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Radon and ‘King Solomon’s Miners’: Faynan Orefield, Jordanian Desert

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Abstract

Concentrations of Rn were measured in ancient copper mines which exploited the Faynan Orefield in the South-Western Jordanian Desert.The concentrations of radon gas detected indicate that the ancient metal workers would have been exposed to a significant health risk and indicate that any future attempt to exploit the copper ores must deal with the hazard identified.Seasonal variations in radon concentrations are noted and these are linked to the ventilation of the mines.These modern data are used to explore the differential exposure to radon and the health of ancient mining communities.

1. Introduction

This paper describes the abundance of the naturally-occurring radioactive gas Rn in ancient $_{222}$ copper mines around the remote desert archaeological site of the Khirbet Faynan (Arabic: the ‘Ruins of Faynan’—probably the Roman city of Phaino) in the Wadi Faynan, Jordan.This site is found at the confluence of the deep gorges of the Wadis Dana, Ghuweir (Ghuwayr, Ghwair) and Shegar immediately after they leave the rocky and desolate 700–1000 m high edge of the Jordanian Mountain Highlands to enter the arid desert basin of the Wadi Arabah (Figs.1 and 2).The scale of ancient mining and smelting in this area was immense.In the immediate vicinity of Khirbet Faynan, there are over 250 copper mines and adits and in excess

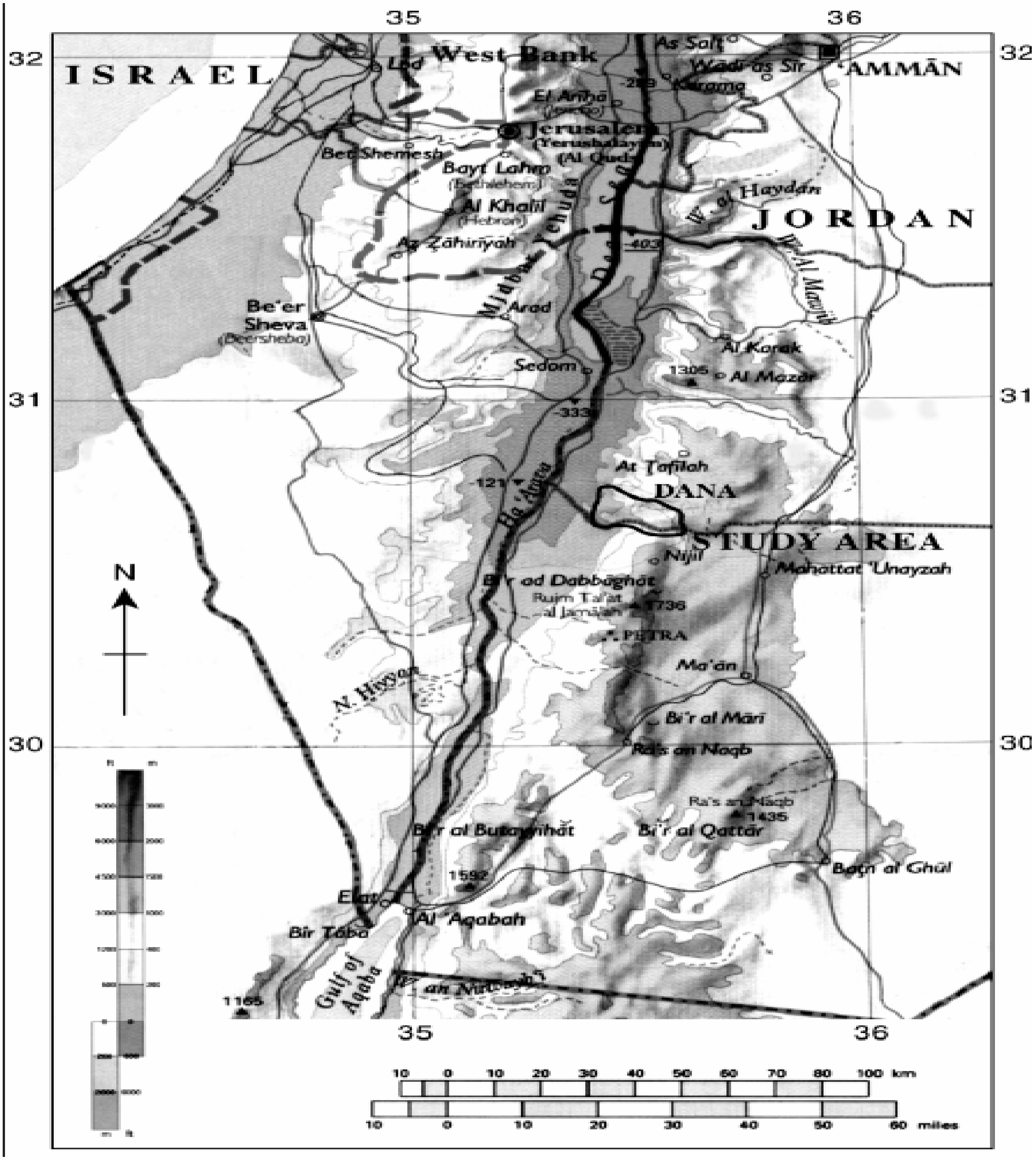

Fig. 1. Location map of the Khirbet Faynan, Jordan, and locations mentioned in text.

