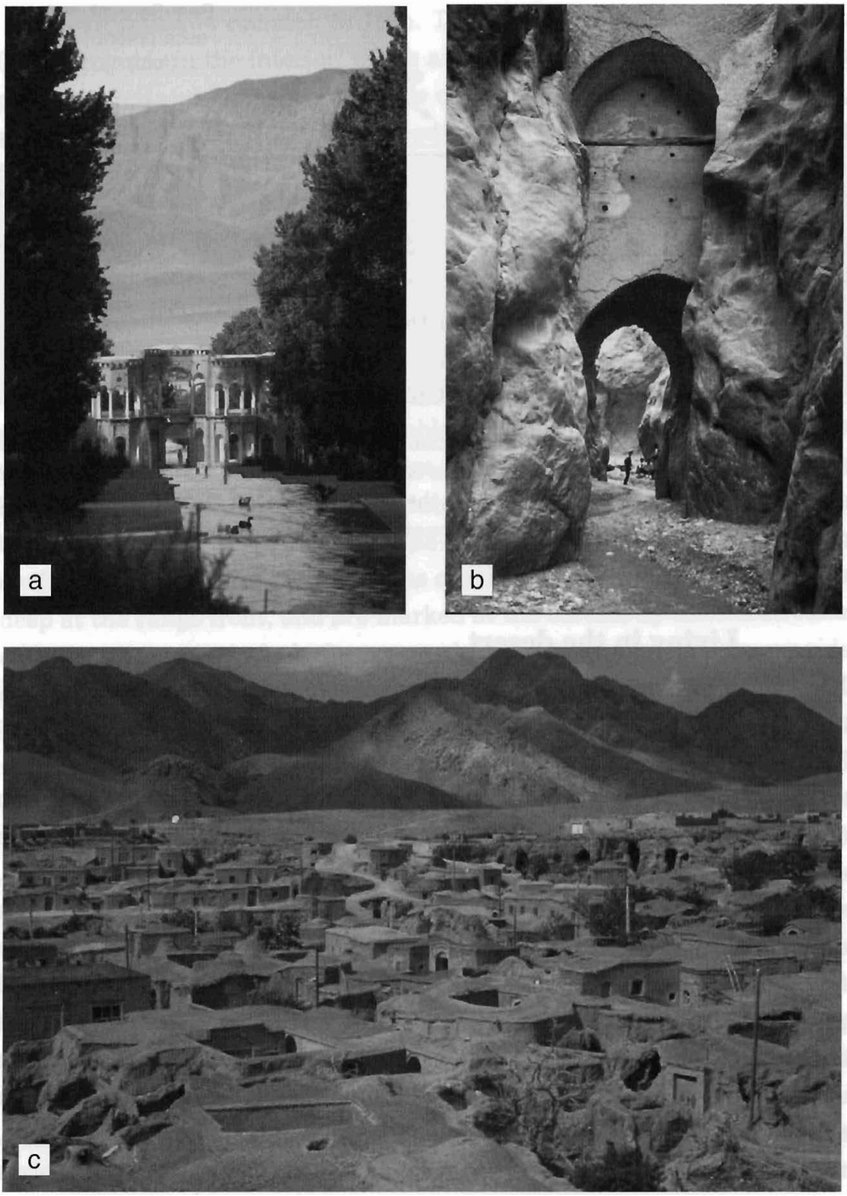

FIGURE 6.4 Living with earthquakes and faults. (a) The water gardens at Mahan, in the desert between Bam and Kerman, fed by qanats from mountains several kilometres away. (b) The seventeenth-century water-gate across the Sardar river at its narrowest point upstream from the oasis of Tabas-e-Golshan. (c) View over the mud roofs of a village near Ferdows in the desert of eastern Iran. The blue roofs are coated with a clay which is impermeable fault gouge excavated from a quarry at the foot of the range front in the background, where the fault comes to the surface.

the river leaves the mountains (Figure 6.4b); but one in which there is a vaulted arch at the base to allow the bed-load of the river through, while limiting the head of water to a height that was manageable. This ingenious, maintenance-free solution to flood control has stood for 350 years, and is still effective today.

