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Fatal attraction: living with earthquakes, the growth of villages into megacities, and earthquake vulnerability in the modern world

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The great earthquake belt which stretches from the Mediterranean through the Middle East into Central Asia results from the ongoing collision between the Eurasian plate and the African, Arabian and Indian plates to the south. Through much of this belt, the topography is created and controlled by fault movement in earthquakes. Many habitations are located at the foot of the fault-controlled mountain range-fronts that bound inhospitable deserts or elevated plateaus, in positions that are favourable for trade-routes, strategic control of access or for water supply. As a result, they are vulnerable to earthquakes, which often seem to have targeted population centres precisely. For many centuries, an uneasy accommodation was reached between human needs and the earthquake-controlled landscape, sometimes brilliantly exploited by local hydrological engineering, as in Iran. Occasional earthquakes would occur, killing a shocking proportion of the population, but the populations of the settlements themselves would be relatively small. Many once-small rural communities have now grown into towns, cities or megacities, while retaining their vulnerability through poor building standards. Earthquakes that occur in these places today now kill many more than they did in the past, as we have witnessed in the last few years. Extreme catastrophes have been rare only because the exposure of modern megacities to earthquake hazards has been relatively short (approx. 50 years); an increase in the number of such catastrophes now seems to be inevitable.

Keywords: earthquakes; seismic hazards; active faulting; Iran; qanats; megacities

1. A tale from the desert

In February 1994, the small desert village of Sefidabeh in southeast Iran was destroyed by an earthquake of moderate size (magnitude, M_w, 6.1). Most of the approximately 300 buildings in Sefidabeh collapsed, having been built of adobe, or sun-dried mud-brick, the traditional indigenous building material from which both walls and heavy roof domes are constructed. Adobe is a notoriously dangerous material in earthquakes (Ambraseys & Jackson 1981), and the fact that only six people died in this case is attributed to the lucky chance of a foreshock 24 h beforehand, and to the local time of the mainshock (11.30), so that many people were outdoors anyway. But there is more to this story.

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One contribution of 20 to a Discussion Meeting Issue 'Extreme natural hazards'.

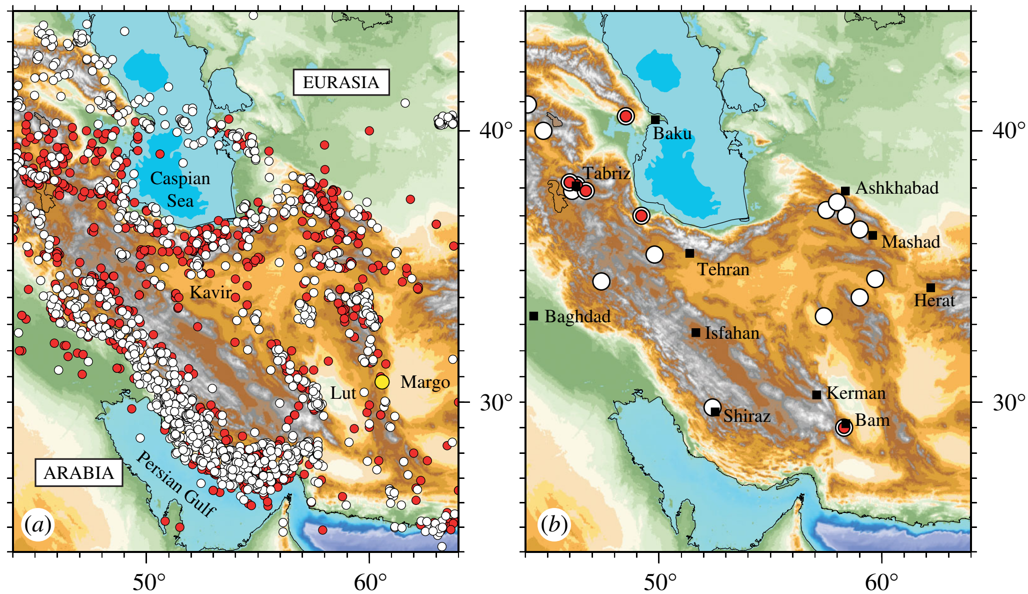

Figure 1. Earthquakes in Iran and its surroundings. (*a*) White dots are well-located earthquakes of magnitude greater than 4 during 1963–2002 from the updated catalogue of Engdahl *et al.* (1998). Red dots are earthquakes of the previous 1000 years, thought to be bigger than magnitude 5, from Ambraseys & Melville (1982), complete only to 41° N. The yellow dot is the location of the village of Sefidabeh, mentioned in the text. The deserts of the Dasht-e-Margo, Dasht-e-Lut and Dasht-e-Kavir are labelled and relatively free of earthquakes, which concentrate near the edges of the high topography. (*b*) Earthquakes of the last 1000 years that have killed more than 10 000 (white dots) or 30 000 people (red dots); see table 1. Of these 15 earthquakes, 5 occurred in the last 50 years.