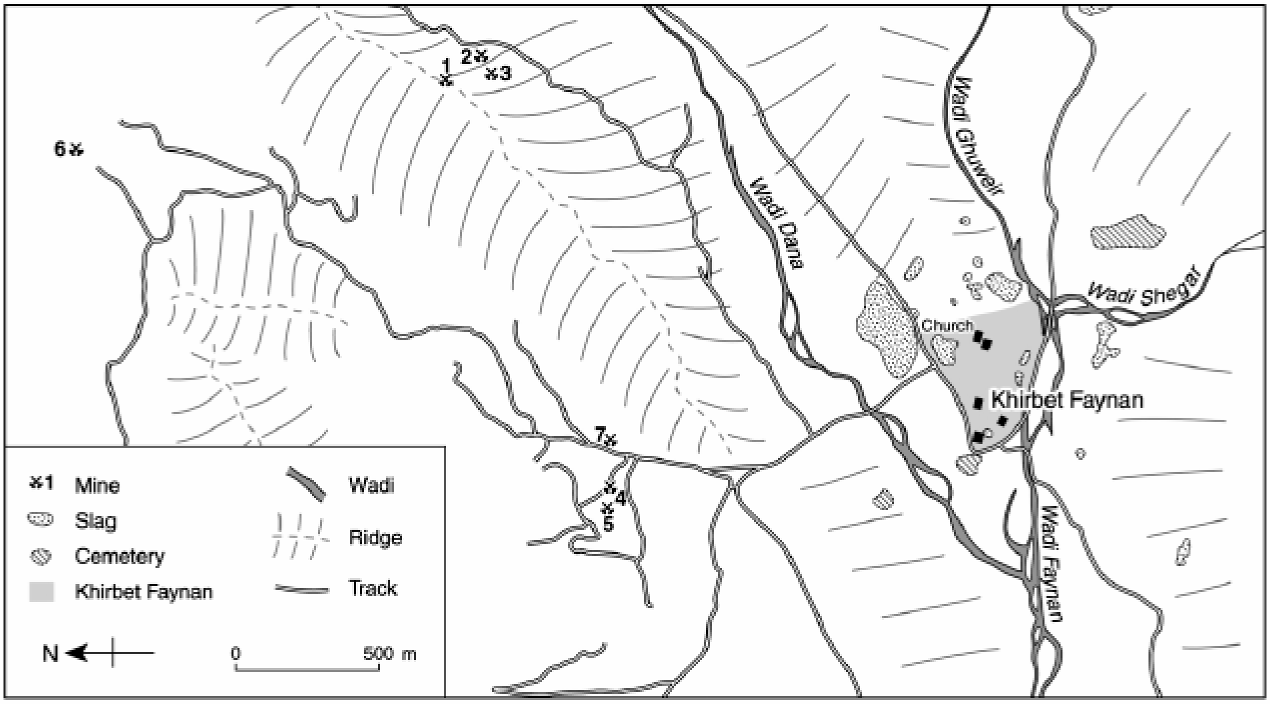

Fig. 2. The topography, surveyed mines and slag in the vicinity of the Khirbet Faynan (adapted from Hauptmann 2000).

of 250 000 tons of ancient copper slag remain at the surface within the 12 km area of the copper ^{2} ore district (Hauptmann 2000), which still contains an estimated 19.8 million metric tons of copper (Jordanian Natural Resources Authority, 2003—www.nra.gov.jo).These mines and adits include one of the largest known mine galleries in the Roman Empire 'Um el Amad' (Arabic: The Mother of Pillars; a reference to the rock pillars left in place to support the roof of the excavated cavern).Typically they have been observed to have poor ventilation in a region where for much of the year the climate of the area is very hot and arid (Barjous, 1992; Rabb'a, 1994).Whilst legend maintains that the Khirbet Faynan was one of King Solomon's mines (Pyatt et al., 1999), detailed geoarchaeological studies have unequivocally demonstrated that this area was one of the most important centres for the mining and smelting of metalliferous ores in the old world during prehistoric and classical times and used by the Roman Empire as a penal centre where special classes of criminals, such as Christians were sent, effectively to be worked to death (Eusebius of Caesarea, 1969; Barker et al., 1998, 1999, 2000; Hauptmann, 2000).Slaves working in imperial mines such as those at Faynan, which had a regular supply of workers, appear to have experienced particularly bad working conditions, to have been bound in chains, beaten and forced to work night and day until death (Shepherd, 1993, p.64).Experience of health risks in both modern and abandoned mines (summarised in Gillmore et al., 2001; Tomasek et ˆ˘ al., 2001) suggests that long-term occupance of badly-ventilated, dusty mines might have caused significant potential risk from Rn and its progeny ^{222}.To explore this hazard several mines in the district were monitored using passive fission track detectors.The results of this survey are used to explore the possible consequences for health and demography of exposure to radon gas for the minerals-workers and the wider community associated with the mining and processing of metal ores in the period 2500 to 1500 years ago, and highlight the risks inherent in any modern exploitation of the metals of the Faynan Orefield.

1.1. The geological setting

The mines and adits that exploited the Faynan Orefield penetrated complex ore bodies that were formed by several distinct phases of mineralisation–variously involving copper, lead, beryllium and manganese (Bender, 1974; Barjous, 1992; Rabb'a, 1994; Hauptmann, 2000; Hauptmann et al., 1992).Several of these major sedimentary rock formations were identified and mined in antiquity. These include the Numayr Dolomite Limestone within the Burj Dolomite Limestone Shale of Hauptmann (2000) (see also Barjous 1992; Rabb'a, 1994) and the Massive Brown Sandstones of the 'Umm Ishrin Sandstone' (Barjous, 1992; Rabb'a, 1994; Hauptmann, 2000), both of Cambrian age.These sedimentary rocks overlie a geological complex of metal-rich, fractured and water-yielding Proterozoic granitic and volcanigenic bedrocks.Whilst the copper ores were the main objectives of the ancient mining, numerous other toxic metals are present in significant quantities, including minerals such as thorium and uranium that are known to be source elements for isotopes of radon.Inevitably , many potentially toxic metals and gases would have been liberated during quarrying, ore-processing, smelting and transport