After the devastating 1968 earthquake at Dasht-e-Bayaz in eastern Iran (magnitude 7.1, approximately 12 000 killed) several qanats were cut and offset by horizontal movement on the causative fault, which slipped up to 4 metres in places. These qanats were then either abandoned or repaired by reconnecting the offset channels. There is clear evidence on the ground, and in aerial photos (Figure 6.5) for earlier generations of qanats that had been offset and abandoned in previous earthquakes. Even more remarkable are subsidiary, minor, qanat tunnels that had been dug long ago so as to feed into the main channels, and which followed precisely the line of the 1968 fault rupture. These side-tunnels exploit a change in water-table level across the fault, caused by the impermeable clay fault gouge, to tap and increase the water flow into the main tunnels. Thus the local tunnel-builders were aware, and had exploited, the fault-related hydrology for a considerable time before the modern earthquake (and before seismologists or geologists understood any of this).

Figure 6.4c shows a view over a desert village near the town of Ferdows (destroyed in 1968, 1000 killed), towards a fault-bounded range front. The houses are built of adobe walls, with roofs either of mud-brick domes or of poplar logs laid horizontally and sealed with mud. Most of the roofs have a distinctive blueish hue, caused by the clay that is used to seal against the winter rains. The clay comes from a quarry at the foot of the range front, and is in fact the fault gouge itself, made from finely ground volcanic rocks. The material is suitable for this purpose, being fine and relatively impermeable. Such blueish mud roofs are a common sight at range-front villages in eastern Iran.

Villages, mega-cities and population growth

The point of the examples cited so far is to illustrate that, for centuries, desert-rim existence in Iran had established a way of living with earthquakes. Earthquake faulting, and the topography it produces,

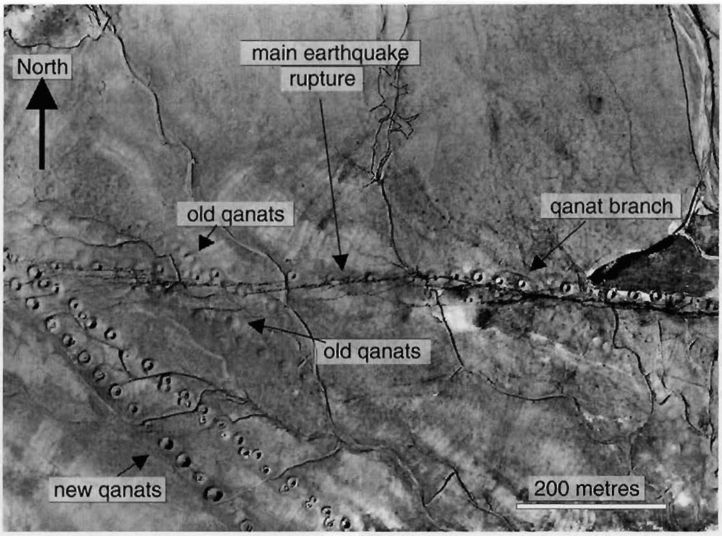

FIGURE 6.5 Aerial photo of qanats in the Nimbluk valley, taken after the 1968 Dasht-e-Bayaz earthquake in eastern Iran. The earthquake fault rupture runs east–west across the centre of the picture and moved horizontally, with the north side sliding to the west. Multiple generations of qanats are visible, the most recent were cut by the 1968 faulting, but these were replacements for earlier qanats, whose lines of craters are now heavily eroded, that were presumably abandoned after earlier earthquakes. One qanat follows precisely the line of the fault rupture, increasing the water flow into the main north-west–south-east qanats by tapping an underground change in water level, ponded by impermeable clay gouge on the fault. (Photo courtesy of N. Ambraseys.)

is largely responsible for the water resources and for the locations of habitations and agriculture, as well as of some building materials. Occasionally, earthquakes moved the faults, and villages were destroyed, but the repeat times of earthquakes on individual faults are likely to be measured in thousands of years and they are most unlikely to recur on a timescale relevant for human memory. When earthquakes do occur, the destruction, and particularly the mortality, can be shocking, because of the vulnerable local building styles. Thus in the town of Tabas in 1978, more than 80% of the population (11 000 out of 13 000) were killed outright; at Bam in 2003 the figure was nearer 30%. Most places are, nonetheless, rebuilt and resettled because their location is, in the end, determined by where water is available and agriculture is possible. In the past, when rural populations were relatively small and dispersed, the frequent earthquakes of magnitude 6–7 that occur in Iran would kill typically a few hundred or thousand people. A modern example is the earthquake near Zarand, north-west of Kerman, in February 2005 (magnitude 6.4), which destroyed two villages, killing 500.