Sefidabeh is a desperately remote and inhospitable location (figure 1*a*), 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 southeast Iran; one of the very few stops on a long, lonely trans-desert trade route between northeast 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. Is this a case of extreme bad luck, or is there more to it?

With our modern technology and understanding of earthquake-related faulting, we now know exactly what happened (Berberian *et al.* 2000; Parsons *et al.* 2006). Analysis of the earthquake seismograms shows that the fault which moved was a reverse fault (or thrust) inclined at about 45° to the horizontal, in which one block is pushed towards, and on top of, another. More detailed information comes from analysis of space-based radar measurements, fixing precisely the location of the fault (a few kilometres south of Sefidabeh), its length (approx. 12 km), how deep it goes (approx. 10 km), and how much it moved (approx. 2 m). 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 instead 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,

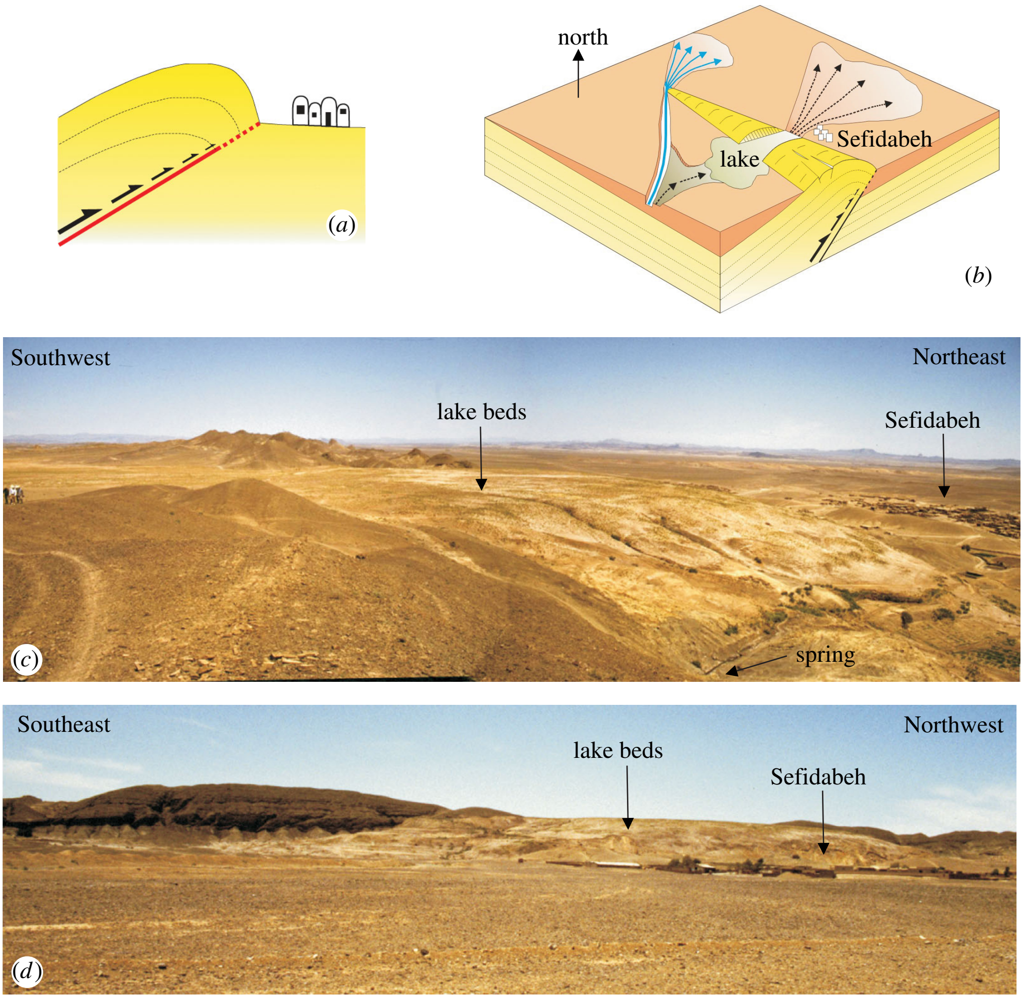

Figure 2. (*a*) Schematic cross-section of a 'blind' thrust (or reverse) fault, in red, adjacent to a village (not to scale). Slip on the fault (black arrows) dies out towards the surface, which deforms by creating a fold. (*b*) Simplified cartoon of a blind thrust and its fold at Sefidabeh. The fold 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 northwest end of the fold (Parsons *et al.* 2006). (*c*) View looking northwest across the abandoned lake beds, now uplifted 70 m above the level of Sefidabeh village. Note the spring at the base of the white lake sediments, and the people on the left, for scale. (*d*) View looking southwest across Sefidabeh to the white lake beds on the ridge behind the village.