1.2. *The risk from Rn 222*

Rn gas is a naturally-occurring isotope in the 222 decay series of U.Rn has a half-life of 3.82 238 222 days and decays by a-emission.The decay products are also radioactive and two progeny, Po 214 and Po, also decay by a-emission.They make 218 substantial contributions to the total radiation received by people working underground.In the natural environment, Rn is likely to emanate 222 from primary or secondary uranium-sources in the granitic and metamorphic proterozoic bedrocks of the Faynan and then become trapped within the many fissures, fractures, faults and pores of the mineralised Cambrian sedimentary bedrocks beneath impermeable strata.Rn is the most 222 soluble of the noble gases.In addition, it is possible that radon levels in the caves and adits within the dolomite limestone may have been raised by degassing from groundwater (Brill et al., 1994), which feeds the perennial springs that emerge from the proterozoic bedrocks immediately beneath the mineralised strata.Eventually the gas passes through natural geological barriers and leaves the lithosphere through weathered materials or the soil to disperse and become relatively harmless through turbulence in the external atmospheric environment (Faulkner and Gillmore, 1995).

The potential health risks from Rn are rela- 222 tively well-documented.Radon progeny may be inhaled and retained in the lung via aerosol particles to which they adhere.These are both too small to be filtered by nasal hairs and too large to be exhaled.Ore extraction within the mines and processing would have created dust; ancient mines were notoriously poorly ventilated.Strabo (cited in Davies, 1979, p.16) commented that the deadly vapours in Greek mines killed slaves so quickly that the owners had to buy the cheapest possible. Pliny, Vitruvius and Theoprastus (cited in Shepherd, 1993, p.33 –34) give similar examples.

When retained in the lung, inhalation of Rn 222 may result in a potentially large radiation dose being absorbed in the tracheobronchial epithelium from the short-lived alpha particle-emitting products Po and Po (Brill et al., 1994).The 218 214 magnitude of the radiation dose depends upon the rate of radionuclide deposition and residence time of particles in the lung.The rate and depth of breathing will have an impact on the depth of penetration into the lung, the deeper aerosol particles having the longer residence time.Between 5 and 30% of the total potential alpha energy is a result of alpha particle emission from daughter isotopes being bound to relatively coarse dust particles—i.e. larger than 1000 nm—sizes that would be expected, for example, in a modern working uranium mine.Gillmore et al. (2000a,b, 2001) demonstrated that Rn has complex modes 222 of transport and dispersion in caves and mines, with accumulation taking place in localised areas of dead air where the ventilation is poor.Whilst unquantified, the Faynan mines and adits typically have poor ventilation.One consequence of sustained exposure to elevated concentrations of radon is a link with lung cancer (Lorenz, 1944; Strong et al., 1975; Behounek, 1970; Samet et al. 1991; Brill et al., 1994; Phillips and Denman, 1997; Field et al., 2000; Kendall, 2000).In the United Kingdom, within the population at large, everyday exposure to radon progeny is thought to result in approximately 2000 deaths each year from lung cancer.This figure, which represents 6% of the annual total of 33 000 lung cancer deaths per year (Green et al., 1992), makes radon the second largest cause of lung cancer after smoking (Spear, 2000).Several surveys have explored the possibility of relationships between exposure to radon and cancers other than cancer of the lung (Henshaw et al., 1990; Harley and Robbins, 1992; Kendall, 2000; Tomasek et al., 1993).Recent studies have ´˜ highlighted a radon hazard in domestic settings throughout Jordan (Abumurad, 2001a,b); it is reasonable, therefore, to consider the impact of radon exposure upon an ancient population.

1.3. *Ancient mining, people and environment in*

Faynan

The scale of ancient metal mining and extraction that was carried out in the Faynan, and its range of environmental impacts, has important consequences for understanding mining communities which existed up to and including the early industrial revolution.Extracting and processing ores from mines and adits would always have been dangerous tasks bringing their toll of misfortune, illness and accident.Historical and archaeological sources provide limited information on the social structure, demography or morbidity of this and similar ancient communities.It is clear from the account of Bishop Eusebius of Caesarea (1969) writing at about 300 A.D., that forced labour was intensively used at Khirbet Faynan.He noted that the slaves who extracted the ores in mines and adits had very short life expectancies—to be described in terms of days, weeks or months.This was, in part, that the result of deliberate cruelty that ranged from brutal (beating), through barbaric (deliberate maiming) to execution (decapitation, burning at the stake).Gender differences in the roles of forced labourers during the second century B.C. were noted by the ancient Greek Geographer, Agartharcides, when he visited the mines of Arabia. He recorded that whilst men were directly used in the actual mining within shafts and adits, women and children were engaged outside the mines in ore-processing (reported in Agricola, 1950)—all these activites are likely to have led to exposure to radon released during mining, ore crushing, grinding, leaching and transportion (Clements et al., 1980; Jha et al., 2001).It is also evident from Eusebius and Agricola that these mine labourers and minerals processors (slaves and indentured labourers) were guarded, that they worked at the direction of skilled ‘professionals’ and ‘overseers’, that they were under the overall control of administrators and imperial officials who were based at Khirbet Faynan.Mining and smelting activities were controlled by a well-defined class of professional people operating within established rules (Shepherd, 1993, p.44 –57).Such professional people were not brutalised and skilled slaves who acted as mine bosses could be sold for great sums of money (Shepherd 1993, p.62). Other aspects of the health and well-being of this community have been emphasised by geochemical analyses reported by Grattan et al. (2001, 2003) of human skeletal remains from the adjacent large fourth–seventh century A.D. (Byzantine) cemetery (Findlater et al., 1998; Karaki, 1999). These geochemical data suggest that significant heavy metal burdens were experienced in this industrial community.The high concentrations of metals such as lead, cadmium and copper, detected in many of the excavated human bones, suggest that profound health problems may have been induced in the human population who had ingested, breathed or otherwise been in sustained contact with toxic metals in what had become, and remains, a very contaminated and unhealthy environment (Pyatt et al., 1999, 2000, 2002a,b; Pyatt and Grattan, 2001).Modern visits to these mines indicate that even minimal movements would have required physical exertion and the inhalation of