The problem is that villages grow, and have grown, rapidly, while building quality remains equally vulnerable, though it may change from weak adobe houses to poorly built multi-storey apartment blocks, and so mortality rates remain appallingly high. Thus the village of Sefidabeh (6 killed in 1978) can become the large rural town of Tabas (11 000 killed in the town in 1978; 20 000 including other villages of the oasis), or the small cities of Bam (40 000 killed in 2003) or Rudbar (40 000 killed in 1990), or the mega-city of Tehran, which now has a daytime population of 10–12 million. The case of Tehran is instructive. It is situated at the base of the Alborz mountain range front (Figure 6.6), which is elevated by movement on an active fault. Several other active faults are also situated nearby. Until as recently as the 1930s, Tehran's water supply came entirely from qanats that penetrated these faults, though now the water table has been considerably lowered by groundwater extraction, and the qanats are no longer operative. In former times, the site of Tehran was occupied by relatively small towns on a major trade route. These predecessors of modern Tehran were damaged or destroyed completely in earthquakes of probable magnitude about 7 in 855, 958, 1177 and 1830, but the number of killed was probably quite small by modern standards, perhaps measured in hundreds or thousands. The modern Tehran is a mega-city that grew rapidly on the same site in the later twentieth century. While the Tehran site was occupied by relatively small towns, the city of Tabriz was always bigger, more prosperous and far more important as a trade-route crossroads. Tabriz was devastated by major earthquakes on its nearby faults in 1721 (more than 40 000 killed) and 1780 (more than 50 000 killed), at a time when the population was a small fraction of today's.

The message is clear: there is no sign that the concentration of population into large towns and cities in Iran is accompanied by a decrease in the mortality rate during earthquakes. Many major towns and cities are situated adjacent to range fronts and faults, in places that made sense

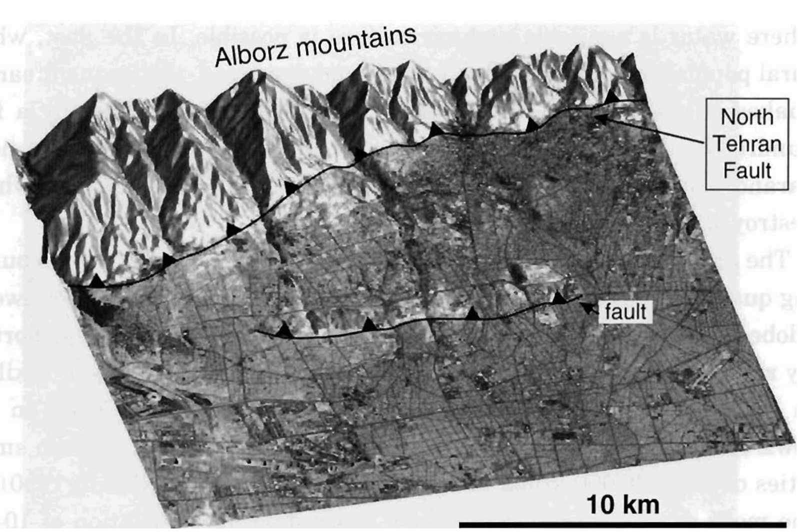

FIGURE 6.6 Perspective view looking north over Tehran, formed by draping a satellite image over a digital topographic model. The North Tehran Fault runs along the foot of the Alborz mountains. Another fault forms the ridge in the centre of the city; note how rivers incise gorges upstream of the fold, as in Figure 6.2b. This ridge is the location of a new hospital in Tehran as well as of a landmark telecommunications tower. Until the 1930s, Tehran's water supply came from qanats that tapped the faults adjacent to the mountains.

when they were initiated as agricultural settlements, and they retain that vulnerability to earthquakes. In such places, earthquakes that in the past killed a few hundred or thousand people will now kill tens or hundreds of thousands, or more.

The link between how and where people live and earthquakes is particularly dramatic in Iran, but for many other parts of the great earthquake and mountain belts that run from Italy to China, the situation is similar. Throughout this region the mountains are largely created by fault movement in earthquakes, pushing blocks of rocks on top of each other, all ultimately the result of the ongoing collision between the Eurasian plate and the African, Arabian and Indian plates to the south (Figure 6.7). Large tracts of this area are either low, barren, inhospitable deserts, or high, inaccessible and also inhospitable plateaus, such as Tibet. Habitations