because of the binding, a fold develops at the end of the fault. A fault of this type, on which slip fails to reach the surface is called a 'blind' fault. 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 m high and obvious (figure 2). Furthermore, there is clear evidence in the landscape itself that the ridge is young in origin and had been growing as a result of previous earthquakes. Sefidabeh is built on an old alluvial fan, formed where an ephemeral river that used to flow through the ridge discharged its waters 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 northwest, 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 northwest tip of the ridge instead. The old lake beds remain (figure 2*a*), now dry and elevated 70 m 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 (Parsons *et al.* 2006).

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 had not; Sefidabeh was too remote for anyone to have noticed). Blind thrusts 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 yr^{-1} (Vernant *et al.* 2004). But our ability to recognize the folds created at the surface by blind thrusts dates only from 1980, when one moved in the El Asnam earthquake in Algeria. Earlier devastating Iranian earthquakes of modern times that occurred on blind thrusts include those at Ferdows in 1968 (M_w 6.3, approx. 1000 killed) and Tabas in 1978 (M_w 7.3, approx. 20 000 killed). In neither of these cases were the causative faults recognized at the time, though, in retrospect, they are clear in the landscape (Walker *et al.* 2003). The city of Bam, destroyed in 2003 (M_w 6.8, approx. 40 000 killed) was also located on a blind thrust (which was recognized beforehand; Berberian 1976; Walker & Jackson 2002), though the faulting in that earthquake was more complicated (Talebian *et al.* 2004; Funning *et al.* 2005). In each of these cases, at Sefidabeh, Ferdows, Tabas and Bam, although we know about the causative faults, we have not yet explained why the earthquakes apparently scored bull's-eye hits on the only substantial habitations in the desert for tens of kilometres in any direction.

2. The link with water

The answer is water. Sefidabeh means 'white water', and the village obtains its water from the white lake beds in the uplifted ridge (figure 2*c*,*d*), which leak in a series of springs at its base. In this case, the fault is responsible for the sub-surface 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 it is possible to live and attempt a meagre agricultural existence in this extremely inhospitable 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 thrust faults. 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 (figures 3 and 4). In Iran, these tunnels are called 'qanats', and are one of the glories of the ancient Persian civilization. They can be several tens of kilometres long, up to 100 m 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 Smith (1953) and Wulff (1968).

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 thrust fault to feed the date-growing region of Baravat; one of the most famous date-producing regions in the Middle East (figure 4*a*). 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 Mahan (figure 4*d*) and Tabas (destroyed in the 1978 earthquake).

3. Living with earthquakes

For centuries, Iranian civilization and desert existence has lived with, and exploited, this link between mountains, faulting and water supply. Three short examples serve to illustrate this relationship.

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 thrusts, whose folds are clearly visible in satellite imagery (figure 5*a*). 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 past, the 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 the river leaves the mountains (figure 5*b*); 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 has stood for 350 years, and is still effective today.

After the devastating 1968 earthquake at Dasht-e-Bayaz in eastern Iran (M_w 7.1, approx. 12 000 killed), several qanats were cut and offset by horizontal movement on the causative fault, which slipped up to 4 m in places. These qanats

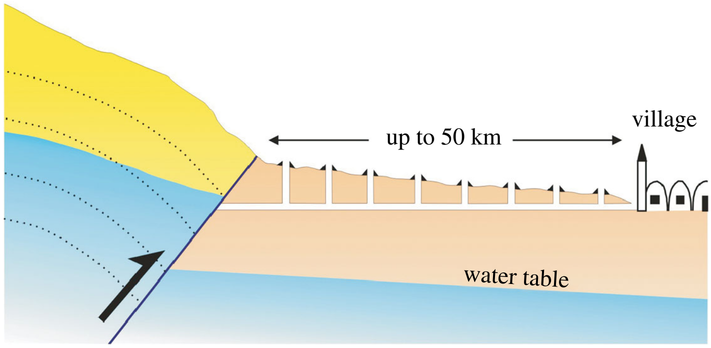

Figure 3. Cartoon of an irrigation tunnel (qanat) dug through alluvium towards a range-front, where the water-table is elevated because of impermeable clay ('gouge') on a thrust fault. Qanats can be up to 100 m deep at the range front.

were then either abandoned or repaired by reconnecting the offset channels. There is clear evidence on the ground, and in air photos (figure 6) 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 7*a* 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-brick 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 that is used comes from a quarry at the foot of the range front, and is in fact the fault gouge itself, made from ground volcanic rocks (figure 7*b*). 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.