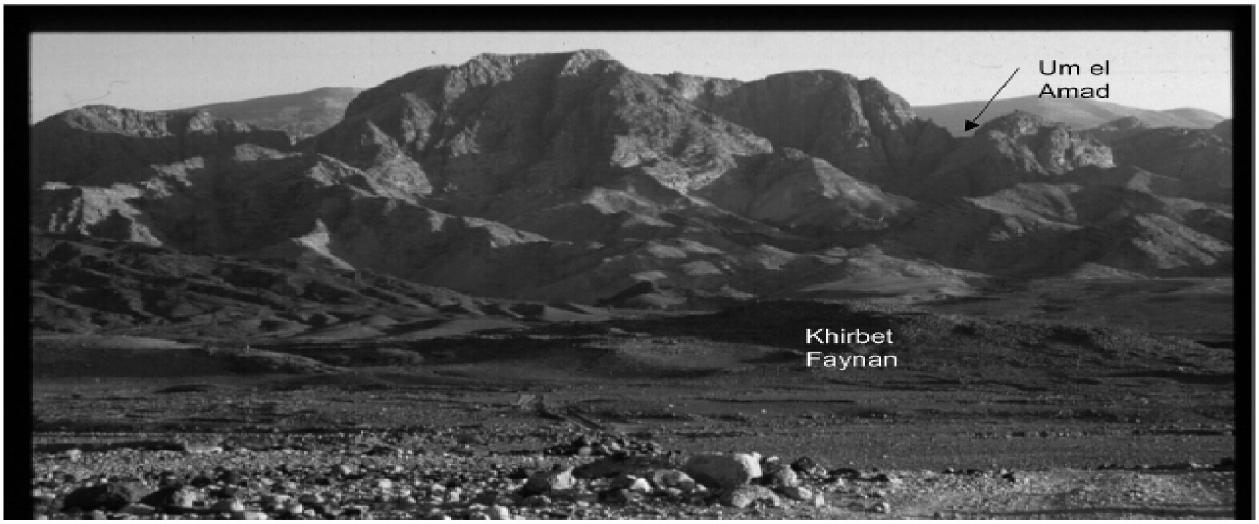

Fig. 3. Looking back from the entrance to Wadi Khalid: in the foreground the Ruins of Khirbet Faynan, in the background Um el Amad, the largest mine in the Roman Empire, is reached through the pass indicated.

dust (Figs.4 and 5).It is also clear that in everyday life in homes and other areas adjacent to metal mines and mineral processing plants, metal pollutants can concentrate in significant quantities within the bodies of administrative staff, workers' families and other nearby inhabitants through direct contact, ingestion and drinking as well as inhalation (Jha et al., 2001; Lipsztein et al., 2001).

Given the minimal life expectancies of the male and female forced labourers in the Faynan and elsewhere (Montag, 1962; Karaki, 1999), it appears possible that the greatest sustained exposure to both metal pollution and any radon gas might have been amongst the skilled professionals, overseers and guards in the mines, and at sites of ore crushing and smelting, who may be assumed to have generally enjoyed a longer lifespan, balanced by a longer term exposure to pollutants which are effective over a longer timescale

2. Methods

The radon concentrations in air reported here were estimated using passive alpha track-etch devices from NE Technology—a source approved by the United Kingdom National Radiological Protection Board.These devices were used because of their robustness, ease of handling and visibility and because a number could be placed to record simultaneous values.The standard unit of radiation measurement employed here is the Becquerel, one atomic disintegration per second (Waltham, 1991), per cubic metre of air (that is Bq m).The ^{y3} concentrations of radon at various locations were determined at eight copper mines in three different locations—in the Wadi Dana, the Wadi Khalid and at Um el Amad (Figs.2 and 3).The placement and recovery of the passive detectors in these mines and adits around Wadi Faynan presented numerous difficulties which stemmed from the extreme remoteness, arduousness and difficulty of working in this mountainous, isolated, and challenging desert terrain.The placement of the passive detectors reflected an uneasy compromise in the field between experimental design, personal safety, preventing deliberate or accidental movement of the detectors, ensuring the detectors could be relocated, and our capacity to visit these sites on only three occasions.The presence of sheep–goat herds precluded placing detectors on open sites where in antiquity ores were processed and slag deposited.Time-averaged readings of radon