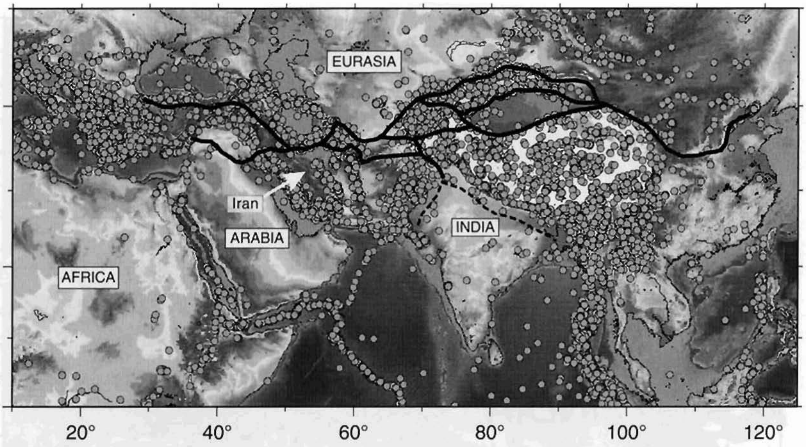

FIGURE 6.7 A map of earthquakes (gray dots) in the Mediterranean, Middle East and Asia in the period 1964–2002. The earthquakes follow, and are ultimately responsible for the growth of, the mountains that run from Italy to China, and are caused by the northward motion of Africa, Arabia and India into Eurasia. The ancient east–west trade routes, shown as black lines, follow the earthquake belts along the edges of the mountains, avoiding the flat inhospitable deserts adjoining them. Habitations along these routes have evolved from small villages, into towns, and now cities of a million or more people. Thus earthquakes which, in the past, killed a few hundreds or thousands, will now kill many more, when they recur.

concentrate around the edges of these regions, at the range fronts, because their locations are on trade routes, are of strategic importance controlling access, or are near water supplies. But the range fronts are often faults, and many of these places have been destroyed in past earthquakes.

Thus we come to the 2005 Pakistan earthquake (magnitude 7.5) which destroyed the Himalayan town of Muzaffrabad, killing at least 80 000. The fault responsible for this earthquake also pushed one side (Tibet), over another (India), and is ultimately responsible for building the Himalayan range itself. The part that moved in 2005 was a 100-km section of a much longer system of faults that stretches east–west for 3000 km, from northwest Pakistan to Assam (Figure 6.8), all of which moves because India and Tibet converge at about 20 mm per year. Figure 6.8 shows the locations of earlier earthquakes on this fault system, some of them much larger than the one in 2005. Three such events happened in the last century, in 1905,

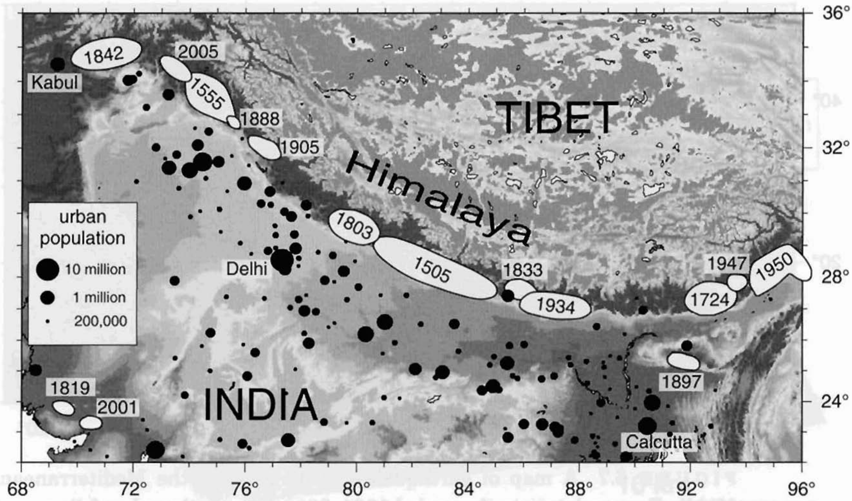

FIGURE 6.8 White areas with dates are the sites of large earthquakes along the Himalayan range front between 1500 and 2005. Also shown are significant population centres in the region, many of which are vulnerable to future repeats of these past earthquakes. (Data from Roger Bilham.)

1934 and 1950. Each one killed a few thousand people, but since those times the population of the Ganges basin has increased dramatically, and it is now one of the most densely inhabited regions on Earth, with many cities of over a million people. The flat plain of the Ganges valley contains thick sequences of water-saturated sand and mud washed off the rising Himalaya and deposited by the river. When shaken in strong earthquakes, the sediments liquefy, releasing water which spouts to the surface as springs and sand 'volcanoes'. The effect is similar to walking on a sandy beach just washed by an incoming wave: water-saturated sand 'flows' easily through one's toes. Such liquefaction of sand is well known, and is described dramatically by a geologist who observed the 1934 earthquake in Bihar:

> As the rocking ceased ... water spouts, hundreds of them throwing up water and sand, were to be observed on the whole face of the country, the sand forming miniature volcanoes, whilst the water spouted out of craters, some of the spouts were quite 5 feet high. In a few minutes – as far as the eye could see – was a vast expanse of sand and water, water

> and sand. The road spouted water, and wide openings were to be seen across it ahead of me, and my car sank, while the water bubbled and spat, and sucked, till my axles were covered. 'Abandon ship' was quickly obeyed, and my man and I stepped into knee deep water and sand and made for shore. (From: 'The Bihar-Nepal earthquake of 1934', *Memoirs of the Geological Survey of India*, vol. 73, p. 34, 1939.)