4. From villages to megacities

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, 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

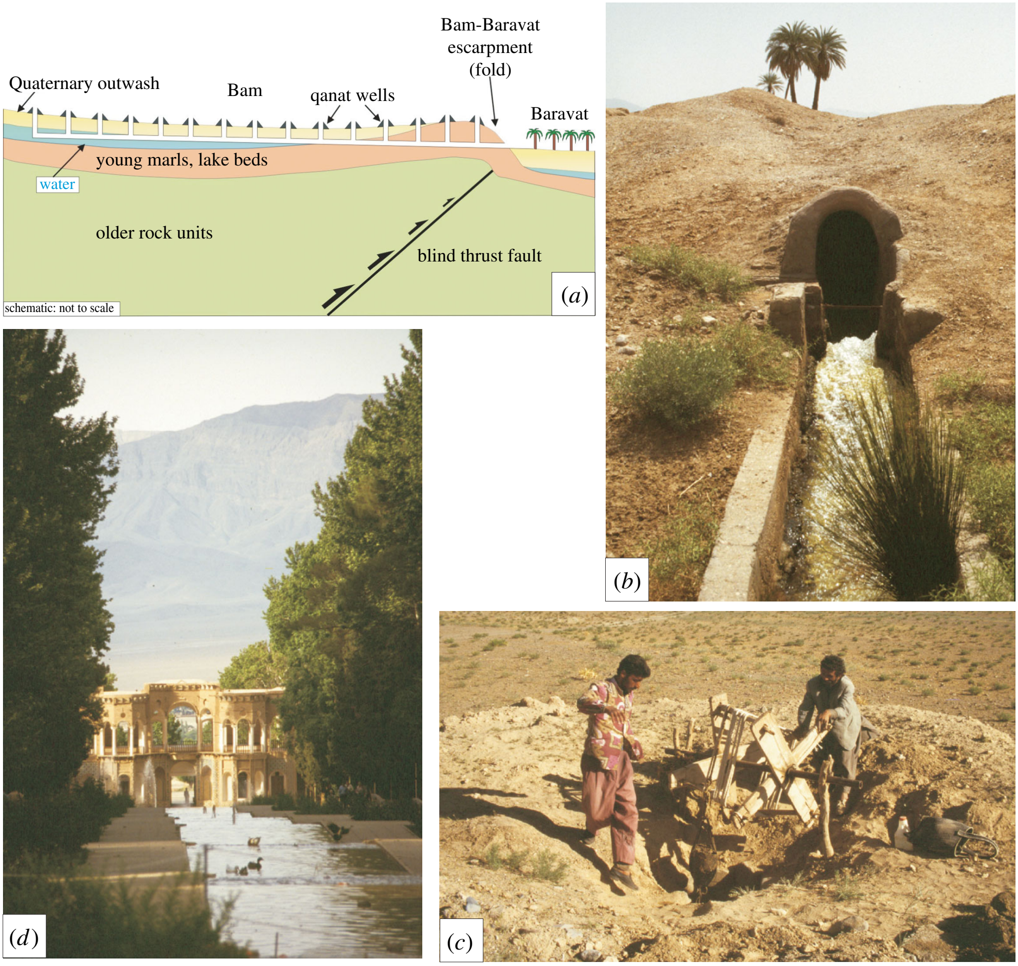

Figure 4. (*a*) Schematic section of the qanat systems feeding the date growing region of Baravat adjacent to Bam. The blind thrust fault has created a fold which ponds the sub-surface water flow through the Quaternary outwash, as the underlying lake beds (marls) are relatively impermeable. (*b*) A qanat tunnel emerging near a village. (*c*) A windlass working at a vertical qanat shaft, bringing excavated material to the surface from an underground worker below. The discarded material forms a crater rim at the surface, preventing flash-floods from washing material back into the hole. (*d*) The water gardens at Mahan, between Bam and Kerman, fed by qanats from mountains several kilometres away.

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, at 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 M_w 6–7 that occur in Iran would kill typically a few hundred or thousand people. A modern example is the earthquake near Zarand in February 2005 (M_w 6.4), which destroyed two villages, killing 500 (Talebian *et al.* 2006).

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 (six 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; figure 8*a*) or Rudbar (40 000 killed in 1990), or the megacity of Tehran, which now has a daytime population of 10–12 million (figure 8*b*). The case of Tehran is instructive. It is situated at the base of the Alborz mountain range front (figure 8*b*), which is elevated by movement on an active thrust fault. Several other active faults are also situated nearby. In former times, the site 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 $M_w \sim 7$ in the fourth century BC, 855, 958, 1177 and 1830 (Ambraseys & Melville 1982; Berberian & Yeats 1999), but the number killed was probably quite small by modern standards, perhaps measured in hundreds or thousands. The modern Tehran is a megacity 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 (figure 1*b*) was always bigger, more prosperous and far more important as 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 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 situation is similar throughout much of the Mediterranean-Middle East-Central Asia earthquake belt.