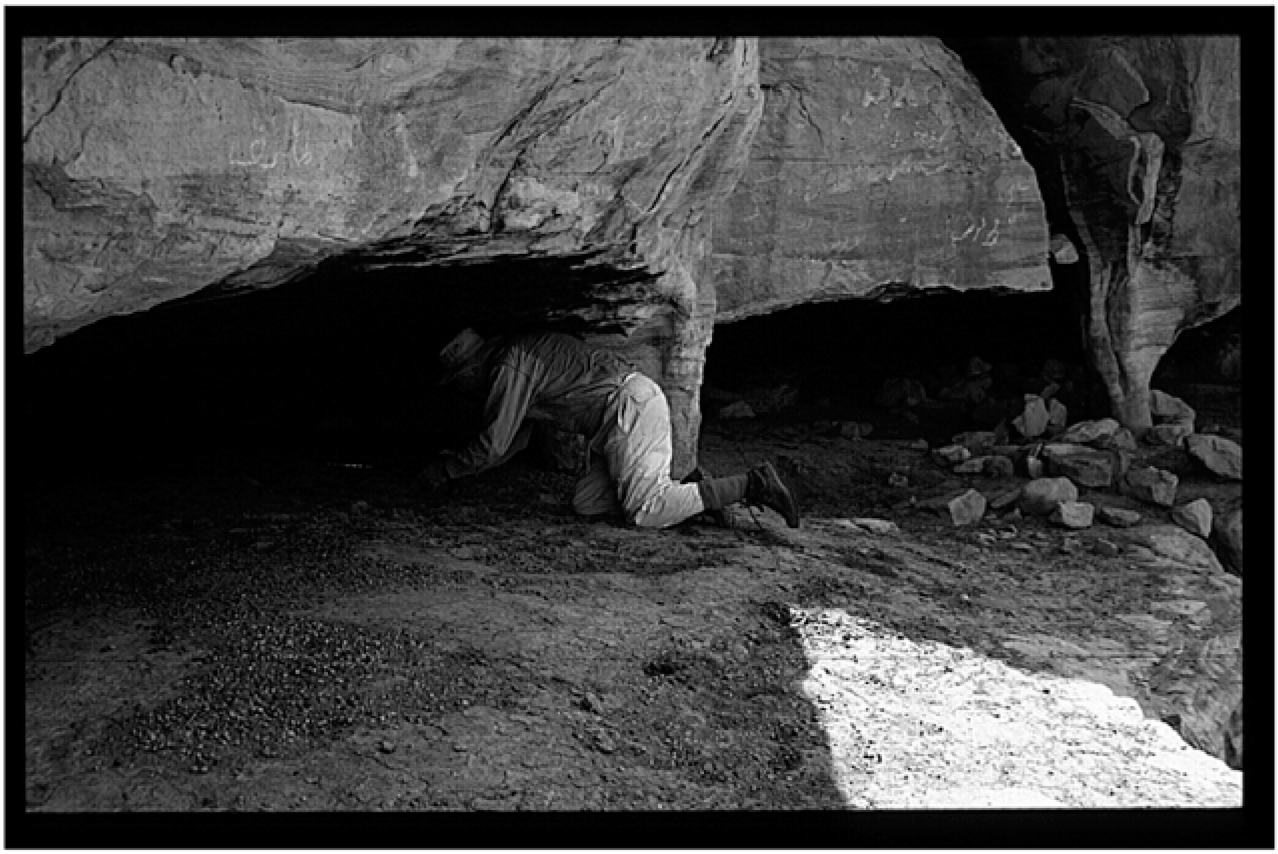

Fig. 4. The deliberately narrow entrance to Um el Amad mine.

concentrations were taken for exposures in the winter of 1999–2000, from November to January, and from January to March.

Alternative units of radon measurement that can be employed are ‘Working Levels’ (WL) that are based on international agreed standards—and ‘Curies’ (Ci).Waltham (1991) suggested approximate conversion factors between these measures, as follows: 370 Bq m s0.1 WLs10 pCiyl y3 (picocuries per litre).However , Lao (1990) suggested that, although 1 pCiyls37 Bq m , 1 WL y3 should be calculated as 200 pCiyl, using an average equilibrium factor (*F*) of 0.5. Whilst UNSCEAR (1988) suggested that for modern domestic environments *F* is typically 0.35, it is evident that mine and cave environments studied here are very different to domestic environments. Preliminary studies by Gillmore et al. (2000a,b, 2001) indicate that within metalliferous mines elsewhere, *F* is seen to vary from 0.17 to 0.4. Given the preliminary nature of such work, in this study, we have made a conservative assumption and we have assumed *F* to be 0.5. In this account, ‘Working Levels’ have been converted to Bq m for comparative purposes using the guidance y3 given in Lao (1990).

3. Results

The results obtained from the atmospheric radon detectors are set out in Table 1 together with details of their locations.The data obtained indicate that radon gas does accumulate in the mines of the Faynan orefield and reaches sufficient concentrations to be a cause for concern.

The mines of Wadi Dana are located approximately 200 m above the Wadi floor and are exposed to the south.This outcrop of the DLS was exploited during Roman times, but all three mines had been widened during prospection in the 1980s.Smaller adits cut in ancient times may be accessed from mines 1 and 2.In the Wadi Dana mines the average radon measurements in surveys 1 and 2 were 629 Bq m and 813 Bq m , y3 y3 respectively.The mines of Wadi Khalid, exploit the same ore source as the Wadi Dana mines, but the dip of the geological strata has resulted in most of the mine access being located close to the bed of the Wadi, and consequently these mines are more sheltered.Mines 4–6 have been enlarged by recent prospection (see Fig.6 for entrance to mine 5), but mine 7 is an adit of Roman or perhaps older age.In the Wadi Khalid mines the average radon measurements in surveys 1 and 2 were 671 Bq m and 1033 Bq m , respectively.However , y3 y3 these average figures obscure notable results obtained from mines 6 and 7.Mine 6 faces southeast and is protected from south-westerly winds by a substantial pile of recent mining debris.In the second survey period the radon measurement reached 2493 Bq m , the highest value measured y3 in this survey.Mine 7, an unaltered ancient adit, with a very small and sheltered entrance that faced north-west, returned consistently high radon concentrations in both surveys, 1088 Bq m and 996 y3 Bq m , respectively, (Fig.5 illustrates the internal y3 dimensions of an unaltered Roman adit).The survey of Um el Amad, presented particular difficulties; the mine is only accessible after many hours trekking high into the mountains to the south of Khirbet Faynan and hence only one survey was possible.This mine exploited a different geological stratum, the Massive Brown Sandstone, which appears to present less of a radon risk.Fission Track Detectors were placed 30 and ;150 m from the entrance of the mine.The average radon measurement was 263 Bq m , the lowest in this y3 study, with a marked increase in concentrations towards the back of the mine (Table 1), where ventilation is extremely poor.