A large earthquake on the Himalayan front will cause such effects over a substantial part of the Ganges valley, liquefying an area perhaps 100–200 km long and a several tens of kilometres from the mountain front. The consequences of such liquefaction for multi-storey buildings is to make them sink, then collapse, as was observed widely in the 1964 Niigata earthquake in Japan. An important difference between the situations in 1934 and today is that the population throughout the Ganges valley is now not only much bigger, but is concentrated in large cities and living in poorly constructed multi-storey apartment blocks. Of particular concern is the obvious 'gap' in earthquakes along the Himalayan front north of Delhi, where no major event has occurred since at least 1500 and where the concentration of major cities is particularly dense. There is little doubt that earthquakes which once killed a few thousand would now kill many more, perhaps hundreds of thousands or more, when they recur in the future, as is inevitable. Thus the earthquake at Muzaffrabad in 2005, though by no means the biggest known earthquake along the Himalayan front and certainly not in the most densely populated part of it, killed many more people than any of the previous known earthquakes in Figure 6.8. The lesson of Muzaffrabad is that there is worse to come.

Tsunamis and the earthquake cycle

The Sumatra–Andaman earthquake of 2004 was the second largest on Earth in the last 100 years; only the 1960 Chile earthquake was larger. To put this massive event into some perspective, the fault that moved was 1200 km long (a distance from London to Rome) and slipped up to 25 metres. By comparison, the fault that destroyed Bam in Iran in 2003 was 12 km long, and moved about 1 metre. The time taken to tear the fault from one end to the other took 7 minutes in Sumatra, compared with 7 seconds in Bam. As in all the previous examples, the fault in the Sumatra earthquake pushed one block (Sumatra) on top of another (the Indian Ocean), and is the same type of fault that occurs round most of the edge of the Pacific as well.

Most of the people who perished in this earthquake died in the tsunami, and most of those lived close to the fault that moved, in Sumatra, though several thousand were killed when the tsunami hit the more distant shores of Thailand, Sri Lanka, the Maldives and East Africa. To appreciate what happened, and the consequences for the future, one must first understand the nature of the earthquake cycle, illustrated in Figure 6.9. The Indian

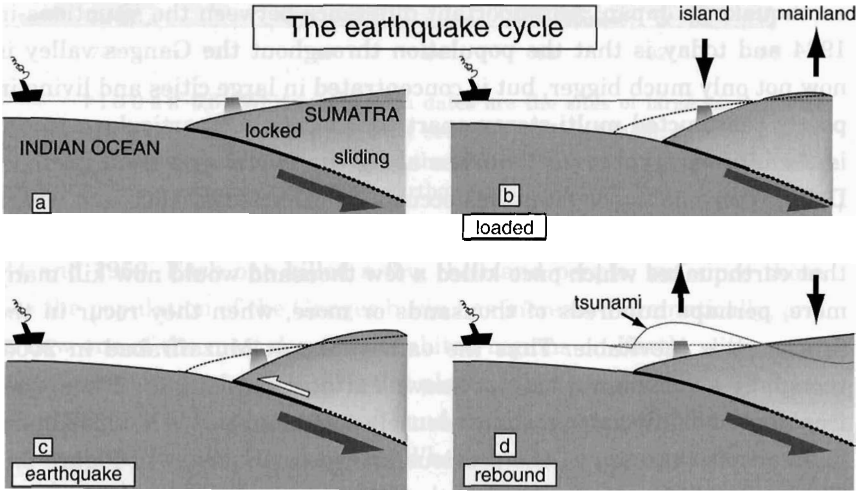

FIGURE 6.9 The earthquake cycle. (a) As the Indian Ocean slides eastwards beneath Sumatra at about 60 mm per year (big arrow), the fault (solid black line) separating them is locked by friction above 40 km depth. Below this depth (dashed line) the rocks are sufficiently hot and weak to slide continuously. (b) As the locked fault is dragged down by the steady movement of the Indian Ocean, the island adjacent to fault is submerged, while the mainland coast is bulged up. Their original levels in (a) are shown by the dashed line. At this stage the fault is 'loaded' and ready to slip in an earthquake. (c) When the earthquake happens, the fault is released (white arrow). (d) The sea bed returns to its original level in (a), but this happens so quickly that the sea surface itself is offset, creating a broad wave, or tsunami, which then flows away in both directions. The cycle then repeats, with about 200–300 years between earthquakes.