5. Earthquake vulnerability in the modern world

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 topography is largely created by fault movement in earthquakes, ultimately the result of the ongoing collision between the Eurasian plate and the African, Arabian and Indian plates to the south. Large tracts of this area are either low, barren, inhospitable deserts, or high, inaccessible and also inhospitable plateaus, such as Tibet. Habitations 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. Many have been destroyed in past earthquakes when their populations were relatively small, but have now grown into very large, and very vulnerable, cities.

The relentless rise in global population and in the growth of megacities in the developing world is discussed in a number of papers by Bilham (1995, 1998,

Table 1. Earthquakes in Iran that killed more than 10 000 people over the last thousand years. (Note that 5 of these 15 earthquakes occurred in the last 50 years. Sources are Munich Re (MR01), Utsu (2002) or myself (JAJ). Fatality figures are uncertain, especially for older earthquakes, and the ones here are generally lower estimates; discussions of the older events are in Ambraseys & Melville (1982). Even for the 2003 Bam earthquake, the official fatality figure was 24 000, though most people believe it was considerably more. The figure for Tabas includes other villages in the oasis; 11 000 died in the town itself. Note the absence of Tehran in this table, which although it was badly damaged or destroyed in 855, 958, 1177 and 1830 did not exist in its present form, but was a relatively minor town with small population. By contrast, Tabriz, historically a busier, bigger and more important place, is included three times.)

date			dead	lat.	long.	place	source
1008	04	27	16 000	34.6	47.4	Dinevar	MR01
1042	11	04	40 000	38.1	46.3	Tabriz	MR01
1336	10	21	25 000	34.7	59.7	Khwaf	MR01
1405	11	23	30 000	36.5	59.0	Nishapur	MR01
1641	02	05	13 000	37.9	46.1	Tabriz	Utsu
1667	11	18	12 000	37.2	57.5	Shirvan	Utsu
1721	04	26	40 000	37.9	46.7	southeast Tabriz	MR01
1780	01	08	50 000	38.2	46.0	Tabriz	MR01
1824	06	25	20 000	29.8	52.4	Shiraz	MR01
1893	11	17	15 000	37.0	58.4	Quchan	MR01
1962	09	01	12 000	35.6	49.8	Buyin Zara	MR01
1968	08	31	12 000	34.0	59.0	Dasht-e-Bayaz	MR01
1978	09	16	20 000	33.3	57.4	Tabas	MR01
1990	06	20	40 000	37.0	49.2	Rudbar	MR01
2003	12	26	40 000	29.0	58.3	Bam	JAJ

2004). As he points out, the existence of earthquake building codes 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 megacities of more than 10 million inhabitants are in locations vulnerable to earthquakes (figure 9), and the reason we have not yet had an extreme catastrophe in one of them is probably because they have only been exposed for a short time (about 50 years) compared with typical recurrence times of earthquakes (hundreds or thousands of years).

Figure 9*b* shows the most damaging earthquakes, in terms of lives lost, of the last 1000 years. Accurate fatality figures for historical earthquakes, and even for modern extreme events like the 1976 Tangshan and 2004 Sumatra earthquakes, are notoriously difficult to obtain. Figure 9*b* is an updated and amended version of an earlier figure from Bilham (1995), with most of the fatality data from Munich Re (1991), updated with my own research. The map simply distinguishes earthquakes that killed more than 10 000 people from those that killed more than 100 000. At that level of discrimination, it is probably accurate, in spite of the uncertainty in the precise figures. Figure 9 is alarming because it highlights the vulnerability of cities in the Mediterranean-Middle East-Central Asia earthquake belt, as well as the coastal regions of South and Central America and Indonesia, for which tsunamis pose an additional risk, as demonstrated in Sumatra in 2004.