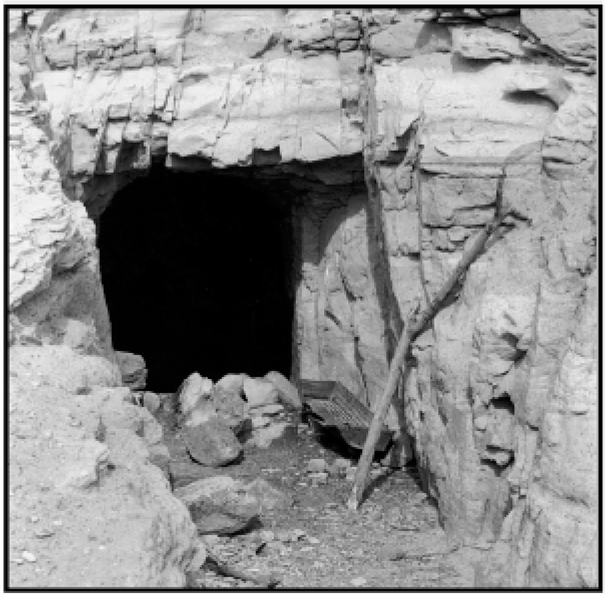

Fig. 6. The enlarged entrance to mine 5, Wadi Khalid.

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4. Discussion

These concentrations of radon in the Faynan are notably higher than those detected elsewhere in recent studies of domestic situations in Jordan. Typically such measurements have been obtained in relation to dwellings or soils on the limestone uplands and often at or close to major cities. Domestic concentrations of radon are typically between 5 and 80 Bq m (Al-Kofahi et al., 1992; y3 Ahmad et al., 1997a,b; Khatibeh et al., 1997; Abumurad, 2001a,b).In the town of Tafilah, situated on the limestone plateau above the Wadi Faynan, domestic concentrations varied between 20 and 66 Bq m , whilst further north at Kerak y3 they ranged from 33 to 123 Bq m (Al-Kofahi y3 et al., 1992).Abumurad (2001a,b) calculated the probability of dying from lung cancer induced by lifetime exposure to radon on the limestone plateau area in Northern Jordan with indoor concentrations varying between 62 Bq m (summer) and 81 Bq y3 m (winter) as ;0.09. Building materials at y3 Ghor es-Safi in the Wadi Arabah to the north-west of the Faynan (Fig.1), studied through gamma ray spectroscopy, gave a radium equivalent for Rn, Th and K of 85.53 Bq kg —well 226 232 40 y1 below the limit of 370 Bq kg set for such y1 materials by OECD.Concentrations similar to those detected in the Faynan were also found at an old phosphate mine near Amman (Kullab et al., 2001).

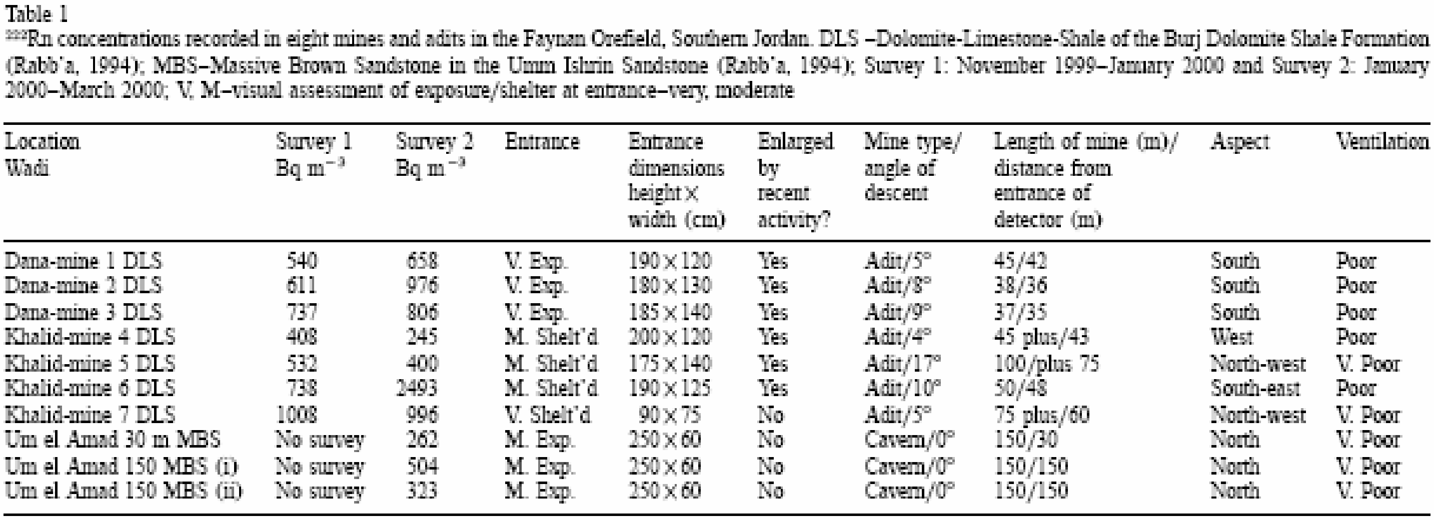

Table 1

^{222}Rn concentrations recorded in eight mines and adits in the Faynan Orefield, Southern Jordan. DLS –Dolomite-Limestone-Shale of the Burj Dolomite Shale Formation (Rabb'a, 1994); MBS–Massive Brown Sandstone in the Umm Ishrin Sandstone (Rabb'a, 1994); Survey 1: November 1999–January 2000 and Survey 2: January 2000–March 2000; V, M–visual assessment of exposure/shelter at entrance–very, moderate