Ocean slides beneath Sumatra at a steady rate of about 60 mm per year (Figure 6.9a). The fault is the interface between them, but is locked by friction and does not move at depths less than about 40 km; below that depth the rocks are sufficiently hot and weak and can slide past each other steadily. Since the fault is locked, it is dragged down by the moving Indian plate, causing the island near the fault to be submerged, while the adjacent mainland is bulged up and raised higher (Figure 6.9b). Eventually the strain accumulated on the fault overcomes the frictional resistance and the fault is released (Figure 6.9c), uplifting the island and sinking the mainland, so that they return to their original positions (Figure 6.9d), and the whole cycle can then repeat again (back to Figure 6.9a). In Sumatra the repeat time between earthquakes is around 200–300 years. When the fault moves in the earthquake, the land surface above the fault is restored very quickly, changing elevation by up to 5 metres in about 5 seconds. As a result, the sea surface also changes quickly, uplifted near the island and dropped near the mainland, forming the wave known as a 'tsunami'. The wavelength of the tsunami (i.e. twice the distance from peak to trough) is about 300 km, much greater than the average water depth of the deep oceans (about 5 km), and it is this property that allows the tsunami to travel round the world with little change in shape and a speed of around 800 km per hour.

This basic process, and the properties of such tsunamis, have been well understood for some time. Since the wave keeps its shape as it travels, people to the west of the fault (left side of Figure 6.9), in Sri Lanka, the Maldives and East Africa, experienced a big up-pulse followed by a down-pulse. Those in the east (right of Figure 6.9), in Thailand and coastal Sumatra, experienced first a down-pulse, or withdrawal of the sea, followed by an up, or large incoming wave. Even travelling at 800 km per hour, it takes 15–20 minutes for the down pulse of the wave to travel its length before the high incoming wave that follows it can arrive. After the event, many newspapers showed shocking pictures of tourists in Thailand who went down to the beach to examine the exposed sea bed, with its mud, old wrecks and stranded fish; some of these people were drowned when the incoming high wave followed 15–20 minutes later.

From this simple account, it is clear that what matters in this situation is education, or knowing what to do. If the sea withdraws, you have about

10–15 minutes to run inland and try to reach higher ground. If you are on the beach and feel a large earthquake, it is best to assume there will be a tsunami to follow, and run inland without delay. Around the Pacific, in south, central and north America, in Japan, the Philippines, and New Zealand this lesson is repeated frequently to schoolchildren and, because such earthquakes and tsunamis are relatively frequent, the general level of awareness is high. In the Indian Ocean, such events are much rarer, and most people did not know what to do. There were, however, exceptions. The people of Simeulue Island, west of Sumatra and in the position of the island in Figure 6.9, did know what to do, because of an earlier earthquake in 1907, the memory of which had been passed down through older people. On that island only seven people were killed out of 75 000, compared to well over 200 000 killed in northern Sumatra. Similarly, in some of the Andaman and Nicobar islands north of Sumatra, the indigenous ancient tribes knew what to do, and survived, while more recent immigrants from the Indian mainland did not, and drowned.

As in the earlier examples from Iran, the earthquakes affect and control the landscape on a timescale that is relevant to human occupation. Figures 6.10a and 6.10b show part of Simeulue Island, whose coast was uplifted in the rebound after the 2004 earthquake (Figure 6.9d): the chequerboard pattern exposed in the mud flats now uplifted above high-tide level is formed by old rice paddy fields that were submerged and abandoned in the sinking, or loading, phase of the earthquake cycle (Figure 6.9b), probably several generations ago. Now they have been returned to an elevation that allows them to be cultivated again. The December 2004 earthquake was followed by another, also very big earthquake, in March 2005, further south-east along the coast of Sumatra. Figure 6.10c shows part of the island of Nias, taken in January 2005, when the island had been submerged by the fault-loading phase (Figure 6.9b), drowning an earlier coconut plantation. After the March 2005 earthquake, the land rebounded (Figure 6.10d) returning the once-drowned plantation to a position above high-tide level. These examples show that it is not surprising that a rudimentary knowledge of the effects of large earthquakes should survive in coastal populations, providing they are stable and sedentary enough for such experience to accumulate as folklore. Observations similar to those in Figure 6.10 show us that the fault further south-east of the 2004 and