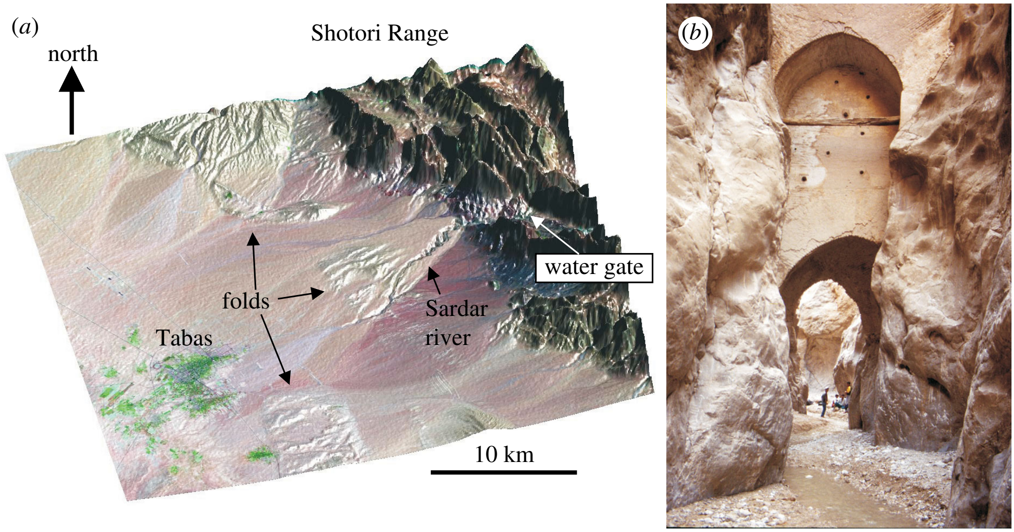

Figure 5. (*a*) Perspective view from the south of the desert oasis at Tabas, formed by draping an ASTER satellite image over digital topography. The outwash surfaces from the mountain are interrupted by folds, through which drainage, like the Sardar river, incises. The folds are above buried blind thrusts, which moved in the 1978 earthquake, destroying Tabas. The Sardar river cuts a deep gorge through the rising fold northeast of Tabas, but incision ceases as soon as the river has crossed the southwest front of the fold. Image courtesy of J. Hollingsworth. (*b*) The seventeenth century water-gate across the Sardar river at its narrowest point; see (*a*) for location. The height of the top of the wall above the arch is about 20 m.

Many of the red dots indicate earthquakes that killed more than 10 000 at times when the cities involved had populations far lower than they have today. Of the 113 earthquakes included in figure 9*b* over the last 1000 years, 34 occurred in the last 100 years alone.

Another way of viewing the situation is with the histogram in figure 9*c*, which shows the number of earthquakes killing more than 10 000 (grey) and 50 000 (red) per century for the last 1000 years. The histogram shows the relentless increase in fatalities with the expanding global population after 1600, and it is quite clear where the trend is heading (see also Bilham 2004). We are only 5 years into this century, but already we have had the catastrophies of the earthquakes in Gujarat (2001; 19 000 dead), Bam (2003; 40 000 dead), Sumatra (2004; greater than 200 000 dead, though many of these perished in the tsunami), and Pakistan (2005; 73 000 dead).

The other point to note is the great success of the developed nations in reducing the earthquake hazard of their urban populations, at least for moderate-sized earthquakes. In California, and increasingly in Japan, earthquakes of M_w 6–7, 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, M_w 7.1, 64 killed) and Northridge in southern California (1994, M_w 6.8, 50 killed) occurred in regions that would be considered urban or suburban compared with Bam (2003, M_w 6.8, 40 000 killed) or Tabas (1978, M_w 7.3,

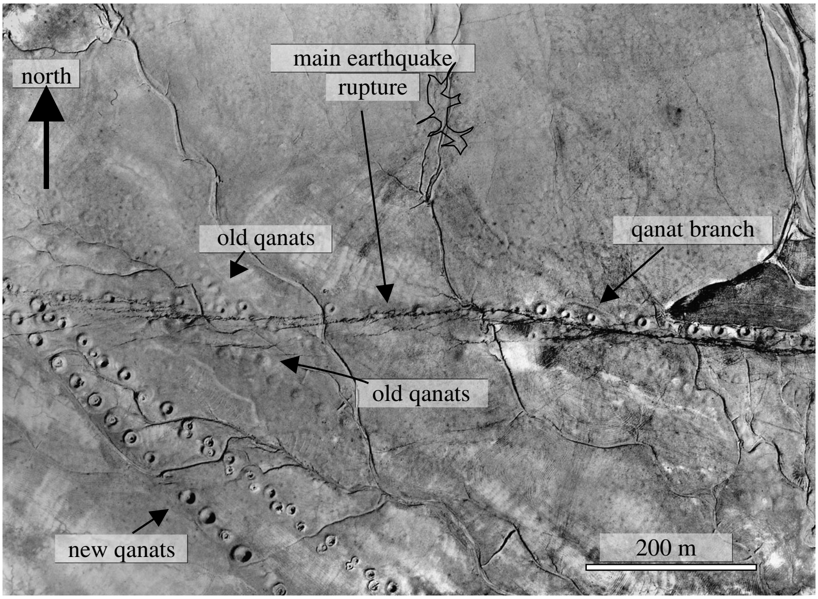

Figure 6. Air photo of qanats in the Nimbluk valley, taken after the 1968 Dasht-e-Bayaz earthquake. The earthquake fault rupture runs east–west across the centre of the picture and moved horizontally, with the north side sliding to the west. Multiple generations of qanats are visible, the most recent 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 northwest–southeast qanats by tapping an underground change in water-level, ponded by impermeable clay gouge on the fault (Ambraseys & Melville 1982). Photo courtesy of N. Ambraseys.