Location Wadi	Survey 1 Bq m^{-3}	Survey 2 Bq m^{-3}	Entrance	Entrance dimensions height × width (cm)	Enlarged by recent activity?	Mine type/ angle of descent	Length of mine (m)/ distance from entrance of detector (m)	Aspect	Ventilation
Dana-mine 1 DLS	540	658	V. Exp.	190 × 120	Yes	Adit/5°	45/42	South	Poor
Dana-mine 2 DLS	611	976	V. Exp.	180 × 130	Yes	Adit/8°	38/36	South	Poor
Dana-mine 3 DLS	737	806	V. Exp.	185 × 140	Yes	Adit/9°	37/35	South	Poor
Khalid-mine 4 DLS	408	245	M. Shelt'd	200 × 120	Yes	Adit/4°	45 plus/43	West	Poor
Khalid-mine 5 DLS	532	400	M. Shelt'd	175 × 140	Yes	Adit/17°	100/plus 75	North-west	V. Poor
Khalid-mine 6 DLS	738	2493	M. Shelt'd	190 × 125	Yes	Adit/10°	50/48	South-east	Poor
Khalid-mine 7 DLS	1008	996	V. Shelt'd	90 × 75	No	Adit/5°	75 plus/60	North-west	V. Poor
Um el Amad 30 m MBS	No survey	262	M. Exp.	250 × 60	No	Cavern/0°	150/30	North	V. Poor
Um el Amad 150 MBS (i)	No survey	504	M. Exp.	250 × 60	No	Cavern/0°	150/150	North	V. Poor
Um el Amad 150 MBS (ii)	No survey	323	M. Exp.	250 × 60	No	Cavern/0°	150/150	North	V. Poor

These concentrations of radon in the Faynan mines are lower than those reported for recently active or abandoned mines elsewhere—especially where there have also been extensive mineralisa109 tions in uranium as well as copper or other ores. For example, Sengupta et al. (2001) recorded 2419–3844 Bq m in Cu–U mineralisations in y3 the Bihar, whilst in the poorly ventilated mines in the Ore Mountains of Czechoslovakia, Behounek (1970) reported 11 840–331 150 Bq m .In y3 closed iron ore mines in Kiruna and Malmberget in Sweden, concentrations of 200–4000 Bq my3 were detected.At present, the highest radon gas concentrations determined in abandoned copper mines are in the south-west of England (UK), where a concentration of 7 100 000 Bq m was y3 measured by Gillmore et al. (2001).Nevertheless, this Faynan study remains important as the first attempt to quantify the radon risk associated with mining activity in the ancient world.

These data indicate that there are notable variations in radon concentrations between the survey area and between the early–late winter time periods studied.A large variation in radon concentrations detected in one mine (Khalid 6) was from 736 to 2493 Bq m ; the latter figure is the y3 highest detected in this survey.Such variations are not unusual in caves and abandoned mines; seasonal fluctuations of a factor of =10 have been observed in the UK (Gillmore et al., 2000a,b, 2001).Przylibski (1999) also noted that high concentrations of radon occurred during summer (May–August) in caves in Poland, whereas low concentrations occurred in colder months (December–June), a feature which has also been observed in caves in Spain (Duenas et al., 1999).Extrapo- ˜ lation of this pattern to the Faynan mines would suggest that, at warmer times of the year than our winter surveys, radon concentrations might be significantly higher than have been detected so far. However, the reasons for the variations in the Faynan mines are unknown—there are no simple relationships suggested between radon concentrations and mine volume, entrance size or aspectinferred ventilation.The recent enlargement of entrances observed at Dana 1–3 and Khalid 4–6 indicates that these mines are likely to be better ventilated now than in the past, and the consistent radon values returned from mine 7, a sheltered mine with a very small entrance, would seem to confirm this.

All these readings are above the Action Level recommended for places of habitation in the UK by the National Radiological Protection Board (which is 200 Bq m) and most are above the y3 level that would be permitted in the modern UK workplace—that is 400 Bq m .Estimations of y3 the length of time it may be considered safe for long term occupation of these particular minesy adits, assuming that these recorded concentrations are representative of contemporary conditions, may be made using the approach developed by Denman and Parkinson (1996).They estimated dose from observed radon concentration as follows:

y3 Dose (mSv)s(Radon concentration in Bq m)
=(duration in hours)y126 000

If we make the conservative assumption of an exposure time of only 8 h per day for a year, at a radon gas level of 2493 Bq m (Khalid mine 6), y3 the dose received could be calculated as 57.77 mSv.Given that the recommended maximum for a member of the public in the UK is 1 mSv (IRR, 1999) in a year, it is clear that long-term exposure in these mines could expose the individuals concerned to considerable risk of developing radoninduced illnesses.Overall, taking an average reading from each of the three areas surveyed (Table 1) we can conservatively estimate that miners would have been exposed to an annual dose of 16.7 mSv in the Wadi Dana, 19.8 mSv in the Wadi Khalid and 8.4 mSv in Um el Amad. Reactivation of these mines in the future would, therefore, present a health hazard to underground workers that required mitigation.

The modern environment of these mines and adits differs in several respects from that which would have been experienced on a long-term basis by the ancient mining professional, guards, administrators, etc.First, mine entrances—normally only passable through crawling (Fig.4)—have been significantly enlarged to facilitate contemporary ore surveys (Table 1 and Fig.6).They must be better ventilated than in times past, a point well illustrated by the consistently high radon levels detected in Wadi Khalid 7, an unmodified ancient adit.

Second, the modern atmosphere within the mines is essentially passive.In ancient times the presence in working mines of large quantities of large and small particulates in the atmospheres of these mines and adits is likely to have been important.Quarrying, rock-breaking and crushing, the working and movement of people and ores—all would have created vast quantities of dust in these poorly ventilated mines.