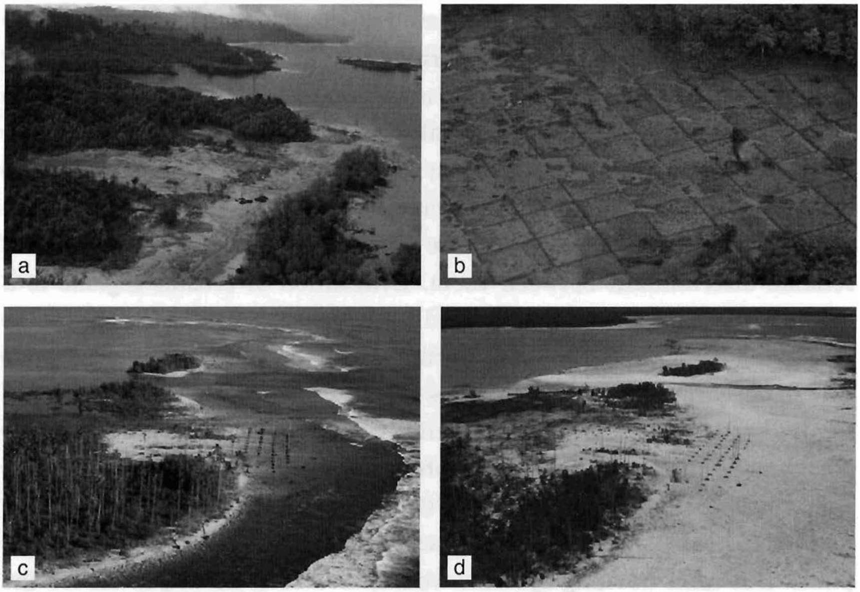

FIGURE 6.10 Observations of the earthquake cycle on human timescales. (a) Aerial photo of Simeulue Island, taken after the December 2004 earthquake. The island is in the position shown in Figure 6.9b, and has rebounded up after the earthquake (Figure 6.9d) lifting it out of the water. High-tide level before the earthquake was at the base of the trees; the mud flats are now exposed at all stages of the tide. (b) Close-up of part of the mud flats near (a): the chequerboard pattern reveals rice paddy fields, originally submerged in the loading phase of the cycle (Figure 6.9b) and abandoned, but now re-exposed after the earthquake. (c) Part of the coastline of Nias Island, before the March 2005 earthquake. High-tide level is at the beach near the palm trees. Note the regular pattern of tree stumps in the water in the centre of the picture: these are the remains of a coconut plantation, dragged beneath the sea and killed during the loading cycle (Figure 6.9b). (d) View of the same area as (c) taken after the March 2005 earthquake: the entire region has rebounded and been uplifted by the earthquake (Figure 6.9d), so that the coconut plantation is now exposed at all stages of the tide. This picture was taken near to high tide. (All photos courtesy of Kerry Sieh.)

2005 earthquakes, closer to the urban centres of Padung and Djakarta, is loaded and ready to break sometime in the future; this story from Sumatra is not over yet.

In the aftermath of the 2004 disaster, there was much talk of tsunami warning systems in the ocean. These exist already in the Pacific, in the form of ocean-bottom pressure sensors that can detect a tsunami wave as it passes over them, and issue an alert via satellite-based communications. Such a system can give warnings of a few hours to places a few thousand kilometres distant from the earthquake source area, such as Hawaii. They were installed to reduce false alarms; not all oceanic earthquakes generate tsunamis that will travel large distances, and seismological information alone is rarely sufficient, or can be processed quickly enough, to be a reliable discriminant between them. Evacuation of coastal regions is a difficult and expensive business, and false alarms reduce the willingness of coastal populations to heed warnings. In the case of the Sumatra–Andaman earthquake, such systems would probably not have been able to give sufficient warning in Thailand (which the tsunami reached after 40 minutes), might have been helpful in Sri Lanka (2 hours), probably would have helped in the Maldives (3.5 hours) and certainly would have helped in East Africa (8 hours), if accompanied by effective contingency plans. But such warning systems would have been no use at all for the local coastal populations in Sumatra, who sustained by far the majority of the casualties, and who had less than 20 minutes after the earthquake before the tsunami hit. A necessary condition for saving lives in that situation is knowing what to do. That, of course, may not be sufficient in itself: in some low-lying coastal and delta regions there may be no high ground nearby, and some attention to engineered infrastructure may be necessary, in the form of constructing evacuation routes, high stable structures that will allow a wave to pass beneath them ('vertical evacuation'), or even barriers to deflect or reduce the initial impact of the wave: these are all aspects that are being addressed in the circum-Pacific, and much expertise is available. Nonetheless, the effectiveness of education in tsunami-prone regions is so clear that it should be given very high priority.