20 000 killed in total) in Iran. Expressed as proportions of the population, the mortality figures of the Californian earthquakes are insignificant 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. As Tucker (2004) points out, the costs of the 1989 and 1994 Californian earthquakes were 0.2 and 1% of the regional (not national) gross domestic product (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 M_w 7, in which shaking durations and ground displacements are much larger, is uncertain (Heaton *et al.* 1995).

6. What can be done?

An article of this sort should not end without at least some comment on what can or should be done about the earthquake vulnerability of large megacities in the developing world. The problem is immense and urgent, and most of it is both beyond the scope of this article and the competence of its author. It is a problem

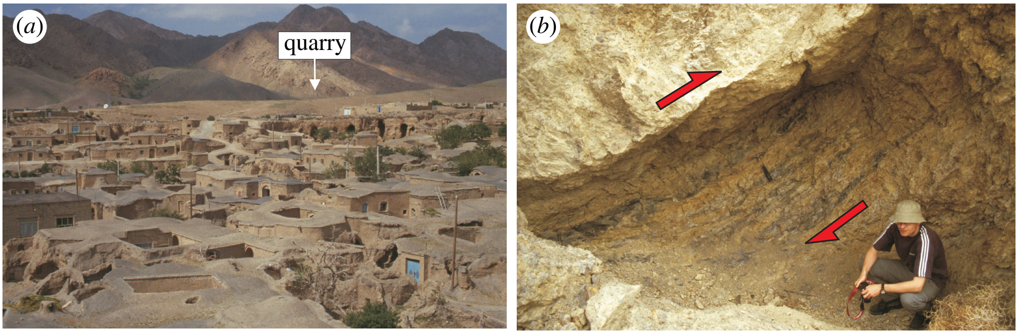

Figure 7. (*a*) View over the mud roofs of a village near Ferdows. The blue roofs are coated with a clay which is impermeable fault gouge excavated from a quarry at the foot of the range front in the background, where the thrust fault comes to the surface. (*b*) The quarry in the fault gouge used to roof the houses in (*a*). The fault gouge is in a zone of smashed volcanic rocks, ground fine by movement on the fault.

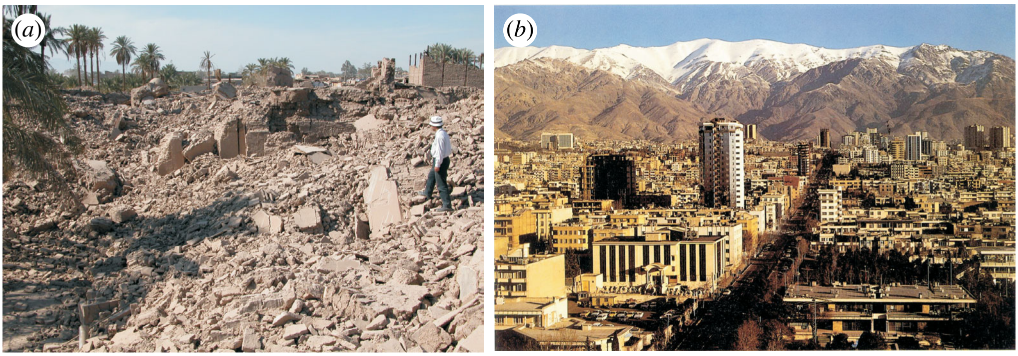

Figure 8. (*a*) View over part of the old inhabited region of Bam, destroyed in the 2003 earthquake. In this part of the town, construction was of adobe sun-dried brick, and was 100% destroyed. Head-high rubble fills the view, and it is no longer possible to distinguish where the narrow streets and alleys were. (*b*) View over the modern megacity of Tehran, adjacent to the Alborz range-front, which is bounded by a known active thrust fault. The city has 10–12 million day-time inhabitants.

that is being addressed by committed individuals, agencies and professional organizations of many kinds (Tucker 2004). It involves not just steps that need to be taken to prepare for the inevitable extreme catastrophe, so as at least to attempt to cope with its consequences. As Tucker (2004) points out, 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 these megacities 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 20 years (Bilham 2004; Tucker 2004). 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 practise and good land-use planning. The purpose of this article is to add to the efforts of Bilham, Tucker and others to alert and inform people of the situation we now face.