The combination of radon progeny and the dust particles associated with poor air may itself be carcinogenic, as proposed by Boyd et al. (1970) for iron-ore mines in Cumberland, UK.If this took place it would have had a further profound effect on the health of mine workers.If we assume ancient radon concentrations of slightly above the highest detected in our survey—i.e. 3000 Bq m and note high dust levels, there may well y3 have been a synergistic relationship between dust and radon dose to the lungs.The induction rate for lung cancer may, in such a dusty environment, have been as little as 7–10 years.Doll (1959) suggested that this latent period is commonly in the order of 15–30 years in an above ground industrial setting.It is interesting to note that Behounek (1970) suggested that in former mines in the Czech Republic, the average induction time for lung cancer was 17 years, with a minimum of 13 years during the late 1920s to late 1930s. Harting and Hesse (1879a,b), however, indicated that in miners from the Ore Mountains of Saxony, in a period of 8 years (1869–1877), 75% of all deaths may have been due to induced lung cancer. Doll (1959) noted that for 19th Century Schneeburg miners, the dose received by the lungs in that case would have been mostly due to the daughter products of radon carried on ore dust particles.He also suggested that the nature and quantity of atmospheric dust would have a significant effect in controlling the quantity of radioactive substances inhaled.Bale and Shapiro (1955) calculated that, with ‘normal’ dusty air, a concentration of 3=10 curies of radon per litre of air would y9 result in the tracheal epithelium receiving an average dose of 0.2 rad (radiation absorbed doses 0.002 Gy) per day.Fine aerosol particles (less than 2.5 mm) are also associated with significant health effects (Harley et al., 2000).Although their mass concentration may be low, the surface area may be relatively high; this size-fraction of the total aerosol load is a significant carrier of pollutants to the lung (Harley et al., 2000) because its small size results in efficient diffusion to the lung airways.

Third, the presence in antiquity of active mining and rock-breaking, as well as crushing is likely to have directly increased the escape of radon directly as gas from the rock (Jha et al., 2001; Lipsztein et al., 2001) and indirectly at some sites as a result of the quarrying or tapping into radon-bearing groundwaters.In mines, ‘plate-out’ takes place (Phillips and Denman, 1997).This is the preferential adherence of larger particles to the walls of a cave or mine—with the result that lower concentrations of radon progeny will prevail in the mine atmosphere.If there were high loadings of dust in the mine atmosphere—from the ingress of dust in a storm, from mining the ores, or the general stirring of materials through movement in and out of the mines then radon progeny will attach to these suspended particles.Plate-out is then delayed, as the alpha particles are much less mobile.The radioactive species will, therefore, persist in the atmosphere much longer than if dustyaerosol particles were not present (Phillips and Denman, 1997).Such high loadings of particles would mean that radon progeny could be preferentially breathed in by mine workers.The radon loads that might have been ingested on dust via dirty hands, on food, or drunk in water are unknown.However , Cross et al. (1985) indicated that the dose to the respiratory system outweighs the dose to the digestion system.Radon loads in the spring waters emerging from the proterozoic spring waters in the Wadis are unknown; activity levels from hot springs at Zarah in the Dead Sea area to the north-west were below acceptable concentrations in drinking water (Al-Bataina et al., 1997; Moise et al., 2000).

In palaeodemographic terms, the lives of the forced labourers (male and female) in these Faynan mines and adits, and whilst engaged in oreprocessing and smelting may have been too nasty, brutal and short to place them at any conceivable risk from exposure to radon gas.In the Athenian mines of Laurion 8 years was estimated to be the maximum life expectancy of a forced labourer (Montag, 1962).The present research in the Faynan indicates that the lives of many members of the controlling professional classes with sustained exposure may have been at risk of life-threatening soft-tissue cancers after 7–15 years exposure. These arguments suggest that the skeletons of people who died at or after 40 years of age or more may be relatively few in number in comparison with those of agricultural communities who lived in less polluted environments.Skeletal remains of people with such longevity might have been the resident professionals who were the fortunate, long-term resiliently healthy; visitors or powerful people who lived and worked some distance from ore extraction and processing; and the more elderly of the constantly changing population of forced labourers.

5. Conclusions

Two winter surveys of the Rn concentrations 222 in abandoned copper mines and adits in the Faynan Orefield in Southern Jordan detected levels that would result in an annual dosage of between 8.8 and 57.77 mSv to long-term users of these mines. Concentrations in the Faynan mines and adits varied according to the time of survey, and the influence of other factors such as exposure, aspect and mine volume are not clear.In Nabatean to Byzantine times when mining and minerals processing were at their peak, it is likely that forced labourers who would have occupied the mines for substantial periods of time, and may have never been allowed to return to the surface (Shepherd, 1993, p.90), would have inhaled higher and more dangerous doses.The combination of greater physical exertion, rock-extraction, breaking and passage promoting dust and increased rates of radon exhalation from bedrocks, and low rates of radon plateout, in mines that were even more poorly ventilated suggests significantly higher rates of radon and progeny lodging in mine workers' lungs.Contemporary accounts indicate that forced labourers working in the mines were treated with such brutality that they were unlikely to have survived long enough to face a risk from exposure to radon. Significant potential risk may, however, have been faced by the more powerful people in the ancient mining community—professional miners, guards, overseers and administrators—who would have experienced sustained exposure to the atmosphere of the working mines and ore-processing sites.

Comparisons with the populations working in metalliferous mine sites elsewhere during the last century suggest that serious soft-tissue diseases may have begun to manifest to themselves after 7–20 years of sustained exposure.In the Faynan orefield, the immune systems of these managerial classes are likely to have been already weakened by exposure to suites of noxious and toxic metal pollutants that occur in the very polluted environment of the minerals processing centre of Khirbet Faynan.This analysis which is based on field surveys, published geological and epidemiological evidence, and surviving contemporary accounts, provides a first exploration of radon-induced sickness and mortality that might have prevailed in the mining communities of ancient world.King Solomon's miners, if such they were, are likely to have led short and unhealthy lives and we may now add radon-induced illness to the list of diseases induced by heavy metal toxicity to which they were exposed.

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