Earthquake vulnerability in the modern world

The developing world has seen a relentless rise in population and its concentration into large towns, cities and megacities. In the great earthquake belts of Asia, many of these concentrations are adjacent to mountain fronts and faults, largely because of their agricultural origins. Yet their development has not been accompanied by a decrease in their vulnerability to earthquakes. The existence of building codes in many of them, poorly enforced or observed, has had little effect in many of the countries concerned, and mortality rates remain shockingly high: for example, 20–35% of the population (between 240 000 and 500 000) died in the 1976 Tangshan earthquake in China. Half the world's mega-cities of more than 10 million inhabitants are in locations vulnerable to earthquakes, and events that in the past killed a few hundred or thousand people will now kill tens or hundreds of thousands, or more. The reason we have not yet had an extreme catastrophe, with over a million killed in one earthquake, is only because these cities have been exposed for a short time (about fifty years) compared with typical repeat times of earthquakes on faults (usually hundreds or thousands of years). But a catastrophe of those dimensions seems to me to be inevitable, and will probably occur in this century.

Meanwhile, the developed nations have had great success in reducing the earthquake vulnerability of their urban populations, at least for moderate-sized earthquakes. In California, and increasingly in Japan, earthquakes of magnitude 6 to 7, which can routinely kill tens of thousands in rural areas of the Middle East and Asia, are now principally stories about economic loss. The earthquakes at Loma Prieta in northern California (1989; magnitude 7.1, 64 killed) and Northridge in southern California (1994; magnitude 6.8, 50 killed) occurred in regions that would be considered urban or suburban compared with Bam (2003; magnitude 6.8, 40 000 killed) or Tabas (1978; magnitude 7.3, 11 000 killed) in Iran. Expressed as proportions of the local populations, the mortality figures of the Californian earthquakes are insignificant (much less than 0.1%) compared to those of the two in Iran (roughly 30% and 85%). This comparison is not to lessen the importance of economic loss, as that can also be devastating for developing countries. The costs of the 1989 and 1994 Californian earthquakes were 0.2% and 1% of the regional (not national) GDP, while the cost of the 1972 Nicaragua and 1986 El Salvador earthquakes were 40% and 30% of those countries' *entire* GDP. The experiences of California and Japan are testaments to good building-design codes, sensibly enforced, though whether those same designs will prove effective in earthquakes much bigger than magnitude 7, in which shaking durations and ground displacements are much larger, is uncertain. Nonetheless, the message that good buildings save lives could not be clearer, and is an issue far more important than demands for earthquake prediction, which has remained scientifically elusive.

The future: what can be done?

What can be done about the appalling earthquake vulnerability of large mega-cities in the developing world? The problem is immense and urgent, often generating a response of despair in local politicians who can see no achievable result with the limited resources at their disposal, which are anyway in demand by other projects. Certainly, it involves preparation for the inevitable extreme catastrophe, so as at least to attempt to cope with its consequences. But it also needs a sustained determined effort at hazard mitigation and reduction *before* such a catastrophe occurs, and one that must embrace a large number of cities. The problem of what to do about populations that are already housed in poorly constructed apartment blocks that accompanied the rapid growth of mega-cities is particularly difficult. One thing at least is clear: we can expect 2 billion people to be added to the cities of developing countries over the next twenty years. This will be the biggest construction boom in history, and for those people at least, we should try and ensure that this construction conforms to good building practice and good land-use planning. In this more limited goal, education plays a key, and deliverable part. In the 1994 Northridge, California earthquake, the modern USC hospital, located near the fault that moved, was completely undamaged and remained functional, with no interruption to operations. The famous quote was that 'Not one test tube was lost.' Patients refereed to 'a gentle rocking' and did not know a major earthquake was occurring until they heard about it later from hospital staff. In the same-sized earthquake of 2003 at Bam, in Iran, all the modern hospitals and clinics ceased to function through collapse or damage. When the public in the developing world start to realise that total destruction is not inevitable, and to demand that their new buildings conform to modern standards in the West, some progress, at least, will have been made.

The next chapter considers another threat to survival whether the risk of mortality is modulated by global inequalities – famine.

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