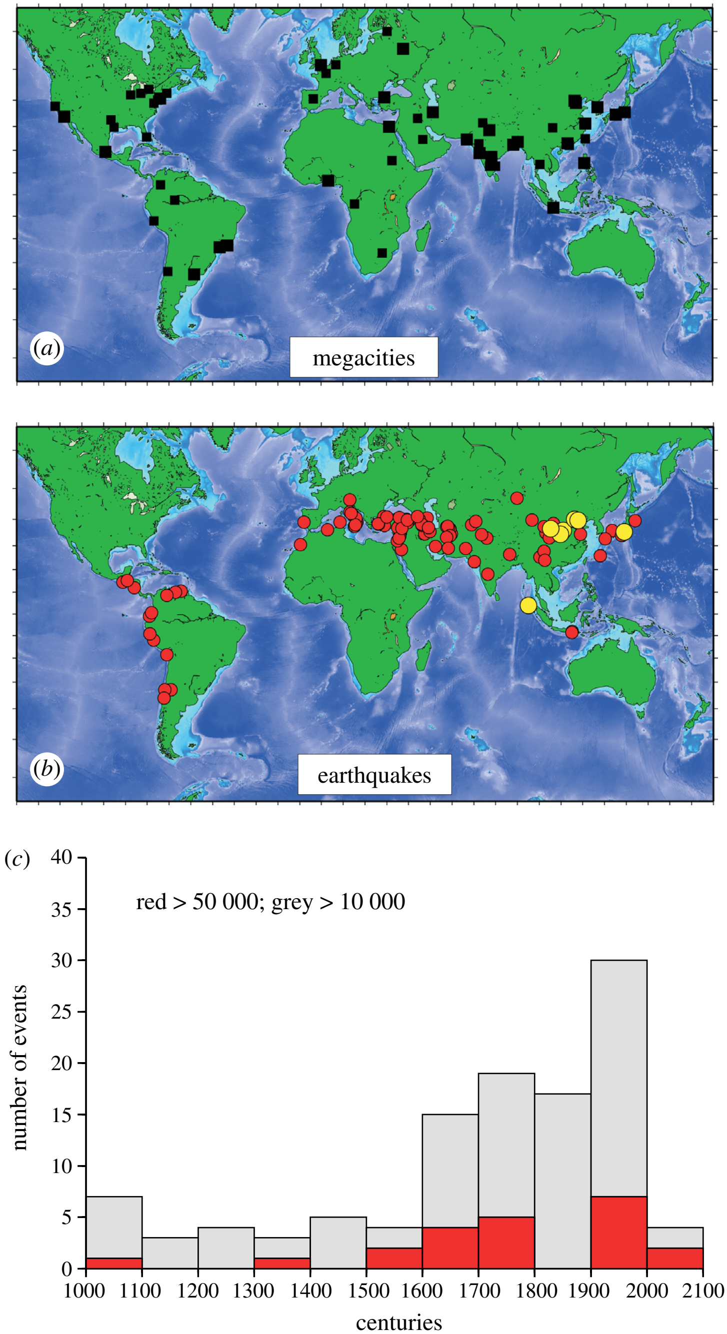

Figure 9. (*a*) Cities with more than 5 million (small squares) or 10 million (large squares) population. (*b*) Earthquakes of the last 1000 years known to have killed more than 10 000 (red dots) or 100 000 (yellow dots) people. There are 113 earthquakes in this figure, many of their symbols overlying each other. A total of 34 of these earthquakes occurred in the last 100 years alone. (*c*) Histogram of the number of earthquakes killing more than 10 000 (grey) or 50 000 (red) people per century.

I take this opportunity to express my admiration for, and thanks to, Roger Bilham of the University of Colorado at Boulder and Brian Tucker of GeoHazards International (www.geohaz.org); two academic seismologists who have devoted some or all of their later careers to alerting the world to the issues only touched on in this paper, and to transferring professional knowledge of earthquake behaviour towards the practical task of addressing the appalling earthquake vulnerability of megacities in the developing world. Their grim prognoses, persistently and clearly articulated over many years, are proving all too correct. Our ability to work on the tragedy of earthquakes in Iran owes much to the vision and dedication of M. Ghorashi and M. Korehie of the Geological Survey of Iran, and to the pioneering work of N. Ambraseys and M. Berberian, with all of whom it is an honour to have been associated. This work is also supported by a NERC grant to COMET (http://comet.nerc.ac.uk). Cambridge Earth Sciences contribution ES 8511.

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Discussion

G. R. Conway (*Chief Scientific Adviser, Department for International Development, UK*). I want to ask about siting of buildings and communities. In the case of Sefidabeh, its siting near a spring is logical. How far away would it have to be sited to reduce casualties: a mile, 10 miles?

J. Jackson. The way to reduce casualties is to improve the quality of the buildings. Bad buildings will fall down, whether they are 1 or 10 km from the fault; as shown by Tabas (1978), which was destroyed 10 km in front of the fault (figure 5*a*) and Hotkan (2005), destroyed 10 km behind the fault (Talebian *et al.* 2006). Villages have to be situated near the range-bounding faults because that is where the alluvial fans produce fine-grained sediments for agriculture. The desert areas away from the range-front faults are often barren salt flats, and no-one can live there anyway.